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Research paper

Analysis of the selection of materials for road construction taking into account the carbon footprint and construction costs

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Abstract: The analysis of the costs and emissions of greenhouse gases for individual phases of construction investments allows for the implementation of solutions and the prevention of negative environmental impacts without significantly increasing construction costs. The share of individual investment phases in the amount of carbon dioxide (CO_2) produced for the construction and use of buildings depends mainly on the materials used and the implemented design solutions. In accordance with the idea of sustainable construction, materials and design solutions with the lowest possible carbon footprint should be used. This can be achieved by using natural building materials, materials subjected to appropriate chemical composition modifications, or materials in which their production does not require large amounts of energy. The aim of the article is to determine the value of the purchase costs of selected road materials (concrete paving blocks, cement-sand bedding, concrete curbs, semi-dry concrete and concrete underlay, washed sand, and crushed aggregate with a fraction of 0–31.5 mm) for the implementation of a road investment. In addition, the authors focused on determining the size of the embodied carbon footprint due to GHG (greenhouse gas) emissions and GHG removals in a product system, expressed as CO_2 equivalents for the same materials that were subjected to cost analyzes. The article presents the results of original analyzes, and indicates the optimal solutions in terms of minimizing the cost of purchasing road materials and minimizing the carbon footprint. The discussion also covers the issue of changing the chemical composition in the context of the potential impact on the reduction of material costs and CO_2 equivalent emissions.

Keywords: carbon footprint, cost estimation, construction materials, road materials

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1. The carbon footprint and the costs of building materials – a literature review

1.1. Costs of building materials

Construction is important for the country economy since construction creates a large number of jobs and uses intermediate products and services (up to 40% of raw materials, chemical products, electrical and electronic equipment, etc.). The results of the construction industry can significantly affect overall economy development [22]. Building materials are the main components of most construction projects. The differences in their prices can have a significant impact on an entire project. As stated in [23], costs of building materials account for a large proportion of construction costs, and therefore a construction enterprise only generates profits when it appropriately deals with the cost of building materials, i.e. minimizes or reduces their overall value. Most construction projects today face the problem of budget overruns, with inflation, local material shortages that cause sudden spikes in individual material prices, and fluctuating construction material transportation costs being the major factors. Construction materials often constitute approx. 40–60% of construction costs. Material costs include the price of the material and the costs of purchasing materials (including, but not limited to, transport costs, processing costs and storage costs). The prices of construction materials fluctuate mainly due to supply, the supply environment, and the demand for the material for other uses [13]. The implementation of material cost management is an effective way to reduce production costs, increase economic efficiency, and maintain competitiveness in the construction market. The production costs of many materials depend on local factors. The differences in the prices of materials are determined by many factors, such as location; the availability of raw materials; the type of transport unit and the percentage of its filling; the distance of the transport; the type of road along which the transport unit moves; the cost of loading, reloading, unloading, and packing materials; insurance; etc. In long-term projects, the prices of building materials should be forecasted with regards to the inflation rate, and then amended in the initial bill of quantities in order to avoid a budget overrun [12]. Materials are consumed in large quantities and need to be delivered to a "random" location (where the built facility is required, not where the materials are available or easily transportable) [11].

The cost of purchasing materials can also fluctuate over short periods of time. A number of conducted studies concerning the supply of building materials are listed below. These studies illustrate common problems and difficulties associated with calculating delivery costs, which include: the complexity of problems related to the delivery of materials, and the large number of criteria affecting the costs of purchasing materials. The article [15] describes the synergy effect between lean construction and agile / flexible management. The authors used the real-time management method, which corresponds with the Construction 4.0 idea and which covers the processes of the production, transport and laying of a concrete mix on a road surface. The article compares the costs of transporting construction materials over a considerable distance (50 ± 5 km) using mainly public roads with the costs of transporting construction materials over a short distance (12 ± 3 km) using technical (service) roads. Research and observation of processes related to, among others, truck fleet management and material deliveries, confirmed the possibility of ensuring a significant increase in efficiency of the transport process. This in turn translates into a reduction in the cost of purchasing materials. Golpira in his research [10] created a model for large construction enterprises that use a decentralized procurement strategy and have warehouses close to multiple projects. One of his conclusions was that a greater number of suppliers corresponds to smaller delay penalties and transportation costs.

Another research [1] aimed to investigate issues that occur in construction material handling and transportation in large-scale construction projects. The authors identified several problems with material transportation, such as: accidents, adverse weather conditions, a lack of material handling equipment, a lack of labor, improper packing systems, the misplacing and stealing of materials, a lack of pre-arrangements, bulk quantities, a limited site area, delay in taking approvals, improper supervision, and an unawareness of the handling process. Material handling is the process of transferring goods from one location to another, as well as the system of managing those goods [4]. The loading and unloading costs processed during the transportation are difficult to calculate and are higher than the material handling cost [17].

Duchaczek in [8] claims that the efficient implementation of the transport process is primarily influenced by the trucks used for this purpose. In his analyzes, the author used the modified Belinger method in the process of optimizing the selection of trucks. The author devoted his attention to heavy goods vehicles that can be used in logistics projects both for the needs of the armed forces and civil logistic companies that provide the construction materials necessary for investments in Poland. Moreover, using the Belinger method, the authors [19] presented an analysis of warehouse logistics using an example of a warehouse of construction products and materials. The research presented activities that involved the optimization of the selection of forklifts in warehouses of building materials with regards to the effective and safe movement of loads around the warehouse area. The criteria adopted for the multi-criteria analysis were: the distance between the racks, the height of the rack, the maximum weight of goods transported by a forklift truck, the costs of purchasing and operating forklifts, and the safety of exploiting the warehouse space.

1.2. The carbon footprint of building materials

The carbon footprint problem has become a very pressing task in recent times. The emission of compounds such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbon (PFCs) and hydrofluorocarbons (HFCs) into the atmosphere is becoming a threat to human health and our existence. The measure of greenhouse gas (GHG) emissions is the carbon footprint. The issues of costs and the carbon footprint are also being tackled more and more often in the construction industry. To reach carbon neutrality, it is necessary to take into account the environmental burden of the production of building materials from the initial project planning phase. To meet this goal, it is necessary to change the methodology of developing a construction budget [21]. The authors highlighted the need for integrated cost and carbon footprint analyzes, and also showed an example of introducing values that indicate the size of the carbon footprint in the Slovak cost estimate program.

More and more research is being done in the production sector to reduce the carbon footprint. For example, in [24] the authors characterized the costs of energy saving and carbon dioxide emission reduction resulting from the application of energy efficient technologies in cement plants in the United States over a period of three years.

The authors in [14] showed an idea of the life cycle carbon footprint (LCCF). The LCCF represents the environmental impact and life cycle cost (LCC), which are considered as the objectives of the optimization. The LCCF is the sum of the operational carbon footprint (OCF) and the embodied / contained carbon footprint (ECF). The OCF is the operational carbon footprint of a building, i.e. CO_2 emissions related to space heating, ventilation, domestic hot water, lighting and appliances. The ECF is the embodied carbon footprint of a building, and covers CO_2 emissions related to the manufacturing, construction, maintenance and replacement of building elements, as well as a building's service / maintenance. The study presented an optimization approach based on a life cycle simulation, including the OCF and the ECF of a building.

According to [7], the use of precast concrete elements can reduce carbon dioxide emissions. For a one m^3 of concrete, prefabrication can lead to a 10% reduction in carbon dioxide emissions. The use of a prefabricated facade can reduce the CO_2 equivalent by 2.1 kg per m^2 of floor area.

Retrofitting existing buildings significantly contributes to reducing the life cycle environmental impact of buildings, with building renovation being seen as the most cost-effective way to achieve this goal [18]. Life Cycle Analysis (LCA) is often used to assess the impact of the life cycle of construction processes and the use of a building on the environment, costs or society. The authors used multi objective genetic algorithms to find the optimal solution for residential complex refurbishment projects in terms of LCCF and LCC over an assumed lifetime of 60 years.

In turn, in [2] the authors elaborated a generalized cost and carbon footprint life cycle analysis methodology for examining the benefits of different building practices for residential light-frame wood constructions subjected to tornado hazards. The authors used a multi-objective approach to reveal the trade-offs between resilient and sustainable practices in typical housing constructions. The authors, in their studies, showed that a balance between resistance, durability and cost can be achieved in the design and renovation of residential buildings – in this case in terms of the risk of tornadoes.

In practice, there are different ways of calculating the carbon footprint due to the elements considered and the phase or phases in the life cycle included in the calculation. For example in [20] authors calculate not only the building and urbanization direct costs, but also the production indirect costs and building and urbanization health and safety costs. For such determined costs, the authors calculated, among others, carbon footprint of fuel consumption, the efficiency factor for electricity production, the carbon footprint of water consumption that is determined assuming water needs, a certain quantity of energy to be carried to dwellings, carbon footprint related to the mobility of workers, the footprint of construction materials.

The footprint of construction materials was calculated as the product of material consumption in [kg] and the emission factor of material in [kg CO_2 eq/kg].

On the other hand, [25] proposed a method based on the quantification of CO_2 emissions. The method is based on the distribution of carbon emissions from regional structures, and the "carbon footprint" data were collected and analyzed by the authors to provide a theoretical reference for regional features [25]. Savings in CO_2 emissions may also apply to equipment and technical devices installed in the building. The authors in [9] discussed the breakdown of the processes that contribute to the total carbon dioxide emissions in the stamping process chain, such as electrical energy used by equipment, lubricant fluid and tool making. Authors in [3] made an attempt to measure both direct and indirect greenhouse gas (GHG) emissions in constructed wetlands. Authors presented a web application as an open and complete tool for the estimation of GHG emissions. The created application allows the introduction of a large number of additional parameters to offer a holistic approach of the process and to obtain a realistic and accurate estimation of CO_2 eq emission [3].

1.3. Cost analysis of materials and the carbon footprint

The examples cited above show a number of factors and problems that affect material costs. While sudden material price spikes, road accidents and weather conditions are difficult to predict in the cost calculation (and should be treated as a risk), most other factors can be included in the calculations quite easily. The issue of the carbon footprint is also more and more discussed with regards to both materials and entire structures in the context of the whole life cycle of a building structure. However, it can be seen that cost analysis that includes benefits for the environment (and in this case the reduction of greenhouse gas emissions) is not yet so common.

The authors, in their article, want to discuss the subject of estimating the cost (prices) of materials together with the cost of their purchase, with particular emphasis on the size of the carbon footprint. The aim of the article is to indicate the possibility of calculating the costs of selected materials used in road construction (while taking into account the purchase costs), and also to present the size of the carbon footprint and the assumptions that should be considered in the decision-making process.

2. Analysis of the material and purchase costs of selected road materials

2.1. Characteristics of a selected road construction investment

The location of the selected construction investment is the town of 'X' located in southern Poland. The investor has planned the construction of an industrial facility in this town due to, among other things, the attractiveness of this economic zone and the universal availability of road aggregates, which results from the location of a large number of granite, basalt and dolomite aggregate mines within a radius of approx. 50 km from the town. For this reason, the offer of local concrete plants is also attractive both for investors and contractors in terms of the prices for concrete mixes.

As part of the road works, the following elements were designed: maneuvering roads, parking spaces for passenger cars and trucks, storage areas, pavements, and access roads. According to the original design solution, the top layer (wearing course) consists of concrete paving blocks with a thickness of 8 cm, which are laid on a cement-sand bedding (in a ratio of 1:4 and with a thickness of 3 cm), and also concrete curbs measuring $15 \times 30 \times 100$ cm that are laid on semi-dry C12/15 concrete. Base layers, depending on their purpose, are made of for:

- maneuvering roads – C6/9 concrete underlay with a layer thickness of 24 cm,
- parking spaces for trucks – C6/9 concrete underlay with a layer thickness of 20 cm,
- parking spaces for passenger cars – crushed aggregate fraction 0–31.5 mm, one layer is 15 cm thick,
- storage areas – C6/9 concrete underlay with a layer thickness of 18 cm,
- pavements – crushed aggregate fraction of 0–31.5 mm, one layer is 10 cm thick,
- access roads – crushed aggregate fraction of 0–31.5 mm, two layers 18 and 12 cm thick.

An alternative design solution was also prepared, in which the structural layer of the C6/9 concrete underlay was replaced with a crushed aggregate underlay with a fraction of 0–31.5 mm, with the following being assumed for:

- maneuvering roads – making an underlay with a thickness of 30 cm, two layers (18 and 12 cm),
- parking spaces for trucks – making an underlay with a thickness of 25 cm, two layers (15 and 10 cm),
- storage areas – making an underlay with a thickness of 22 cm, two layers (14 and 8 cm).

For the analysis of the costs of purchasing the road materials, the materials included in the groups intended for the construction of the substructure and surface layers were selected. The data on the quantitative parameters of individual elements of the road works planned as part of the investment is presented in Table 1. All elements of the works were divided into two variants of their implementation, i.e. works in the amounts resulting from the original design (variant A), and also the replacement design (variant B).

As shown in Table 1, the difference in the demand for road materials results from the replacement of 3,681.48 m^3 of C6/9 concrete underlay with crushed aggregate underlay with a fraction of 0–31.5 mm, which increases the amount of aggregate from 2,414.90 tons to 12,829.17 tons.

The aim of the analysis is to determine the cost of purchasing road materials (concrete paving blocks; cement-sand bedding; concrete curbs; semi-dry and underlay concretes and aggregates, including washed sand; and crushed aggregate with a fraction of 0–31.5 mm). The analysis was performed separately for the aggregate material, for which the purchase costs were taken into account in relation to the possibility of using alternative variants of rail, truck and water transport. For the remaining materials (paving blocks, curbs and

Table 1. Quantitative list of road works to be performed (own study)

No.	Material	Unit	Quantity of material	
			Variant A	Variant B
1	Concrete paving blocks, 8 cm	m^2	20,758.00	20,758.00
2	Concrete curbs, 15 × 30 × 100 cm	m	923.00	923.00
3	Cement and sand bedding, 1:4	m^3	622.79	622.79
4	Concrete C6/9	m^3	3,681.48	0.00
5	Semi-dry concrete C12/15	m^3	73.51	73.51
6	Washed sand	t	370.03	370.03
7	Crushed aggregate, 0–31,5 mm	t	2,414.90	12,829.17

concrete mixes), the variant of road transport from construction warehouses and concrete plants located near the construction site was adopted.

2.2. Cost analysis of road materials

First, the authors present the cost statements of road materials, which were priced and offered by them as part of the inquiries addressed to selected sellers. In the inquiries, potential sellers were asked to price the materials for the ex-works (EXW) case, according to which the transport costs are borne by the buyer. The inquiries addressed to the aggregate mines also indicated the fact that there are two design variants, according to which the order for aggregate with the 0–31.5 mm fraction may concern the quantity of 2,414.90 tons for variant A, or 12,829.17 tons for variant B.

Table 2 presents data on aggregate prices with a fraction of 0–31.5 mm. Aggregate prices were obtained from 10 aggregate mines (AM1–AM10) located near the investment site, and three suppliers from a country that offers aggregate rail transport (companies from Zduńska Wola – K1, Warsaw – K2 and Krzeszowice–Zalas – K3). An offer was also obtained from one operator (Z1) that distributes aggregate using river transport. The amount of aggregate for variant A is 2,414.90 tons, and for variant B – 12,829.17 tons.

Similar cost analyzes were performed for other road materials, such as: C6/9 concrete, semi-dry C12/15 concrete, cement and sand bedding in a ratio of 1:4, concrete paving blocks, concrete curbs, and washed sand. Information on the prices for both the concrete mixes and the cement and sand bedding was obtained from 5 concrete plants (CP1–CP5) located near the investment site, while information on the prices for the concrete paving blocks with a thickness of 8 cm, the concrete curbs of 15 × 30 × 100 cm, and the washed sand was obtained from 5 construction warehouses (P1–P5) offering the sale of concrete accessories and sand.

Table 2. Offered prices of 0–31.5 mm crushed aggregates in PLN (own study)

No.	Seller or supplier	Unit price [PLN/ton]	Prices for variant A [PLN]	Prices for variant B [PLN]
1	AM1	25.50	61,579.95	327,143.84
2	AM2	27.30	65,926.77	350,236.34
3	AM3	31.30	75,586.37	401,553.02
4	AM4	27.25	65,806.03	349,594.88
5	AM5	31.90	77,035.31	409,250.52
6	AM6	29.00	70,032.10	372,045.93
7	AM7	31.90	77,035.31	409,250.52
8	AM8	26.70	64,477.83	342,538.84
9	AM9	28.45	68,703.91	364,989.89
10	AM10	27.85	67,254.97	357,292.38
11	K1	28.70	69,307.63	368,197.18
12	K2	26.80	64,719.32	343,821.76
13	K3	29.20	70,515.08	374,611.76
14	Z1	29.00	70,032.10	372,045.93

2.3. Analysis of the cost of purchasing road materials

In this part of the analysis, the authors calculated the purchase costs of selected road materials. First, the values of the purchase costs of crushed aggregate with a fraction of 0–31.5 mm (in the amount of 2,414.90 tons for variant A and 12,829.17 tons for variant B) were determined. The basic mode of transport was the own road transport of the 10 aggregate mines (AM1–AM10) located near the investment site. Road transport distances vary from 12.5 km (AM6 mine) to 41.4 km (AM10 mine). As alternative transport options, aggregate rail transport from three locations offering the sale of aggregate and rail transport (Zduńska Wola, Krzeszowice–Zalas and Warsaw) was proposed. In this alternative variant, additional road transport of aggregate was assumed for a distance of approx. 1.3 km from the railway siding to the construction site. The second alternative variant of aggregate transport is river transport, along with transporting aggregate by trucks to the construction site from a distance of approx. 15.0 km between the construction site and the river harbor. The transport situation is shown in Fig. 1, which shows the locations of 10 of the aggregate mines (AM1–AM10) marked in black, as well as the distances of aggregate transport by road from the railway siding (RS in green) and the river harbor (RH in blue).

Table 3 presents the purchase costs calculated for variants A and B, and also the total material costs of crushed aggregate with a fraction of 0–31.5 mm, which were determined for 10 cases of road transport from the AM1-AM10 aggregate mines, three variants of rail transport K1-K3 with aggregate delivery by trucks from the railway siding to the construction site (RS–CS for K1–K3) at a distance of approx. 1.3 km, and the Z1 river transport variant with aggregate delivery by trucks from the river harbor to the construction site (RH–CS for Z1) at a distance of approx. 15.0 km. The values estimated in the columns entitled "Total material costs" are the sum of the values of the material prices from Table 2

Table 3. List of purchase costs and total material costs for crushed aggregate with a fraction of 0–31.5 mm (own study)

No.	Route	Transport distance [km]	Variant A		Variant B	
			Purchase costs [PLN]	Total material costs [PLN]	Purchase costs [PLN]	Total material costs [PLN]
Road transport						
1	AM1–CS	39.3	47,452.79	109,032.74	252,093.19	579,237.03
2	AM2–CS	19.9	36,042.38	101,969.15	191,475.36	541,711.70
3	AM3–CS	21.5	38,940.26	114,526.63	206,870.37	608,423.39
4	AM4–CS	14.1	25,537.57	91,343.59	135,668.47	485,263.36
5	AM5–CS	18.7	33,868.97	110,904.28	179,929.11	589,179.63
6	AM6–CS	12.5	22,639.69	92,671.79	120,273.47	492,319.40
7	AM7–CS	26.2	47,452.79	124,488.10	252,093.19	661,343.71
8	AM8–CS	37.6	45,400.12	109,877.95	241,188.40	583,727.24
9	AM9–CS	39.0	47,090.55	115,794.46	250,168.82	615,158.70
10	AM10–CS	41.4	49,988.43	117,243.40	265,563.82	622,856.20
Railway transport						
11	K1–RS	276.0	214,642.35	286,304.51	1,140,288.70	1,520,994.32
	RS–CS	1.3	2,354.53		12,508.44	
12	K2–RS	468.0	295,547.54	362,621.38	1,570,097.97	1,926,428.17
	RS–CS	1.3	2,354.53		12,508.44	
13	K3–RS	290.0	222,194.95	295,064.56	1,180,411.93	1.567.532,14
	RS–CS	1.3	2,354.53		12,508.44	
River transport						
14	Z1–RH	367.0	177,253.66	274,453.39	941,661.08	1,458,035.17
	RH–CS	15.0	27,167.63		144,328.16	

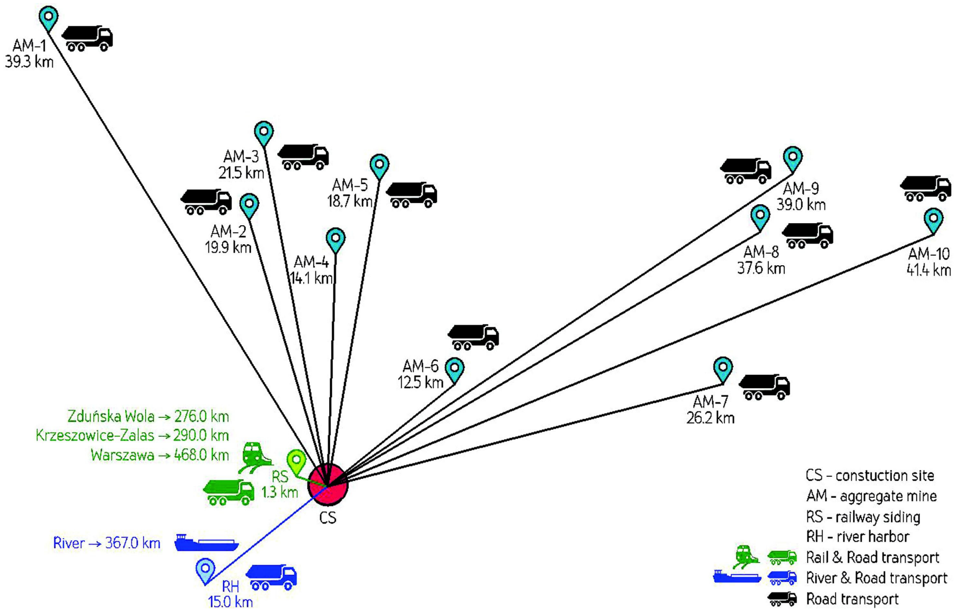

Fig. 1. Distances for the adopted transport variants (own study)

and the purchase costs from Table 3. The amount of aggregate for variant A is 2,414.9 tons, and for variant B – 12,829.17 tons.

Similar calculations were made for the remaining road materials that are part of the contract.

2.4. Choosing the optimal solution in terms of minimizing the cost of the purchase of road materials

In order to indicate the optimal variant of the investment implementation, Table 4 and Table 5 compile variants A and B of the planned road investment for the cases of the delivery of road materials for which the lowest purchase costs were obtained.

As can be seen from the comparison of the values listed in Table 4 and Table 5, the more advantageous variant of implementing the investment in terms of the purchase value of road materials is Variant A (the sum of PLN is 1,163,472.49 PLN). This variant is based on the original design solutions, according to which, for the construction of the layers for the elements: maneuvering roads, parking spaces for trucks and storage areas, a C6/9 concrete underlay with a layer thickness of 24 cm (maneuvering roads), 20 cm (parking spaces for trucks) and 18 cm (storage areas) was adopted. The sum of PLN for variant B is 1,178,729.95 PLN, which is greater than the sum for variant A by 1,178,729.95 – 1,163,472.49 = 15,257.46 PLN (+1.31%).

Table 4. List of cost data for road materials generating the lowest total material costs – variant A (own study)

No.	Material	Unit	Quantity of material [per unit]	Place of purchase	Total material cost [PLN]
1	Concrete paving blocks, 8 cm	m^2	20,758.00	P5	564,410.02
2	Concrete curb, 15 × 30 × 100 cm	m	923.00	P1	15,441.79
3	Cement and sand bedding, 1:4	m^3	622.79	CP3	91,299.77
4	Concrete C6/9	m^3	3,681.48	CP1	378,662.31
5	Semi-dry concrete C12/15	m^3	73.51	CP3	11,167.86
6	Washed sand	t	370.03	P1	11,147.15
7	Crushed aggregate, 0–31,5 mm	t	2,414.90	AM4	91,343.59
				Sum of PLN	1,163,472.49

Table 5. List of cost data for road materials generating the lowest total material costs – variant B (own study)

No.	Material	Unit	Quantity of material [per unit]	Place of purchase	Total material cost [PLN]
1	Concrete paving blocks, 8 cm	m^2	20,758.00	P5	564,410.02
2	Concrete curb, 15 × 30 × 100 cm	m	923.00	P1	15,441.79
3	Cement and sand bedding, 1:4	m^3	622.79	CP3	91,299.77
4	Concrete C6/9	m^3	0.00	–	0.00
5	Semi-dry concrete C12/15	m^3	73.51	CP3	11,167.86
6	Washed sand	t	370.03	P1	11,147.15
7	Crushed aggregate, 0–31,5 mm	t	12,829.17	AM4	485,263.36
				Sum of PLN	1,178,729.95

3. Analysis of the size of the generated carbon footprint in the process of the production, transport and application of the selected materials

3.1. Built-in and operational carbon footprint

According to ISO standards, the carbon footprint of a product is the sum of GHG (Greenhouse gas) emissions and GHG removals in a product system, expressed as CO_2 equivalents. The carbon footprint includes, inter alia, such gases as carbon dioxide (CO_2), dinitrogen monoxide (N_2O), hydrofluorocarbons (HFCs), methane (CH_4), perfluorocarbons (PFCs), and Sulphur hexafluoride (SF_6). The amount of greenhouse gas emissions in the process of extracting raw materials, producing materials, and applying them in road construction depends on the type of used materials and the adopted design solutions. In turn, the carbon footprint for transport processes depends primarily on the type of transport and the distance that the means of transport must cover in order to bring building materials to the construction site.

Carbon footprint analyzes throughout the life cycle are based on solutions that take into account both the Embodied Carbon Footprint (ECF) and the Operational Carbon Footprint (OCF). The ECF can be defined as the CO_2 equivalent emitted during the construction of a building. The ECF covers the following processes related to the construction of the facility: the extraction of raw materials, the processing of raw materials, the production of building materials, the transport of materials to the construction site, the proper implementation of the building structure, as well as the demolition and disposal of materials at the end of their operation. The OCF, in turn, is the equivalent of CO_2 emitted during the operation phase of a building structure, and is therefore the carbon footprint formed during the use, management and maintenance of a facility.

In the article, the authors focused on determining the size of the ECF in transport processes, as well as in the production and application of selected building materials. All the calculations of the carbon footprint for the production, application, and transport of materials from the mine or from the producer to the construction site were made using the ‘Carbon Calculator ver. 3.2’ from the Environment Agency. This is a Microsoft Excel based tool, published by the Environment Agency, that allows to the material and transport choices in a construction project to be compared and assessed.

3.2. Analysis of the embodied carbon footprint of selected materials

The extraction, processing, production, transportation, and handling of raw materials are energy-and-carbon-intensive processes. Among the various raw materials for cement and concrete, cement manufacturing had the highest environmental footprint, which was responsible for the consumption of about 74.0% energy while also producing 88.0% GHG emissions [5]. The aim of the analysis is to determine the size of the embodied carbon footprint due to the high GHG emission of the basic materials used in road construction, such as the above-mentioned cement and concrete. The analysis was performed for the variants of material solutions for the road pavements presented in point 2, for which a cost analysis was performed. In Table 6 and Table 7, calculations of the carbon footprint in the process of the production and application of materials for variants A and B of the analyzed solutions are presented.

As the analysis of Table 6 and Table 7 shows, the amount of CO_2 emissions and CO_2 equivalent a significantly lower in variant B of the investment. This is due to the elimination

Table 6. The carbon footprint in the process of the production and application of materials for variant A of the investment (own study)

No.	Material	Unit	Quantity of material [per unit]	Embodied tCO_2e per unit of material	Embodied tCO_2e per quantity of material
1	Concrete paving blocks, 8 cm	m^2	20,758.00	0.03038384	630.7078
2	Concrete curb, 15 × 30 × 100 cm	m	923.00	0.00519750	4.7973
3	Cement and sand bedding, 1:4	m^3	622.79	0.4004	249.3651
4	Concrete C6/9	m^3	3,681.48	0.3080	1,133.8958
5	Semi-dry concrete C12/15	m^3	73.51	0.3630	26.6841
6	Washed sand	t	370.03	0.0051	1.8872
7	Crushed aggregate, 0–31.5mm	t	2,414.90	0.0050	12.0745
				Sum of tCO_2e	2,059.4118

Table 7. Carbon footprint in the process of the production and application of materials for variant B of the investment (own study)

No.	Material	Unit	Quantity of material [per unit]	Embodied tCO_2e per unit of material	Embodied tCO_2e per quantity of material
1	Concrete paving blocks, 8 cm	m^2	20,758.00	0.03038384	630.7078
2	Concrete curb, 15 × 30 × 100 cm	m	923.00	0.0051975	4.7973
3	Cement and sand bedding, 1:4	m^3	622,79	0.4004	249.3651
4	Semi-dry concrete C12/15	m^3	73.51	0.3630	26.6841
5	Washed sand	t	370.03	0.0051	1.8872
6	Crushed aggregate, 0–31.5 mm	t	12,829.17	0.0050	64.1458
				Sum of tCO_2e	977.5873

of the C6/9 concrete underlay in favor of increasing the material for the aggregate underlay layer. The difference in the embodied carbon footprint without transport processes is 2,059.4118 – 977.5873 = 1,081.8245 tCO_2e (–52.53%).

3.3. Analysis of the carbon footprint of the transport of building materials

Although the tightening of vehicle emission standards has reduced exhaust emissions of noxious gasses, such as nitrogen oxides, hydrocarbons, carbon monoxide and particulate matter, attention has shifted to the growth in carbon dioxide (CO_2) emissions from the freight sector [16]. Calculations of the CO_2 equivalent value in transport processes for the analyzed example are made below. The calculations took into account road transport, and for aggregate with a fraction of 0–31.5 mm, rail and inland river transport.

First, the analysis covered the road transport of crushed aggregate from 10 aggregate mines (AM1–AM10) located near the investment site, rail transport from three locations offering the sale and transport of aggregate (including transporting at a distance of 1.3 km from the railway siding to the investment site by trucks), and river transport (along with transporting 15.0 km from the river harbor to the investment site by trucks). In Table 8, the transport distances and calculated values of the CO_2 equivalent for 14 variants of aggregate

Table 8. The amount of CO_2 equivalent for the aggregate transport variants (own study)

No.	Route	Transport distance [km]	Variant A (amount of aggregate 2,414.9 m^3) [tons fossil CO_2e]	Variant B (amount of aggregate 12829.17 m^3) [tons fossil CO_2e]
Road transport				
1	AM1–CS	39.3	10.128	53.807
2	AM2–CS	19.9	5.129	27.246
3	AM3–CS	21.5	5.541	29.436
4	AM4–CS	14.1	3.634	19.305
5	AM5–CS	18.7	4.819	25.603
6	AM6–CS	12.5	3.221	17.114
7	AM7–CS	26.2	6.752	35.871
8	AM8–CS	37.6	9.690	51.479
9	AM9–CS	39.0	10.051	53.396
10	AM10–CS	41.4	10.670	56.682
Railway transport				
11	K1–CS	276.0	24.956	132.579
12	K2–CS	468.0	42.084	223.570
13	K3–CS	290.0	26.205	139.214
River transport				
14	Z1–CS	367.0	17.479	92.857

transport are shown: 10 variants of road transport from AM1–CS to AM10–CS, three variants of rail transport from K1–CS to K3–CS, and the variant of river transport Z1–CS.

In Table 9, calculations were made for 5 variants of transporting concrete mix from various concrete plants (CP1–CP5) to the construction site. The table shows the transport distances and the carbon footprint values for variants A and B of the investment.

Table 9. The carbon footprint of transporting concrete mix to the construction site (own study)

No.	Route	Transport distance [km]	Variant A (amount of concrete C6/9 – 3,681.48 m^3, C12/15 – 73.51 m^3 and cement and sand bedding – 622.79 m^3) [tons fossil CO_2e]	Variant B (amount of concrete C6/9 – 0.00 m^3, C12/15 – 73.51 m^3) and cement and sand bedding – 622.79 m^3) [tons fossil CO_2e]
1	CP1–CS	1.2	0.138423951	0.002709873
2	CP2–CS	2.6	0.299918561	0.005871391
3	CP3–CS	7.1	0.819008379	0.016033413
4	CP4–CS	7.1	0.819008379	0.016033413
5	CP5–CS	16.3	1.880258673	0.036809103

In Table 10, calculations were made for 5 variants of transporting concrete paving blocks from different locations (P1–P5) to the construction site. The table shows the transport distances and the carbon footprint values for variants A and B of the investment.

Table 10. The carbon footprint of transporting paving blocks to the construction site (own study)

No.	Route	Transport distance [km]	Variants A and B (amount of concrete paving blocks 20,758.00 m^2) [tons fossil CO_2e]
1	P1–CS	0.3	0.017217516
2	P2–CS	1.2	0.068870062
3	P3–CS	7.3	0.418959544
4	P4–CS	7.9	0.453394575
5	P5–CS	14.6	0.837919089

3.4. Choosing the optimal solution in terms of minimizing the size of the carbon footprint

Taking into account the most advantageous amounts of the generated carbon footprint in the production, transport and application of the selected materials for the selected investment, the lowest total value of the carbon footprint expressed in [tons fossil CO_2e] is provided by variant B of the investment implementation. This variant assumes the replacement of the construction layer of the C6/9 concrete underlay with a crushed aggregate underlay with a fraction of 0–31.5 mm. Table 11 summarizes the information on the calculated optimal (minimum) value of the CO_2 carbon footprint equivalent in the production and application of materials, as well as transport of aggregate, concrete and paving blocks for variant B of the investment.

Table 11. The carbon footprint in the process of the production, application and transport of materials for variant B of the investment (own study)

No.	Process type	Seller	Embodied tCO_2e per quantity of material
1	Production and materials application into the construction	–	977.5873
2	Transport of crushed aggregate, 0–31.5 mm	AM6	17.114
3	Transport of semi-dry C12/15 concrete and cement and sand bedding in a ratio of 1:4	CP1	0.002709873
4	Transport of concrete paving blocks, 8 cm, concrete curbs, $15 \times 30 \times 100$ cm, and washed sand	P1	0.017217516
		Sum of tCO_2e	994.7212

4. Discussion of the presented results

The cost analyzes carried out in point 2 of the article indicate that the optimal variant of the implementation of a selected road investment in terms of minimizing the costs of purchasing road materials is variant A. As it results from the comparison of the cost values calculated in Table 4 and Table 5, the purchase value of road materials for variant A is PLN 1,163,472.49. The purchase value of road materials for variant B is PLN 1,178,729.95, and is greater than variant A by PLN 15,257.46 (+1.31%), which, according to the authors, is a slight difference. Moreover, after carrying out the cost analyzes, the following conclusions can be drawn:

- at a distance of approx. 25.0–40.0 km, the costs of road transport of material from the aggregate mine is on a similar level,
- if there were no aggregate mines available in the immediate vicinity of the investment site, rail or inland river transport of aggregate would be a more advantageous option due to the lower costs of purchasing material at a distance of more than 280.0 km.

The analyzes of the carbon footprint presented in point 3 prove that the most advantageous variant of the implementation of a selected road investment in terms of minimizing the carbon footprint is variant B. From the comparison of the values presented in Table 6 and Table 7, it can be seen that the amount of CO_2 equivalent emissions is significantly lower in variant B of the investment. In variant A, the emission value was equal to 2,059.4118 tCO_2e, and in variant B – 977.5873 tCO_2e. The emission reduction by as much as 1,081.8245 tCO_2e (–52.53%) in the case of variant B results from replacing the C6/9 concrete underlay with a layer of aggregate underlay with a fraction of 0–31.5 mm. According to the authors, this difference is significant.

However, taking into account the comprehensive assessment of both variants of the road investment in terms of not only minimizing the size of the carbon footprint, but also the costs of purchasing road materials, it should be noted that the costs of purchasing the road materials for variant B of the investment implementation for the case corresponding to the lowest possible CO_2 equivalent emission in the process of the production, application and transport of the materials amounted to PLN 1,192,885.67. This value is greater than the optimal cost of purchasing road materials for variant A of the selected investment (PLN 1,163,472.49) by PLN 29,413.18 (+2.47%). It is also greater by PLN 14,155.72 (+1.19%) than the lowest cost of purchasing road materials for variant B (PLN 1,178,729.95). According to the authors, the presented cost differences are so insignificant that in the case of the investment in question, the choice of design solutions (primary and replacement design) should be guided by the criterion of minimizing the carbon footprint.

In the aspect of minimizing costs and the carbon footprint, it is possible to consider a change of materials or a change in the composition of materials. Zima in [26] indicates that cement production has the greatest carbon footprint, which results in large differences depending on the concrete mixture class and used ingredients. The remaining ingredients, such as fly ashes and concrete admixtures, do not have a significant impact on greenhouse gases emissions. The concrete mixture cost is basically proportional to the amount of cement in the mixture. Table 12 shows the changes in the composition of the mixtures during the production of concrete paving blocks, as well as the impact of these changes on the amount of carbon footprint produced and the cost of the material.

Table 12. The carbon footprint, cost and compressive strength for concrete paving mixes (own study based on [6])

Mix no.	Water [kg/m^3]	Cement [kg/m^3]	PWTA [kg/m^3]	CO_2 emission [ton/m^3]	Cost of a piece of paving block [EUR]	Compressive strength [MPa]
M1	79.3	396.8	0.00	0.379798	0.41	20.0
M2	91.3	357.1	39.68	0.343352	0.38	16.0
M3	99.2	317.5	79.37	0.306999	0.36	14.0
M4	146.8	277.8	119.1	0.270562	0.33	12.0
M5	182.5	238.1	158.7	0.234120	0.31	10.0

Table 12 clearly shows that both the cost and the carbon footprint of materials containing concrete, such as paving blocks, can be reduced. Of course, changing the composition of the concrete mix, which involves reducing the weight of cement with the use of an additive in the form of processed waste tea ash (PWTA), increases the demand for water and reduces the compressive strength of the concrete blocks. However, depending on the desired needs, such additives can be used in the context of lowering the material price and the carbon footprint value. Such activities have set the direction of development in the production of sustainable building materials for the coming years.

5. Conclusions

The costs of construction works are an extremely important factor influencing investment decisions. However, in the case of contracts for construction works, other factors are also important, e.g. social factors. The issue of excessive greenhouse gas emissions in the construction process has increasingly appeared in an open discussion concerning sustainable construction.

The article shows, based on the example of two variants of implementing a road investment, how changes in the structure of the substructure construction layers may affect the investment costs and the size of the carbon footprint. The issues of the types of transport of the basic materials used in construction works were also discussed, indicating differences in the prices and carbon footprint with different transport means and distances. Finally, the cost relationships and carbon footprint emissions for selected materials were discussed, and solutions were indicated that relate to changes in the composition of concrete mixes, e.g. in the production of concrete paving blocks, which can in turn reduce both the costs and the amount of greenhouse gas emissions in road construction works.

The analyzes prepared by the authors may indicate that the problem being solved concerns a two-criteria optimization issue. Because the differences in purchase value of road materials between variants A and B were, according to the authors, insignificant (from +1.19% to +2.47%), the authors did not attempt to solve the optimization problem using analytical methods, focusing on the criterion of minimizing the carbon footprint as the most important criterion thanks to which the reduction of the carbon footprint will be noticeable (by over –50%).

In the future, the authors plan to extend their analyzes based on a two-criteria approach by applying the existing analytical methods to multi-criteria optimization. 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. It is all the more justified as large infrastructural investments in Northern Poland make it possible to choose the transport of some construction materials (e.g. road and hydraulic aggregate) using river and sea transport when purchasing them in other European Union member states.

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Koszty materiałów drogowych w ujęciu kryterium minimalizacji wartości miary śladu węglowego

Słowa kluczowe: kosztorysowanie, materiały budowlane, materiały drogowe, ślad węglowy

Streszczenie:

Analiza koszów i emisji gazów cieplarnianych dla poszczególnych faz inwestycji budowlanych pozwala na wdrożenie rozwiązań i zapobieganie negatywnemu wpływowi na środowisko bez znaczącego zwiększania koszów budowy. Udziałposzczególnych faz inwestycji w ilości wytworzonego dwutlenku węgla (CO_2) do budowy i użytkowania obieków budowlanych zależy głównie od zastosowanych materiałów i wdrożonych rozwiązań projektowych. Zgodnie z ideą budownictwa zrównoważonego, winno się stosować materiały i rozwiązania projektowe o możliwie najmniejszym śladzie węglowym.

Celem artykułu jest określenie wielkości koszów nabycia wybranych materiałów drogowych na wykonanie inwestycji drogowej. Dodatkowo autorzy skupili się na określeniu wartości wbudowanego śladu węglowego w procesie produkcji budowlanej, kóry wyrażany jest w postaci ekwiwalentu CO_2 dla tych samych materiałów, kóre poddano analizom kosztowym. W artykule przedstawiono wyniki autorskich analiz, wskazano rozwiązania optymalne z uwagi na minimalizację koszów nabycia materiałów drogowych i minimalizację śladu węglowego.

Analizę kosztową podzielono na dwie części. W pierwszej części dokonano szczegółowej analizy cen materiałów drogowych (kostki betonowej, podsypki cementowo-piaskowej, krawężnika betonowego, betonów półsuchego i podkładowego, piasku płukanego, a także kruszywa łamanego o frakcji 0–31,5 mm), zaoferowanych przez lokalnych sprzedawców/dostawców. Wyodrębniono dwa warianty realizacji inwestycji, kóre wynikają z projektu pierwotnego (wariant A) oraz zamiennego (wariant B). Różnica w zapotrzebowaniu na materiały drogowe w obu wariantach realizacji wynika z zastąpienia betonu podkładowego C6/9 w ilości 3 681,48 m^3 kruszywem łamanym o frakcji 0–31,5 mm, przez co ilość kruszywa w wariancie B wzrasta z 2 414,90 ton do 12 829,17 ton. W analizie koszów zakupu materiałów drogowych (część 2) wzięto pod uwagę opcje transportu samochodowego kruszywa łamanego z 10 kopalni (AM1–AM10) umiejscowionych w pobliżu terenu inwestycji oraz alternatywne możliwości transportu kolejowego kruszywa z trzech lokalizacji oferujących sprzedaż i transport

kolejowy kruszywa, a także transportu rzecznego wraz z dowiezieniem kruszywa samochodami ciężarowymi na plac budowy z portu przeładunkowego.

W analizie wielkości generowanego śladu węglowego, autorzy wyodrębnili części dotyczące oszacowania wielkości wbudowanego śladu węglowego w procesach produkcji i wbudowania materiałów budowlanych w konstrukcję oraz wielkości wynikającej z procesów transportu materiałów budowlanych. Analizy dokonano dla warianów rozwiązań materiałowych nawierzchni drogowych i opcji transportu, dla kórych dokonano uprzednio analizy kosztowej.

Analizy kosztowe przeprowadzone w punkcie 2 artykułu wskazują, że optymalnym wariantem realizacji wybranej inwestycji drogowej pod względem minimalizacji koszów nabycia materiałów drogowych jest wariant A, odpowiadający pierwotnym rozwiązaniom projektowym. Jak wynika z porównania wartości kosztowych wyliczonych w Tabelach 4 i 5, wartość nabycia materiałów drogowych dla wariantu A inwestycji wynosi 1 163 472,49 PLN. Wartość nabycia materiałów drogowych dla wariantu B jest równa 1 178 729,95 PLN i jest większa od wariantu A o 15 257,46 PLN (+1,31%), co zdaniem autorów jest niewielką różnicą. Analizy śladu węglowego przedstawione w punkcie 3 artykułu świadczą z kolei, że najkorzystniejszym wariantem realizacji wybranej inwestycji drogowej pod względem minimalizacji śladu węglowego jest wariant B. Jak wynika z porównania wartości przedstawionych w Tabelach 6 i 7, wielkość emisji ekwiwalentu CO_2 jest znacząco niższa w wariancie B inwestycji. W wariancie A otrzymano wielkość emisji równą 2 059,4118 tCO_2e, a w wariancie B – 977,5873 tCO_2e. Redukcja emisji aż o 1 081,8245 tCO_2e (–52,53%) w przypadku wariantu B wynika z zastąpienia podbudowy betonowej C6/9 warstwą podbudowy z kruszywa o frakcji 0-31,5 mm. Zdaniem autorów różnica jest istotna.

Biorąc pod uwagę kompleksową ocenę obu warianów inwestycji drogowej pod względem nie tylko minimalizacji wielkości śladu węglowego, ale również koszów nabycia materiałów drogowych, należy wskazać, że koszty nabycia materiałów drogowych dla wariantu B realizacji inwestycji dla przypadku odpowiadającego najmniejszej możliwej emisji ekwiwalentu CO_2 w procesach produkcji, wbudowania i transportu materiałów, wynoszą 1 192 885,67 PLN. Wartość ta jest wyższa od optymalnej wartości koszów nabycia materiałów drogowych dla wariantu A wybranej inwestycji (1 163 472,49 PLN) o 29 413,18 PLN (+2,47%) oraz o 14 155,72 PLN (+1,19%) od najniższej wartości koszów nabycia materiałów drogowych dla wariantu B (1 178 729,95 PLN). Zdaniem autorów, przedstawione różnice kosztowe są na tyle nieistotne, że w przypadku przedmiotowej inwestycji, należałoby się kierować przy wyborze rozwiązań projektowych (projekt pierwotny i zamienny) jednak kryterium minimalizacji śladu węglowego aniżeli kryterium kosztowym.

Dyskusja (punkt 4 artykułu) obejmuje swoim zakresem również zagadnienie zmiany składu chemicznego w kontekście potencjalnego wpływu na redukcję koszów materiałów i emisji ekwiwalentu CO_2. Autorzy posłużyli się przykładem modyfikacji składu mieszanki przy wytwarzaniu kostki betonowej poprzez redukcję masy cementu przy zastosowaniu dodatku w postaci przetworzonych popiołów pochodzących z odpadów.

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