

# Assessment of Material Solutions of Multi-level Garage Structure Within Integrated Life Cycle Design Process

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**Abstract.** The paper presents an environmental and economic analysis of the material solutions of multi-level garage. The construction project approach considered reinforced concrete structure under conditions of use of ordinary concrete and high-performance concrete (HPC). Using of HPC allowed to significant reduction of reinforcement steel, mainly in compression elements (columns) in the construction of the object. The analysis includes elements of the methodology of integrated life cycle design (ILCD). By making multi-criteria analysis based on established weight of the economic and environmental parameters, three solutions have been evaluated and compared within phase of material production (information modules A1-A3).

## 1. Introduction

Sustainable development has contributed to a new approach to design which includes all requirements imposed on sustainable construction within a single process referred to as integrated life cycle design [1]. This new approach combines design on the level of material, structural element and entire structure; further, it considers selected criteria of technical, economic, environmental as well as social and cultural requirements. The evaluation of potential solutions refers to the entire life cycle of a structure, including the division into information modules corresponding with successive life cycle phases of a civil structure. The assessment of various structural solutions is based on the European Standards [2][3][4][5]. However, its recommendations are limited to the provision of indicators subject to evaluation, without specifying methods for evaluating alternatives and weighing sustainable development criteria. A comprehensive assessment of a building with the consideration of different alternatives and for the entire life cycle makes the design process complicated. Alternatives are evaluated during the design process several times at various levels, in order to find an optimal solution, in view of selected criteria.

One of the key phases in designing a structure is the selection of materials for structural elements. As far as multi-level garages are concerned, high-performance concrete seems like an interesting option. According to the statistics maintained and published by the European Ready Mixed Concrete Organisation, only 11% of ready-mixed concrete is of high-performance type [6]. The analysis of statistics on HPC production shows that these trends do not change, irrespective of benefits from the application of this type of concrete [7]. The benefits particularly include structure durability and reduction of the amount of steel used. Both these features testify to the ecological and economic character of the material in question. Nevertheless, HPC contains more concrete mix cement, whose

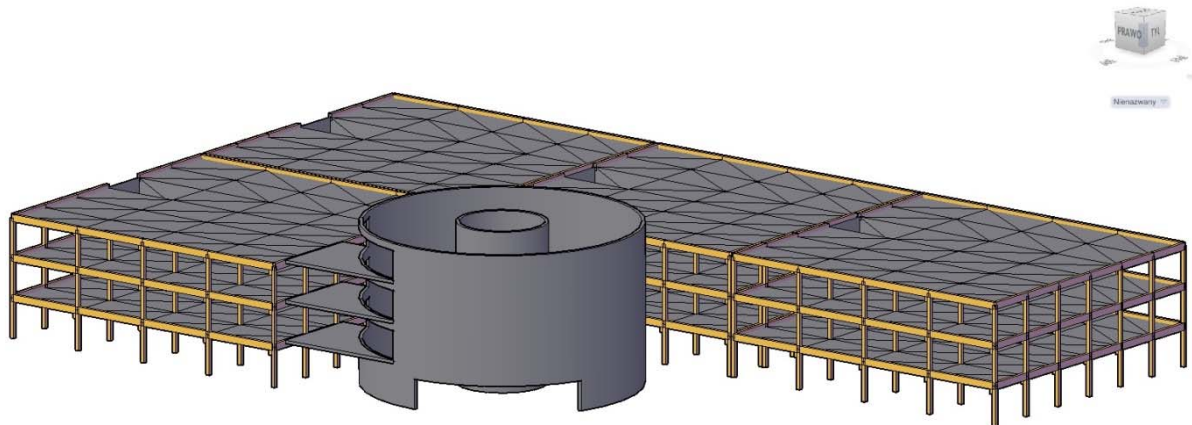


production considerably strains the environment at the production stage; on the other hand, it increases the durability of concrete and allows the reduction of cross-sections of load-bearing elements in the structure. Therefore, to unambiguously evaluate whether a specific technology will bring greater or smaller environmental benefits at the material production stage, proper analyses should be performed. The environmental analysis ought to be additionally completed with economic analysis, as the investor's preferences tilt towards solutions beneficial for the investor in financial terms.

The article contains the evaluation of a multi-level garage structure built with plain concrete and HPC. In this case, environmental and economic criteria are considered as the most important ones from sustainable development criteria. Section 2 precisely specifies the subject and scope of evaluation. It also presents the methodology of structure design, determination of economic and environmental indicators and selected methods for evaluating alternatives – off the set of methods for multi-criteria analyses (section 3). Section 4 contains results of structural analyses, summary of environmental and economic indicators for solutions taken into account and results of multi-criteria analyses with three methods. The Conclusions (Section 5) do not only refer to the evaluation of HPC as an alternative to plain concretes, but also to ILCD-related matters, as this approach does not yet have methods for conducting the design process.

## 2. Subject and scope of evaluation

These studies have been concerned with a four-storey building of a multi-level garage consisting of four elements connected with expansion joints and of a spiral-shaped inclined ramp (figure 1). One of the duplicate segments was analysed, its dimensions as follows: in the plan view 32×30 m and a single storey as high as 4.0 m, slabs and columns with a shaft. The external floor slabs are additionally fastened with reinforced concrete beams. The analysis has not included the building foundations.



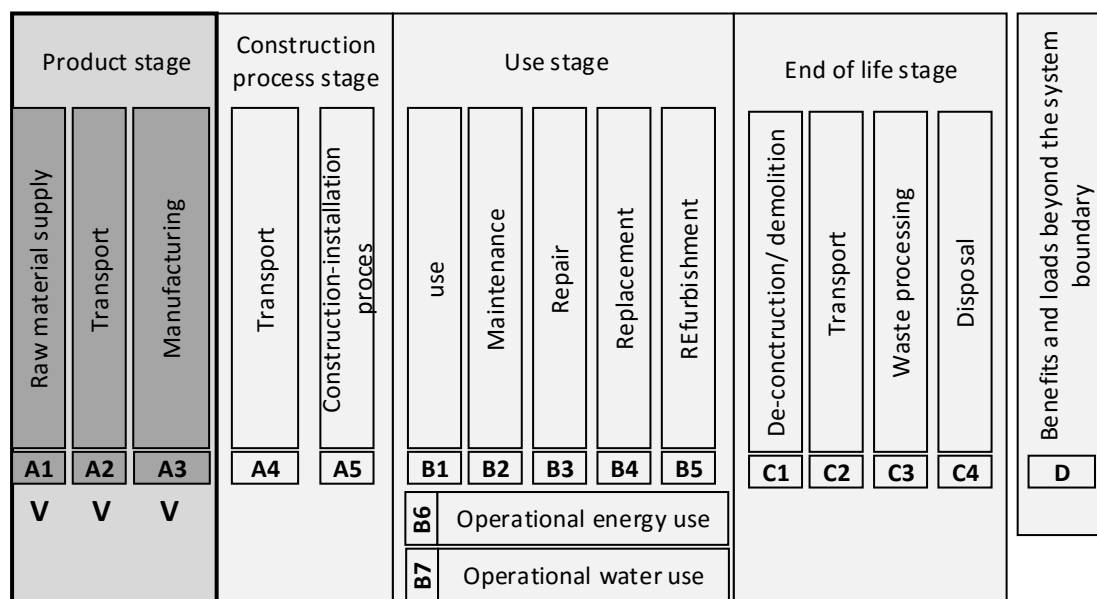
**Figure 1.** General view of the analysed element of the multi-level garage

For the purpose of this analysis the use of two concrete classes has been considered - C30/37 and C70/85 (HPC) unto elements of different sizes. The contents of starting concrete mixes are to be found in table 1.

**Table 1.** Contents of concrete mixes

| Ingredients              | C30/37            | C70/85            |
|--------------------------|-------------------|-------------------|
|                          | kg/m <sup>3</sup> | kg/m <sup>3</sup> |
| Cement CEM I 32,5R       | 380               | -                 |
| Cement CEM I 42,5R       | -                 | 500               |
| Water                    | 190               | 150               |
| Sand                     | 580               | 615               |
| Coarse aggregate/diabase | 1260              | 961               |
| Silica dust              | -                 | 35                |
| Superplasticiser         | -                 | 10                |

The evaluation is from cradle to gate, as it covers modules A1-A3 (figure 2); therefore, it is an integrated design process stage; however, it allows us to reach some conclusions important from the designer's point of view and related to the potential of specific material solutions.

**Figure 2.** Scope of evaluation

### 3. Assessment methodology

#### 3.1. Structure analysis

Three structural alternatives were examined for which Ultimate Limit States (ULS) and Serviceability Limit States (SLS) were checked, which enabled us to specify the consumption of concrete and reinforcement steel in the respective cases:

- Alternative I – concrete C30/37 used on the floor slab as thick as 25 cm, columns 35×35 cm and beams 35×70 cm,

- Alternative II – concrete C70/85 used on the floor slab as thick as 25 cm, columns 35×35 cm and beams 35×70 cm,
- Alternative III – concrete C70/85 used on the floor slab as thick as 20 cm, columns 30×30 cm and beams 30×60 cm.

The verification of ULS and SLS was based on standards [8][9][10]. The analysis included dead weights of respective structural elements as well as operating and environmental loads. All the calculations were performed with Autodesk Robot Structural Analysis Professional 2013.

### 3.2. Determination of environmental and economic indicators

To determine the influence of the building on the environment according to standard [2][3], the following indicators were used:

- environmental impact indicator – LCIA category,
- resource consumption indicator,
- indicators related to other environmental information.

To avoid double calculation of environmental benefits and loads, the analysis comprised 11 indicators [11] (table 2).

The estimation of the environmental impact of concrete is of additive character. Environmental indicators were developed on the basis of environmental statements (EPD) from suppliers of half-products used for the preparation of concrete mixes and structural reinforcement. Environmental impacts (LCIA indicator) due to the consumption of water from the water pipe network were determined in GaBi, based on model EU 27: Tap water.

The material price was considered as an economic indicator; it was specified based on the analysis of market prices of construction materials.

### 3.3. Multi-criteria analysis

The complex nature of sustainable development results in a multi-aspect analysis of adopted alternatives for the erection of the civil structure. The multi-criteria problem requires the consideration of the simultaneous impact of all the analysed criteria on the final decision, which is a choice of an option closest to the optimal solution under specific conditions. The multi-factor analysis was performed with three methods, justified with the attempt to achieve the repeatability of results confirming the advantage of one technology over the others and to exclude subjectivism resulting from preferences of the decision-maker. During the studies, we applied the Multiple Criteria Comparative Analysis, analytic hierarchy process (AHP) and TOPSIS method.

The essence of the mathematical methods is establishing a scalar whose numerical value determines the alternative evaluation indicator [12]. Due to the distinctness of units characterising the adopted criteria, it is required that primary numerical data be replaced with dimensionless values while coding [13]. The coding method adopted in this article is normalisation; the calculations take the character of variables into account. All the analysed criteria are destimulants and the increase of each variable value causes the complex phenomenon level to decrease, in this instance the extent to which the civil structure meets sustainable development standards. The calculation of synthetic indicators is preceded by the adoption of environmental criteria weights [11] and assumption of their relevance for the final choice of the solution on level 0.3 and costs on level 0.7, (table 2). In practice, the level of relevance is dependent on preferences of the decision-maker, such as the investor.

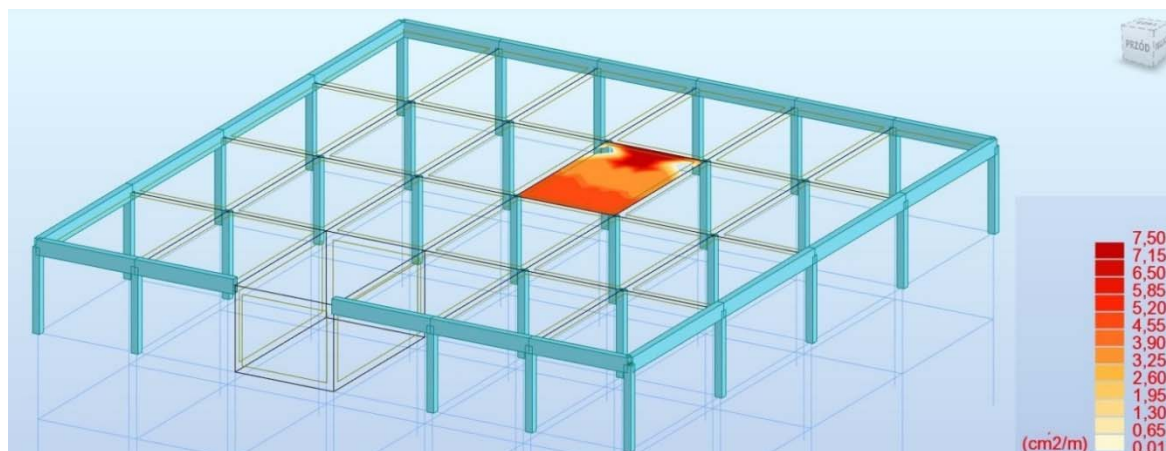
**Table 2.** Summary of environmental and economic indicators and adopted weights

| Symbol | Criterion  | Weight |
|--------|--|--------|
| K1     | Global Warming Potential, GWP; kgCO <sub>2</sub> equiv                                 | 0.0726 |
| K2     | Net use of fresh water, m <sup>3</sup>   | 0.0456 |
| K3     | Depletion potential of the stratospheric ozone layer, ODP; kgCFC11 equiv               | 0.0405 |
| K4     | Acidification potential of soil and water, AP; kgSO <sub>2</sub> <sup>-</sup> equiv    | 0.0252 |
| K5     | Eutrophication potential, EP; kg(PO <sub>4</sub> ) <sup>3-</sup> equiv                 | 0.0246 |
| K6     | Radioactive waste disposed; kg   | 0.0210 |
| K7     | Abiotic depletion potential (ADP-elements) for non fossil resources; kgSb equiv        | 0.0198 |
| K8     | Formation potential of tropospheric ozone, POCP; kg Ethene equiv                       | 0.0174 |
| K9     | Hazardous waste disposed; kg   | 0.0150 |
| K10    | Abiotic depletion potential (ADP- fuels) for fossil resources; MJ, net calorific value | 0.0120 |
| K11    | Non hazardous waste disposed, ; kg   | 0.0063 |
| K12    | Purchase cost, PLN   | 0.7000 |

## 4. Result and discussion

### 4.1. Structure analysis

The yielded calculation results indicate that all the examined alternatives meet requirements specified in the design standards related to ULS and SLS. The performed calculations of selected material and structural alternatives enable us to determine the consumption of concrete and reinforcement steel in the respective cases (table 3). The graphic interpretation of the calculation results, as regards the demand for reinforcement steel, can be found in figure 3.

**Figure 3.** Theoretical reinforcement distribution for single plate**Table 3.** Results of the material and structural analysis for the respective alternatives.

| Alternative | Design approach   | Materials | Consumption in the structure |
|-------------|---|-----------|------------------------------|
| W I         | Plain concrete structure  | C30/37    | 2,296.5 m <sup>3</sup>       |
|             |   | B500SP    | 81,510.4 kg                  |
| W II        | Reduction of reinforcement steel through the use of HPC for starting cross-sections             | C70/85    | 2,296.5 m <sup>3</sup>       |
|             |   | B500SP    | 75,644.8 kg                  |
| W III       | Reduction of the amount of concrete through the reduction of cross-sections with the use of HPC | C70/85    | 1,820.7 m <sup>3</sup>       |
|             |   | B500SP    | 65,493.1 kg                  |

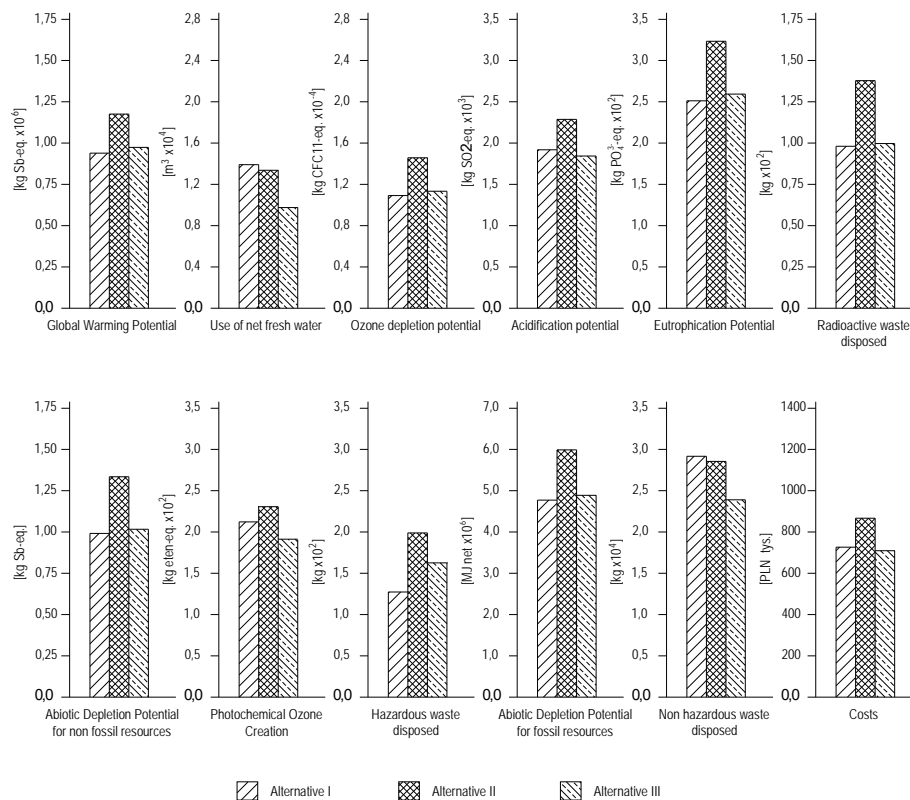
#### 4.2. Economic and environmental analysis

Based on the material and structural analysis, we estimated costs of materials necessary for the structure (table 4). For the purpose of this analysis, we adopted mean prices for respective classes of concrete and reinforcement steel B500SP based on ranges of different manufacturers.

**Table 4.** Results of the cost analysis for respective alternatives.

| Alternative | Materials | Consumption in the structure | Unit cost                 | Total material cost | Total cost     |
|-------------|-----------|------------------------------|---------------------------|---------------------|----------------|
| W I         | C30/37    | 2,296.5 m <sup>3</sup>       | PLN 240.00/m <sup>3</sup> | PLN 551,160.00      | PLN 734,558.31 |
|             | B500SP    | 81,510.4 kg                  | PLN 2.25/kg               | PLN 183,398.31      |                |
| W II        | C70/85    | 2,296.5 m <sup>3</sup>       | PLN 300.00/m <sup>3</sup> | PLN 688,950.00      | PLN 859,150.85 |
|             | B500SP    | 75,644.8 kg                  | PLN 2.25/kg               | PLN 170,200.85      |                |
| W III       | C70/85    | 1,820.7 m <sup>3</sup>       | PLN 300.00/m <sup>3</sup> | PLN 546,210.00      | PLN 693,569.57 |
|             | B500SP    | 65,493.1 kg                  | PLN 2.25/kg               | PLN 147,359.57      |                |

As the analysis indicates, the best solution in terms of costs is Alternative III, which involves reduced cross-sections of structural elements of HPC (C70/85) and, thus, a lower consumption of concrete. In this instance, the application of HPC has caused the structural weight to decrease, which in turn has reduced the demand for reinforcement steel. The change of the concrete class to a higher one in relation to plain concrete (Alternative II), regardless of the lower consumption of steel, causes the cost of the examined alternative to be higher. It is, above all else, due to the fact that the unit price of HPC exceeds the price of plain concrete by 25%. Therefore, it can be concluded that such a solution is unprofitable in the case of structures for which changing the concrete class is considered from plain to HPC without the simultaneous reduction of geometric dimensions of specific elements. Figure 4 presents the calculated environmental indicators.



**Figure 4.** Environmental indicators as regards different alternatives



#### 4.3. Multi-criteria analysis

Firstly, the alternative solutions were evaluated by calculating 9 synthetic indicators – multiplication (W1), corrected multiplication (W2), summation (W3), corrected summation (W4), additive (W5), corrected additive (W6), weighted averages: arithmetic (W7), geometric (W8) and harmonic (W9).

The AHP method, developed by T. L. Saaty, enables the analysis of the alternatives through the dissection of a multithreaded problem and creation of a hierarchical structure, thus facilitating the determination of a solution which is the most favourable under specific conditions [14]. During the studies, 12 matrices were created for the comparison of the options (alternatives examined for building the civil structure) and preferences were specified with the nine-point scale by Saaty. With the main goal in mind, that is the selection of a solution which would best fulfil sustainable development assumptions, a matrix for the comparison of criteria was developed [15]. The AHP method was recognised as the most subjective from among the ones selected for the analysis due to the significant impact of the decision-maker on the criteria weights and, as a result, the final shape of the options ranking. However, also in this case, the most favourable is Alternative W3, with the general priority value of 0.474.

The TOPSIS method introduces the concept of a positive ideal solution, meeting adopted requirements to the maximum possible extent and a negative ideal solution, the least compliant with specific standards. As a result of the analysis, the best alternative from the adopted ones is identified, the closest to the positive ideal solution (lowest  $d_i^+$  value) and, at the same time, the farthest from the negative ideal solution (highest  $d_i^-$  value). Based on the relative closeness ( $d_i$ ) of the respective alternatives to the optimal (ideal) solution, the option is specified which proves the most advantageous under particular conditions [16].

In all of the adopted methods, the optimal value of the analysis result leads to the maximum. Therefore, an alternative is sought with the highest values of: synthetic indicators (mathematical method), priority vector (AHP method) and relative closeness to the optimal  $d_i$  solution (TOPSIS). Table 5 contains the results of the three multi-criteria analytical methods applied in the study.

**Table 5.** Summary of results of multi-criteria analytical methods

| Alternative | Analysis method |           |        |       |       |       |       |       |       |       |        |
|-------------|-----------------|-----------|--------|-------|-------|-------|-------|-------|-------|-------|--------|
|             | Mathematical    |           |        |       |       |       |       |       |       | AHP   | TOPSIS |
|             | W1              | W2        | W3     | W4    | W5    | W6    | W7    | W8    | W9    |       |        |
| I           | 0.511           | 2.437E-19 | 11.386 | 0.946 | 0.949 | 0.079 | 0.946 | 0.943 | 0.945 | 0.350 | 0.6891 |
| II          | 0.047           | 2.228E-20 | 9.318  | 0.797 | 0.776 | 0.066 | 0.797 | 0.796 | 0.797 | 0.176 | 0.0676 |
| III         | 0.630           | 3.007E-19 | 11.566 | 0.990 | 0.964 | 0.082 | 0.990 | 0.989 | 0.990 | 0.474 | 0.8214 |

The results of all the methods testify to the advantage of Alternative III over the remaining solutions. This outcome was, to a large extent, produced due to the assumption of the relevance of environmental aspects on level 0.3 and economic ones on level 0.7. Alternative W III is characterised by a lower cost of materials used for the erection of the civil structure, which might have contributed to the final shape of the alternatives ranking. Consequently, for cognitive goals, a multi-criteria analysis of W1, W2, W3 variants were carried out, taking into account only environmental aspects. The summary results of the studies using mathematical, AHP and TOPSIS methods are presented in table 6.

Following the multi-criteria analysis including only environmental issues, a comparison compatible with the previous results, was obtained. It indicates a significant dominance of W3 variant over the other alternatives considering both environmental and economic aspects and it simplifies the choice of this solution, which is the most appropriate to the needs of decision maker.

**Table 6.** Summary of results of multi-criteria analytical methods (only environmental criteria)

| Alternative | Analysis method |            |        |       |       |       |       |       |       | AHP   | TOPSIS |
|-------------|-----------------|------------|--------|-------|-------|-------|-------|-------|-------|-------|--------|
|             | Mathematical    |            |        |       |       |       |       |       |       |       |        |
|             | W1              | W2         | W3     | W4    | W5    | W6    | W7    | W8    | W9    |       |        |
| I           | 0,541           | 2,0813E-13 | 10,442 | 0,950 | 0,949 | 0,086 | 0,950 | 0,941 | 0,946 | 0,388 | 0,6865 |
| II          | 0,058           | 2,2252E-14 | 8,511  | 0,773 | 0,774 | 0,070 | 0,773 | 0,771 | 0,772 | 0,180 | 0,0699 |
| III         | 0,630           | 2,4249E-13 | 10,566 | 0,967 | 0,961 | 0,088 | 0,967 | 0,964 | 0,966 | 0,427 | 0,8147 |

## 5. Conclusions

The article covers the analysis related to selected aspects of integrated design illustrated with an example of a multi-level garage building. The analysis has included economic and environmental criteria within the scope of product phases A1-A3. Three material and structural alternatives have been examined, including plain and high-performance concrete. All the examined alternatives meet requirements of design standards and allow the determination of concrete and reinforcement steel consumption in the respective cases. The application of HPC as a substitute for plain concrete (Alternative II) causes only the decreased demand for reinforcement steel in structural elements. In Alternative III, cross-sections of structural elements are reduced and HPC is used; therefore, the lowest consumption of concrete and reinforcement steel can be achieved.

The analysis indicates that the best solution in financial terms is Alternative III. This is due to the lower amount of construction materials, irrespective of the higher unit price of HPC. The change of the concrete class to a higher one in relation to plain concrete (Alternative II), regardless of the lower consumption of steel, causes the cost of the examined alternative to be higher. It should be emphasised that the cost analysis does not include technological processes related to reinforcement arrangement and concreting, which in the case of Alternative III, characterised by the lowest steel and concrete consumption, will result in additional savings due to outlays on human labour and equipment operation.

It may be noted that in spite of the increased content of cement in the high-performance concrete mix, which intensifies environmental loads related to concrete manufacturing, this solution (alternative III) turns out to be the most advantageous in view of both environmental and economic criteria.

The analysis pertaining to selected elements of integrated design does not include other components, which in the case of concrete structures made of HPC may impact the decision-making process related to the selection of a specific material and structural solution. It should be emphasised that HPCs are characterised by a much higher durability than plain concretes, which usually results in lower operating costs of structures erected with this technology. This may be important for multi-level garages where, due to intended uses, chloride corrosion may occur.

The integrated design process is currently being adopted in engineering practice, which requires additional effort for relevant analyses. What seems to be highly problematic is the necessity of data acquiring and gathering information on the impact of specific technological processes on the environment. Nevertheless, this effort allows the full evaluation of selected material and structural solutions, which could many a time result in the selection of, for instance, materials with higher unit of prices and environmental impact, as demonstrated in this paper.



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