SELECTION OF A CONSTRUCTION TECHNOLOGY FOR A BUILDING OBJECT, ANALYTICAL METHODS

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Summary:
Selection of a technology employed to raise a building object is one of the most important decisions to be made while planning an investment project. The problem has been presented using a model of a one-floor, single-span frame with full columns and a mono-pitch spandrel beam with the solid cross-section, made as a steel and monolithic reinforce concrete construction. A series of criteria and analytical methods have been proposed.

Keywords: variant solutions of a building construction, criteria for analysis of building objects, methods for analysis of variant construction solutions

Introduction

When planning to build a construction, we have an opportunity to choose between different technologies of construction works and between different materials. Wishing to achieve economically satisfying solutions while meeting all other requirements that building constructions should fulfill, comprehensive analyses are made, based on different selection criteria. Above all, the structures of a building should be reliable and lasting, needing the least maintenance work during their usable life. Beside, they ought to be raised in a relatively short time, not incurring excessive labour and financial inputs during their construction. While analyzing a construction plan, first we need to identify its specific features, then determine the assessment criteria and finally optimize these criteria. The fundamental requirements most often comprise:

- reliability of the construction and its useful life,
- technological criteria, which depend on the used materials, machines, production processes, availability and the possibility to transport materials and construction elements to the construction site,
- functionality of the building, depending on its size and specific features,
- economic criteria, which define the costs indices, especially the costs of construction works, the maintenance costs once it is erected, consumption of materials, total weight, share of industrialized solutions in the construction process, durability and value of materials recovered once the useful life of a building is over,
- legal considerations, imposed by the law binding in the area where a given building investment is planned and executed,
- formal issues, such as imposed norms and standards,
- ergonomic and esthetic problems, to which investors and future users of the building pay special attention,
- ecological questions, regarding the impact of an erected construction on the surrounding natural environment (Tarnowski W., 1997r.)

Whenever so many criteria have to be considered, a multi-criteria analysis is employed, in which solutions selected from a whole set of options are the ones for which the value of an objective function fulfilling all criteria attains the extreme value. The objectives which should guide our analysis are to minimize costs, an aim which in the recent years has been most often set as a priority, and to reduce the weight and volume of materials, taking into account the proportions of materials, labour and equipment. An optimal construction solution is also attainable in the potential, strain and elastic strain energy by striving to reach the minimum value and the smallest possible frequency of free vibration. While checking off the above criteria, it is important to bear in mind that the reliability and safe use of a building object are two essential objectives. A construction which fails to satisfy these conditions is automatically discarded. Having to fulfill all the above conditions, a designer faces an immense challenge. Apart from knowing the fundamental design rules and principles, they should also be familiar with the current construction market, the latest technological solutions and possible future developments so as to be able to justify the choices they make for a given construction design. This article discusses comparative analytical methods applied to analyze variant construction solutions, using as a case a choice between a steel and ferroconcrete one-story single-span frame with full columns and a mono-pitch spandrel beam.

Description of a model construction

A model of a one-storey, single-span frame with full-walled columns and a mono-pitch spandrel beam with a full and solid cross-section along its entire length, bearing a uniform bracing load of the roof structure and external forces applied to the roof and the walls. For comparison, it was assumed that the construction would be made of steel and of reinforced concrete. In the presented case, for both the steel and the reinforced concrete constructions, it was necessary to assume that all joints are rigid because such is the type of joint made in a monolithic construction. The following basic parameters were assumed:

- a variable span length, that is the centre to centre span between opposite columns,
- a fixed longitudinal span of the frames,
- a fixed slope of the spandrel beam, and consequently variable heights of columns with the variable span and constant height of the construction.

The described construction is composed of the columns and the spandrel beam. With the assumed work of the construction, the horizontal elements are subjected to bending and shearing. In the ferroconcrete construction, the centre to centre span was determined depending on the adopted conditions, with the adequate dimensions typically smaller than 25% of the span of symmetrically reinforced beams; when designing the steel spandrel, HEB I-beams were used. The described structure rests on columns anchored in foundation bases whose height depends on the roof slope angle. The columns are the main elements exposed to compression and transfer all forces to elements of the foundation. Same as in the case of horizontal elements, the dimension of the centre to centre transverse section of a ferroconcrete construction oscillate within a quarter of the span, and the reinforcement is symmetrical; in the steel construction, it is made of I-beams. Figure 1 shows a design of the construction.

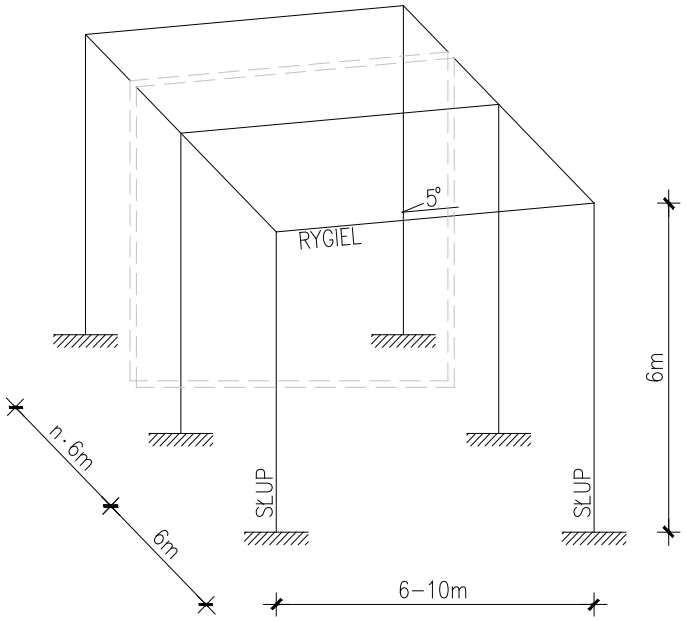


Fig. 1. Computational design of the analyzed construction
Source; the author

The following construction was taken for the calculations: a middle flat frame of a single-span hall with an inclined spandrel beam and a constant slope angle of the roof equal 5°, with the constant height at the highest point of the intersection of the column and spandrel beam equal 6 m and the longitudinal centre to centre span of the frames equal 6 m. The transverse distance between the columns will be variable, from 6 m to 18 m at 2-m intervals. The analyzed building will stand in the IV snow zone and I wind zone according to the Polish standard. The external columns are exposed only to wind, assuming the walls are cased. The length of the hall was assumed to equal n x 6 m, as the analysis comprises only the middle frame and an infinite length of the building affects only the wind load calculation, which simplifies its value to a constant for different widths of the aisle in the particular variants. Below, results of solutions for individual sets of frames are presented in the form of the most optimal – with respect to their strength - steel and reinforced concrete cross-sections for particular elements of the frame, which will serve as a data base for further economic and technical considerations. In the table, depending on the span of the aisle, cross-sections of spandrel beams and columns are divided, but the latter are considered identical in each case, be it the right or the left column.

Tab. 1. Results of the static strength analysis of single-span frames *

No of variant	Span of aisle	Cross-section of left ferroconcrete column	Cross-section of right ferroconcrete column	Cross-section of reinforced spandrel beam	Cross-section of steel column	Cross-section of steel column
1	6m	25x30cm A_{s1}: 4ϕ12 Binders: ϕ6 every 20cm	25x30 cm A_{s1}: 4ϕ12 Binders: ϕ6 every 20cm	25x40 cm A_{s1}: 4ϕ12 Binders: ϕ6 every 27cm	HEB 160	HEB 140
2	8m	30x30cm A_{s1}: 4ϕ14 Binders: ϕ6 every 20cm	30x30cm A_{s1}: 4ϕ14 Binders: ϕ6 every 20cm	30x45cm A_{s1}: 3ϕ16 Binders: ϕ6 every 31cm	HEB 180	HEB 180
3	10m	30x35cm A_{s1}: 4ϕ16 Binders: ϕ6 every 27cm	30x35cm A_{s1}: 3ϕ16 Binders: ϕ6 every 27cm	30x45cm A_{s1}: 3ϕ20 Binders: ϕ6 every 34cm	HEB 200	HEB 200
4	12m	35x40cm A_{s1}: 6ϕ16 Binders: ϕ6 every 27cm	35x40cm A_{s1}: 4ϕ16 Binders: ϕ6 every 27cm	35x50cm A_{s1}: 4ϕ20 Binders: ϕ6 every 34cm	HEB 220	HEB 240
5	14m	35x50cm A_{s1}: 4ϕ20 Binders: ϕ6 every 34cm	35x50cm A_{s1}: 3ϕ20 Binders: ϕ6 every 34cm	35x55cm A_{s1}: 4ϕ20 Binders: ϕ6 every 34cm	HEB 260	HEB 280
6	16m	40x40cm A_{s1}: 6ϕ20 Binders: ϕ10 every 17cm	40x40cm A_{s1}: 4ϕ20 Binders: ϕ10 every 17cm	40x80cm A_{s1}: 4ϕ25 Binders: ϕ10 every 40cm	HEB 280	HEB 300
7	18m	40x70cm A_{s1}: 4ϕ25 Binders: ϕ10 every 15cm	40x70cm A_{s1}: 4ϕ25 Binders: ϕ10 every 15cm	40x80cm A_{s1}: 4ϕ25 Binders: ϕ10 every 40cm	HEB 320	HEB 360

* the results in the above table were calculated for ferroconcrete constructions made of C20/25 cement and A-IIIN RB 500 reinforement steel, while the steel construction was assumed to be made from St3S steel.
Source: the author.

Foundations of the comparison of constructions with the traditional method

Among the foundations underlying comparative analyses of building constructions are the indices, which can only serve the purpose of making comparisons if possessing the same calculation base. There are several types of indices, and they all depend on the values which we refer them to. The basic parameters, which constitute the most common comparisons are:

- a building object as an entity – total costs of the building object are compared, due to the materials, labour and equipment used to raise it; they enable us to juxtapose buildings constructed by different technologies but performing the same function and used in identical conditions;
- the cubic capacity of a building – rarely used as it can be expanded due to technological requirements or the equipment and appliances used inside a given building;
- the floor area – very often used for comparisons; in the case of constructions, it very faithfully reflects surfaces of cross-sections of the elements which diminish the technological, usable surface of the whole building;
- other parameters, which interfere with the production technology, and are outside the scope of this paper, e.g. a unit that measures production and service outputs (Robakiewicz M. 1969)

The basic parameters include the ones which pertain to costs, that is financial outlays, so that we are able to analyze total costs of the construction undertaking. Other parameters refer to outlays in-kind, that is most often materials used to build the building, and consumption of materials, which helps us to compare same materials with different mechanical properties. This is very important in building objects like the analyzed model construction because the construction material contributes over 50% of the total costs of the building investment.

Other, frequently used parameters refer to weights, are closely connected to transport and assembly costs, and rely on the assumption that the lighter the construction, the more resistant the applied materials. Costs of using a building, including for example heating, repairs and maintenance works, are more often taken into consideration, to. There are some other parameters as well, which handle various spatial and design-specific aspects, e.g. safety and durability of a structure, industrialization rate of the building process, etc.

Traditional methods of analyzing building structures

Among the basic traditional methods is an approach in which parameters of the consumption of materials and unit costs are calculated and juxtaposed. The first is the ratio of the volume of reinforced concrete to steel, in appropriate standard units, used in a given structure,

$$Z = [m^3] \text{ reinforced concrete} / [t]\text{steel} \qquad [1]$$

It reflects the ratio of variant consumption of individual materials to erect the same building object, e.g. when a steel structure is chosen, and the used material equals 10 kg per the cubic capacity of the building, or when 0.05 m^3 of reinforced concrete is used, the parameter is equal 5. A reverse equivalent would be the quotient of the unit prices of compared materials.

$$N = \frac{unit - price - of - ferroconcrete - structure}{unit - price - of - steel - structure} \quad [2]$$

The results of this simple analysis is the product of the above parameters. If the Z x N quotient is more than one, then the steel structure in the analyzed building object is less expensive in terms of used materials. Such comparisons can also be made with respect to other outlays, such as engaged equipment or labour (Górski W., 1970r.) While analyzing potential applicability of the above method, it appears than we can compare structures of a given function built from suitable materials, by comparing weights and strength characteristics of different types of steel or concrete. For example, a compressed element made of steel or concrete, it is possible to derive a formula for Z equivalent:

- assuming that elements achieve maximum strength, we transform the formula for the strength of a section submitted to with concentrated force.

$$\frac{Q}{A} = f_d \quad [3]$$

$V^b = \frac{Q \cdot L}{f_d^b}$ - in the case of concrete, we need the volume used in the analyzed element

$G^s = \frac{Q \cdot L \cdot \gamma^s}{f_d^s}$ - in the case of steel, we need the used weight

where:

Q - force compressing the element,
A - cross-section of the element,
f_d - calculated compression strength (f_d^b for the concrete and f_d^s for the steel element),
L - length of the element,
V^b - volume of the concrete element,
G^s - weight of the steel element,
γ^s - volumetric density of steel.

- If we assume in the above formulas that the product Q × L is the same in both cases, we arrive at the final formula to calculate equivalent Z

$$Z = \frac{V^b}{G^s} = \frac{1}{f_d^b} \cdot \frac{f_d^s}{\gamma^s} \quad [4]$$

Below, we present examples of Z equivalents for some classes of concrete and types of steel, which visualize the difference originating from properties of given materials in the analyzed work of a compressed cross-section.

Tab. 2. The comparative index Z of reinforced concrete and steel for a compressed element *

Stael / Concrete	f_d^b [MPa]	S185	S235JR	S275JR	S355J2
f_d^s [MPa]		165	205	225	295
C16/20	11,43	1,84	2,29	2,51	3,29
C25/30	17,86	1,18	1,46	1,61	2,10
C50/60	35,71	0,59	0,73	0,80	1,05
C80/95	57,14	0,37	0,46	0,50	0,66

* results in the table were computed for the steel volumetric density equal 7850kg/m^3
Source: the author

Naturally, the results in the table are approximations of actual results. However, although they lack the ideal precision of calculations, this method of comparisons generates reliable results and can serve as a preliminary evaluation of a planned construction, assuming that same load capacity of the structures made from different materials is ensured. Another methods to compare costs of structures built from different materials is the one where the costs ration index is calculated for assembled constructions made from different materials:

$$\psi = \frac{a}{c \cdot S}[n \cdot c + p \cdot c(S-1)] = \frac{a[n + p(S-1)]}{S} \qquad [5]$$

where:

$a = \frac{G_i}{G_{i+1}}$ - expressed the proportion of weights of structures made from ith material,

$S = \frac{c + w + m}{c}$ - is the ratio of the total costs of a unit quantity of the first material (c), workshop labour (w) and costs of assembling (m) elements to the costs of material as such

$p = \frac{w_i + m_i}{w_{i+1} + m_{i+1}}$ - expresses the ratio of workshop labour (w) and assembly costs (m) of the ith material,

$n = \frac{c_i}{c_{i+1}}$ - expresses the proportion of costs of ith materials.

The above method does not include maintenance costs, which may differ from one structure to another, but for the sake of our subsequent considerations, it was assumed that this type of comparison will suffice to describe the set target of the analysis.

Basis of the multi-criteria analysis

In order to perform a multi-criteria analysis, it is necessary to define specifically what requirements the analyzed structure must fulfill and what the significant criteria would be. These criteria have already been mentioned in the introduction to this article.

Consumption of materials and technology

Nowadays, when planning investment projects, much emphasize is laid on the use of materials. This tendency is congruent with the ecological approach to the construction industry, saving raw materials, decreasing the transportation load and ensuring that the investor can attain financial savings.

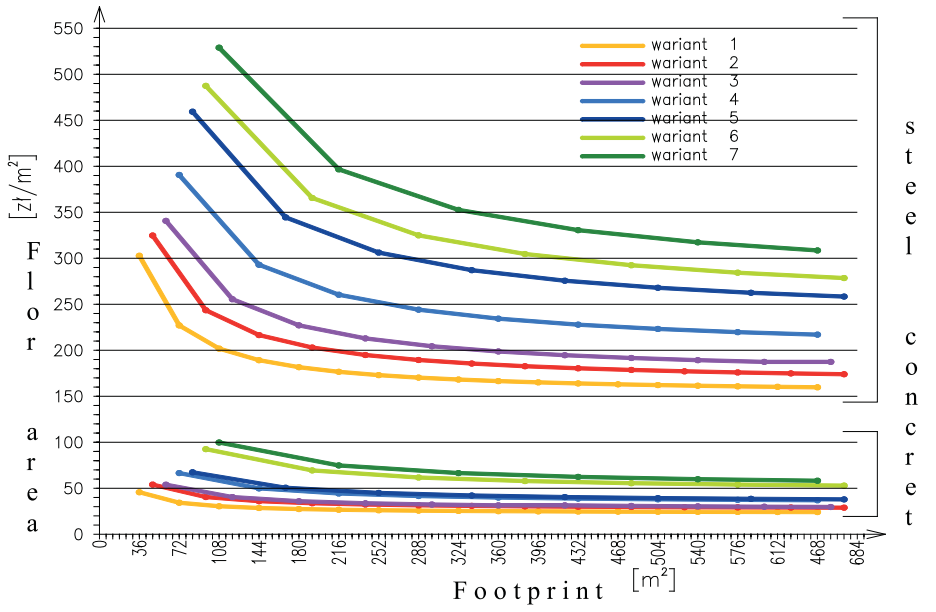


Fig. 2. Cost of used material per 1 m² of the floor area of a building depending on the footprint
Source: the author

The diagram illustrating dependences between costs of materials and footprint has been drafted based on the author's own calculations. The diagram shows an evident advantage of a ferroconcrete structure over a steel one.

It may seem futile to analyze relationships between the consumption of materials and the building's cubic capacity, having examined the its relation to the footprint. And actually many designers will think so. However, we should know that the cubic capacity of a building may change depending on a variety of parameters. The simplest ones,

usually stemming from the applied technology, are the footprint at the constant height of aisles, variable height at the constant floor area and changeable dimensions of a hall only at certain points long- or sidewise.

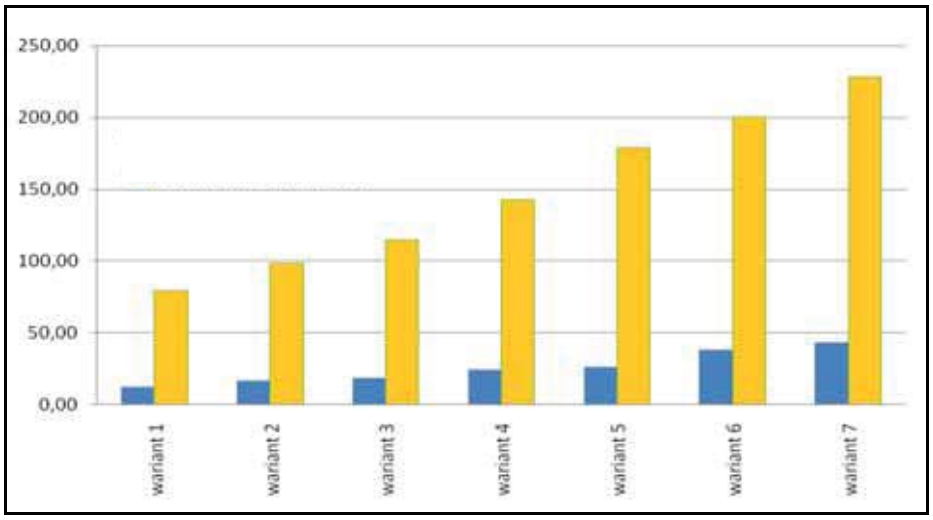


Fig. 3. Comparison of costs of used materials per 1m^2 of the surface of walls in particular variants
Source: the author

The analyzed models are simple halls, which is why the question of the unification of elements will not be considered. We will discuss, however, the effect of the surface of encasement to thee costs of used materials per structure, provided the same system of building the walls. All that needs to be done is to compare frames of the spans presented before to the lateral surfaces alone, and owing to their proportional increase as the length of the hall increases, they can be analyzed in the same way as for a single-span hall.

The total costs of encasing the building will decrease proportionally to the decreasing cubic capacity of the hall, which means the decreasing size of vertical surfaces. However, let us focus on the analyzed variants, which we compare with respect to their unit encasement surfaces. It should be added that the total surface is different for each variant due to the changing widths of spans. In such comparison, as in the above point, the reinforced concrete structure is the most economical solution in terms of the consumption of materials. Comparing halls with the same cubic capacity and footprint, and consequently with the same costs of building outside walls, building objects raised from steel will be a more expensive variant with respect to the costs of materials.

Dimensions and shape of a building object

In comparative analyses of different investment project variants, it is sometimes vital to consider their shape and associated consumption of materials, e.g. allocated to the construction of outside walls, which make up the perimeter of the building. It is necessary to consider halls with the same footprint but with different dimensions in their

projections, which will generate the same cubic capacity but may have a significant impact on the costs incurred by making the encasing walls. We can achieve this goal by introducing a certain index:

$$K = \frac{perimeter - of - the - building - [m]}{the - footprint - [m^2]} \qquad [6]$$

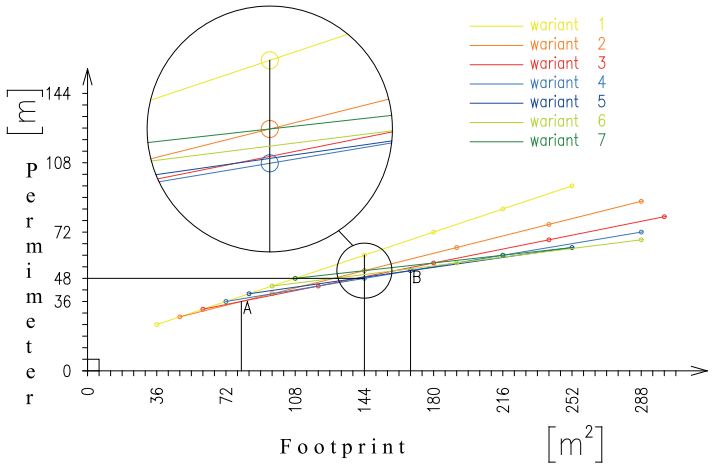


Fig. 4. The *k* index for particular variants, depending on the footprint and perimeter of the building
Source: the author

Dependence [6], from which the diagram was derived, enables us to demonstrate the effect produced by the shape of the building on the final price of the construction, e.g. in order to secure a set footprint without any specific demands as to dimensions of the building at the lowest possible construction costs. With the illustrated *k* index for specific variants, which is dependent on two variables, we can select the most optimal option of the span and length of a hall, so that the surface of the external walls should be as small as possible. Above, a certain detail has been marked for a footprint equal 144 m^2, which indicates that the most economical is the fourth variant, where the perimeter of the building is 48 m, the span is 12 m and the length of the hall is 12 m. For the same floor area, the diagrams drawn from variants two and seven intersect, but they are in the fifth place with respect to the economic aspects. It is worth mentioning that the analyzed hall can be constructed in modules, that is with the constant and set length of each span equal 6 m, the fact marked in the diagram with dots. For the described area of the footprint, only three variants fulfill this criterion. At point A the diagrams of variant two and three intersect, although it might appear that they are both equally optimal solutions for the given surface area of the footprint, they are not modular halls for the set lengths and widths. The situation is similar at point B, where another most optimal intersection appears, but this time it involves variants four and five, but this solution will be the

second optimal because for the footprint of 168m^3 a modular hall will have to have spans measuring 14 m. While analyzing the above diagram more meticulously, we arrive at the conclusion that the most profitable solutions are the ones whose projected shapes are the closest to the figure of a square, e.g. halls measuring 12 x 12 m, 14 x 16m, or 18 x 16 m.

Time of construction works

Another important criterion helping to choose the best solution is the time it will take to construct a given building. Each day at a construction site incurs huge costs, due to the labour done by people and machines. The presented analysis is based on generally accepted time standards determined according to the current behaviour on the market. When conducting such analysis, it is advisable to pay attention technologies employed in order to execute the analyzed variants. As assumed before, the reinforced concrete frames will be made on the site, as monolithic structures, while the steel ones will be raised from prefabricated elements made in a factory. The works required to make ferroconcrete frames include: reinforcement with steel rods (main, transverse and additional reinforcement), making pole scaffold and formwork under the spandrel beam, curing of concrete. We should also add the time needed to make cement, but in the case analyzed herein we assumed that ready-made cement will be delivered from a cement plant.

The works which must be included in an analysis of a steel structure assembled at the beginning are the assembly of elements delivered from a plant and covered with priming paint, and then painting the whole structure on the construction site. A quick look will be enough to see how much the two technologies differ from each other, although they are used to erect seemingly similar building objects. The monolithic structure involves much more complicated works, strongly dependent on numerous external conditions, which has an evident influence on the eventual duration of construction works.

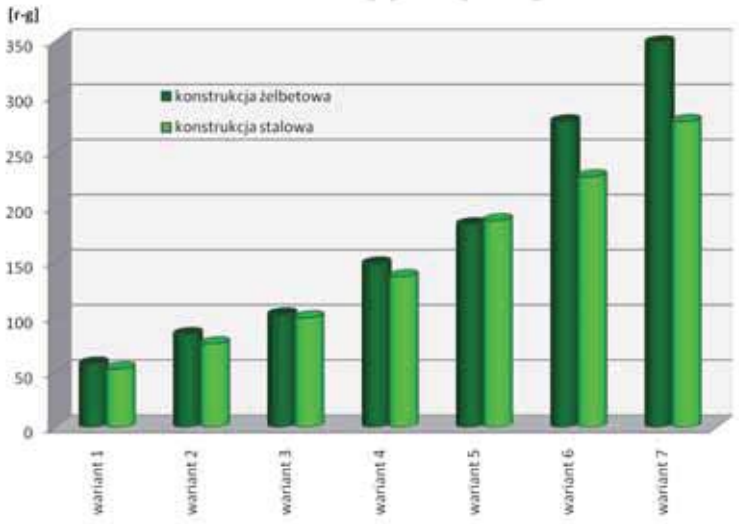


Fig. 5. Comparison of the time needed to build a ferroconcrete and steel structure in particular variants
Source: the author

The diagram illustrates differences in the time it takes to produce one frame in either of the two variants. The numbers corresponding to working hours needed to make elements of the building object oscillate within 53 to 277, which means that the work time extent by 32-50 hours for each 2-meter increase of the frame's span. Eventually, the change of the span between the columns reaching the maximum planned distance causes an increase in the duration of the construction works by as much as 80%. The increasing tendencies are similar in character for both analyzed technologies, and the steel construction is obviously much better than the reinforced concrete one, which takes much longer to make.

Associated costs of construction

When analyzing the structures in terms of the costs incurred by their construction, the costs of labour and materials connected with the major works were presented.

The costs which should be taken into account when delivering and assembling steel constructions covered in priming paint, excluding the cost of the material such as steel itself, are general construction works in respect of labour costs and steel ladders, scaffolds, steel coarse bolts with caps and washers, electrodes for the welding of low carbon steel, compressed technical oxygen, dissolved technical acetylene, grounding anti-corrosive minium phthalic paint, surface phthalic paint, thinner for oil and phthalic paints; the equipment will include: a vehicle crane, a wheeled tractor, a long-load trailer, welding machine, a transportation means.

When describing the works needed to prepare and make ferroconcrete structures, the employed technology should be considered, as it will necessitate using different types of equipment and additional materials. In this case, the costs excluding the costs of basic materials are: general construction works in respect of labour costs; materials such as round timber poles to make pole scaffolds, rough pine boards, round nails, and machines like a wire straightener, scissors for cutting wire, wire bender, a hoist, a vehicle crane, a means of transport, a concrete pump on a motor vehicle.

The diagram below shows the total costs of the above works, materials and equipment, divided into each category.

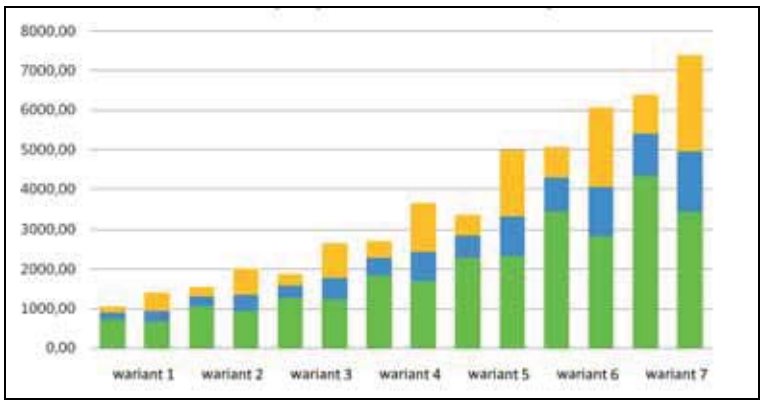


Fig. 6. Comparison of costs of making one ferroconcrete frame and one steel frame in each variant
Source: the author

Safety and durability of constructions

These are the two most important characteristics that all building constructions should possess. According to the Eurocode: 'A durable should satisfy the set requirements throughout its whole planned life cycle, irrespective of its usability, bearing capacity and stability, without leading to any substantial decrease of its suitability to use or excessive and unpredicted costs of maintenance" (PN-EN 206-1, 1990). In each applicable book of standards, there are provisions indicating how a structure should be designed to meet the above demands. However, it is important to abide to these norms at each stage of the construction processes, starting from a designer through the contractor to the end user of a building.

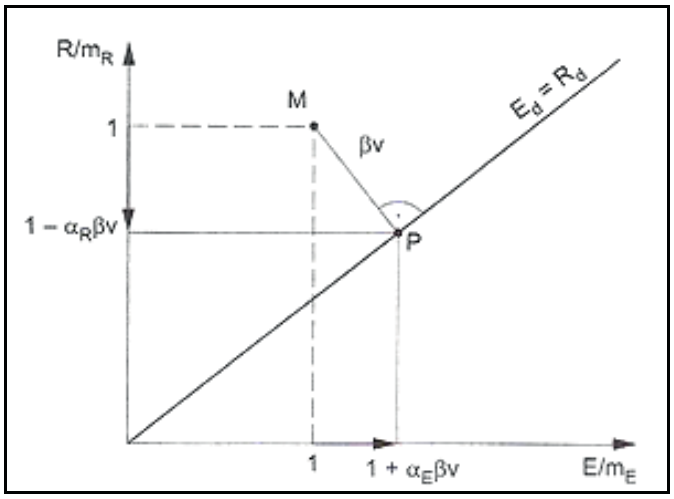


Fig. 7. Safety margin in the area of events *Source: [16]*

The above diagram shows the margin of safety that the analyzed construction has, using the partial safety factors defined in the Eurocode. It illustrates relationships between the bearing capacity and load at the terminal point P, whose coordinates depend on the β reliability index, a sensitivity index and ν safety margin changeability index, as well as the margin left with respect to the actual situation of the analyzed construction (point M0) in the form of the expression βν. This is how the safety of the construction can be defined mathematically, but in reality this aspect also depends on the designer, contractor and final user of the raised building object. The designer, who defines the conditions in which the planned construction will stand, is responsible for any simplifications in calculation procedures, adopted in such a way as to most closely reflect the reality; another task the designer must do is to check the basic reliability conditions and to determine how the construction he will design should be made. The contractor is responsible for ensuring that the building object was erected in compliance with the design and its assumption, and was assembled and prior to that manufactured with the utmost care and accuracy. The last participant of the investment process should use the building according to its designed function, check its technical condition from time to time and, whenever the need arises, perform necessary maintenance work and repairs.

It is somewhat simpler to analyze steel constructions because steel is an isotropic material, owing to which the construction is only slightly divergent from the theoretical computational assumptions. Regarding the aforementioned safety margin factors, the ones which apply to the uncertainty of the dimensions of all cross-sections and resistance specification of steel may not significantly increase the safety margin because there is very little difference between the assumed and actual values, and whenever this gap incidentally grows bigger, it will be levelled by technical checks and controls. The factor which remains highly divergent is load, which - irrespective of the used construction material – is still independent from it, obviously excluding the own weight of the material. Steel elements from a factory go through meticulous controls at each production stage and therefore respond very well to the assumed design conditions. The only element which could raise doubts are the joints. Prefabricated elements are assembled on-site, sometimes in difficult conditions, but if carried out with due care, it should not cause any worries of an unexpected fault. Another advantage of steel elements, arising from their isotropic nature, mentioned previously, is their tolerance to changes in load, either not predicted earlier or caused by some errors made during the construction works. This characteristic feature is also useful during the transport and assembly of steel elements.

Ferroconcrete constructions do not possess most of the above characteristics, especially when made on a construction site. First of all, the material as such is different. In contrast to steel, it is a multi-component material, which makes all the calculation theory more complicated. Apart from ensuring good quality of all components, it is also necessary to guarantee that they will interact with one another properly. The resistance characteristics of such material are therefore varied over a much wider range and attaining a specific strength value is extremely difficult, especially in field conditions. Moreover, it is rarely checked after a given element has been produced. Making the reinforcement exactly according to the design creates many problems and, apart from such mistakes as a wrong diameter of rods or a wrong number of reinforcement rods, practically unverifiable. Common errors are an inadequate thickness of concrete cover or making lengthwise joints between bars, rods or anchors in a way that disagrees with the building art. Other problems are encountered when ready formworks are filled with concrete mix. Irrespective of the quality of formworks, it may happen that when wet concrete whirls the so-called caverns appear, and the builder will not even know about it. All these problems can be compounded by atmospheric conditions, which can alter the whole technological process of making and curing concrete structures. The flaws described above must be alleviate by increasing artificially some of the values taken to calculations, which leads to generating larger cross-sections, reinforced with many steel bars, rods and stirrups, as this is the way to ensure one of the basic characteristics of a good construction, namely its safety.

Looking at both cases, it is safe to claim that both steel and ferroconcrete constructions satisfy all safety conditions. However, when monolithic structures are discussed, there are too many factors which must be looked at to ensure that the construction is almost ideally the same as the design. This, however, results in achieving larger dimensions of cross-sections of elements, thusly the higher own weight of the construction and higher costs involved.

Resistance of constructions to corrosion and fire

Another issue that needs to be considered is the resistance of a construction to unfavourable environmental conditions, substances causing corrosion and high temperature that occurs during a fire. Typically, building standards help us classify individual elements and describe the characteristics they should demonstrate under such circumstances.

All constructions should be as fireproof as possible, which means they should retain their functions during a fire. The recommendations contained in the national guidelines aim at preserving the stability of whole constructions as well as their elements for a set time depending on their class. Another aim is to ensure that further spreading of a fire or smoke, as well as a risk of ignition will be controlled, and the construction will behave in a way that will enable and facilitate fie rescue and escape actions. These conditions are considered in the context of materials used for making whole constructions or their constituent parts, and their interactions during a fire. The two analyzed model constructions belong to non-flammable materials with low smoke emission. Classification of elements depends on two aspects: the criteria and the time during which these criteria must be met. The classification of each element must be determined during the design stage so as to envisage ways of additional, external fire control. The main reason why this is so important to analyze tolerance of constructions to fires is that under high temperatures materials automatically lose resistance. Steel has many advantageous characteristics, but is very sensitive to high temperatures. All steel constructions are typically given fireproof protection, without which they will not last longer than half an hour. The problem is less serious in the case of reinforced concrete structures, but cannot be neglected altogether. Reinforced concrete contains steel elements, which perform an important function in the behaviour of ferroconcrete constructions.

When it comes to protection of ferroconcrete structures, the solution is simple. n order to provide all elements with a desired fireproof class, minimum dimensions of cross-sections and an adequate thickness of concrete cover for the reinforcement are designed. This is usually the only and sufficient method to protect newly raised constructions. Sometimes, however, dimensions of particular elements are limited by technological or architectural demands, which is when other methods must be deployed. These most frequently are: thick-layer covers such as fireclay mortar sprayed directly over the construction, analogously to steel structures. Other systems applied to steel constructions are not suitable to protect ferroconcrete structures from fire.

Resistance to corrosion is different for different materials, and therefore there are different anti-corrosion solutions. Regarding steel, which is used in both systems, corrosion is caused by formation of different salts on the surface of a steel element due to reaction of elements from the metal with other elements. Anti-corrosion methods include prevention of moisture and water collection by giving appropriate shapes to the elements and whole structures, or by reducing their emission when using the building, or by avoiding direct contact between unprotected steel with materials having different electro-chemical potential, e.g. aluminum. However, by being so vulnerable to the effects of external conditions, this material needs additional protective actions. They include two basic forms: paint layers and galvanizing.

These are unnecessary in ferroconcrete constructions because the concrete itself functions as a protective cover. Attention should be paid, however, to the width of gaps and thickness of concrete cover, which are regulated by norms and depend on the environment. According to the European norms, exposition classes are represented by the letter X and, depending on the environment, the number 0 when corrosion risk is absent, C – damage caused by carbonization, D – corrosion due to chlorides, S – effects of chlorides from seawater, F – elements exposed to cyclic freezing and thawing, and A – under chemical effect. Layers of concrete cover also depend on the class of applied cement and the number of checks carried out. The question of scratches is usually solved during the designing stage, by selecting adequate cross-sections of elements and amount of reinforcement.

Considering the above information, it can be concluded that anti-corrosive protection is similar to the ways of ensuring tolerance to high temperatures. Thus, steel constructions require use of different protection systems, while corrosion of ferroconcrete structures is prevented at the design stage by providing sufficiently thick concrete cover. Because the fireproof and anti-corrosive coatings on steel components can be combined, they were not analyzed separately, because the costs of painting steel surfaces would be similar. On the other hand, in our analysis of monolithic structures, the thickness of concrete cover was considered simultaneously regarding the unfavourable influence of the surroundings and an event of a fire.

Use of the construction

The major financial outlays which an investor must incur during the construction process should be amended by adding the costs needed to use and maintain a ready building object. Beside typical costs caused by maintenance, on a more or less same level each year, the analyzed model structures need periodic checks and repairs.

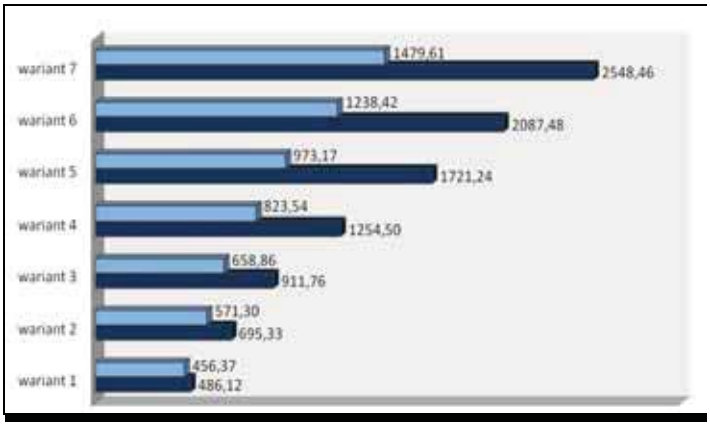


Fig. 8. Costs of renovating one steel and ferroconcrete frame after 10 years, for each of the span variants
Source: the author

The diagram in figure 8 shows differences in costs of renovation of the model solutions. With smaller spans, these costs are similar in both types of constructions, but as the span increases, the difference reaches 42%. In each variant, the financial inputs on renovation are

higher in the case of a steel structure, and differ by 6% to 42% from analogous reinforced constructions. Regarding both types of solutions in the variant with the maximum transverse span of columns, the difference rise by 81% and 69%, respectively. It is also possible to refer the calculated values to 1 m^2 of renovated surfaces. These data are included in the table below.

Tab. 4. Specification of costs of renovating 1 m^2 of steel and ferroconcrete constructions for particular variants

No of variant	Steel construction			Ferroconcrete construction		
	Total cost of renovation [PLN]	Area submitted to renovation [m^2]	Cost of renovation of 1m^2 [PLN]	Total cost of renovation [PLN]	Area submitted to renovation [m^2]	Cost of renovation of 1m^2 [PLN]
1	486,12	15,38	31,60	456,37	20,45	22,31
2	695,33	20,10	34,59	571,30	25,61	
3	911,76	24,35	37,45	658,86	29,53	
4	1254,50	30,54	41,08	823,54	36,91	
5	1721,24	38,93	44,21	973,17	43,62	
6	2087,48	44,96	46,43	1238,42	55,50	
7	2548,46	51,89	49,11	1479,61	66,31	

Source: the author

The data contained in the table verify the commonly accepted claim that reinforced concrete constructions are much more durable and under normal exploitation conditions do not require any major repairs during the planned usability life.

Costs of making the constructions

The total costs of constructions consist of various components. Out of the ones discussed above, the given specification contains costs of erecting the construction, costs of renovation and maintenance and costs of anti-corrosive and fireproof protection.

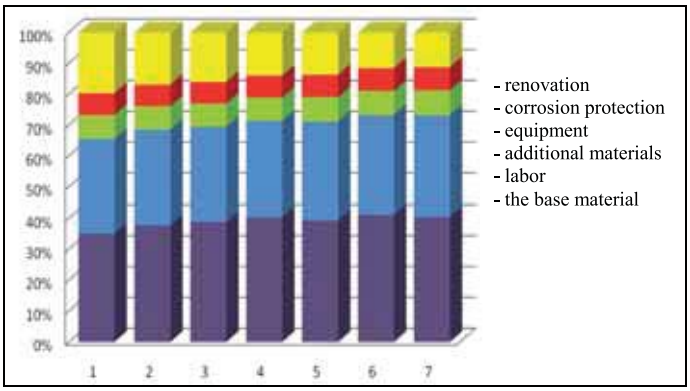


Fig. 9. Contribution of particular costs of building and using a a single ferroconcrete frame in particular span size variants
Source: the author

In ferroconcrete constructions, the highest share to the total costs is contributed by the main construction material and labour – these costs are similar in all variants. The protection of a construction against corrosion or fire is minimal, almost negligible, which implies that it is very hardy to external environmental factors.

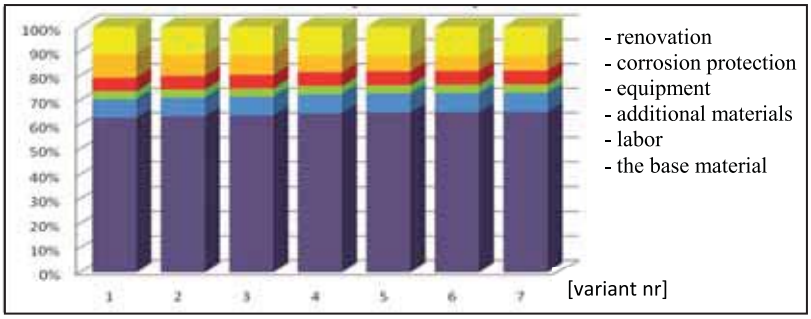


Fig. 10. Share of individual types of costs of building and using a single steel frame in particular span size variants *Source: the author*

Fig.10 shows a very high share of basic construction material in the total costs of erecting and maintaining a steel structure. Steel as a building material is very expensive. Also, notable is a higher percentage of costs of renovation and protection than in the case of ferroconcrete constructions. The other cost components are similar in both cases and do not increase notably as the span increases.

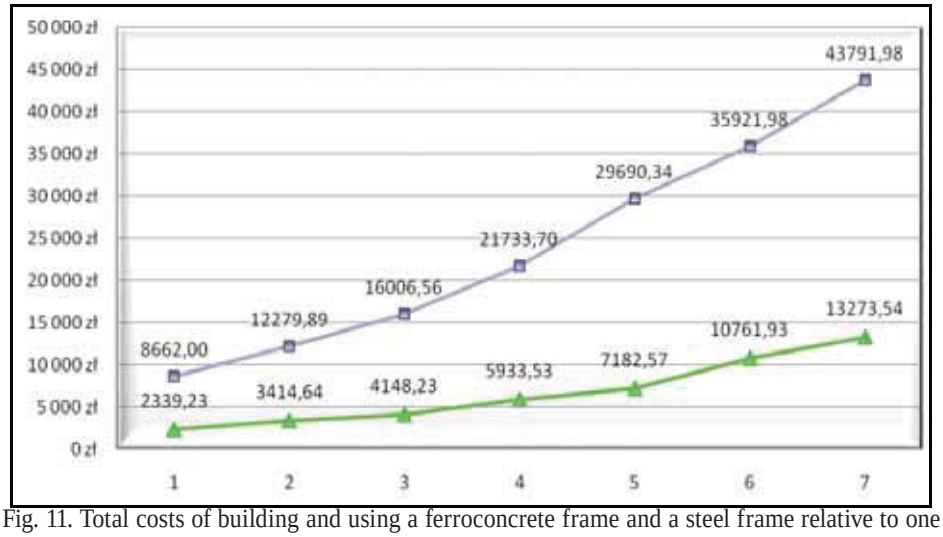


Fig. 11. Total costs of building and using a ferroconcrete frame and a steel frame relative to one frame in each variant
Source: the author

The diagram in fig. 11 confirms our previous observations. Having analyzed all the variants, we can conclude that ferroconcrete constructions are a much more economical solution. Although the differences are small for constructions with smaller spans, it would be uneconomical to choose a steel construction when the span between columns is 18 m, as this solution is 70% more expensive.

The table below juxtaposes other aspects, which cannot be compared otherwise, for example as diagrams, because they are not mathematically comparable. The red colour highlights advantages.

Tab. 5. Main advantages and disadvantages of steel and ferroconcrete constructions

Ferroconcrete construction	**Steel construction**
• low costs of making and maintaining • small errors while building are reparable at relatively low cost, • long time to build, • the multi-component element sensitive to changes in loading direction, • large deviations of dimensions of elements, • difficulty in reproducing design assumptions, • much labour inputs to build, • many factors calling for care and attention on a construction site, • costly reinforcements of the construction, • the construction cannot be disassembled, • the material is practically unrecoverable, • large weight of the whole construction, • cross-sections of elements diminish the usable floor surface and cubic capacity, • difficulties during the assembly of installations inside the building.	• high costs of making and maintenance, • each, even the smallest mistake causes serious consequences, • relatively short time to build, • the isotropic material resistant to changes in loading direction, • small deviations in dimensions of elements, • ease of reproducing design assumptions, • few activities that require control on a construction site, • quite simple and inexpensive ways to reinforce the construction, • possible disassembly of the construction, • the material can be recovered, • relatively light constructions, • cross-sections of elements need not decrease the usable floor area or cubic capacity, • easy to assemble installations in the building.

Source: the author

Analysis with the multi-criteria AHP method

The Analytic Hierarchy Process (AHP) is one of the multi-criteria analytic methods, with which it is possible to evaluate all available variants of an investment project. (Saaty 1990, 1994) The AHP approach enables the user to take into consideration various criteria which condition the attainability of the project's goal. By being a universal method, the AHP has proven practically useful in solving a broad scope of problems, from military through social and economic to technical ones. (Abu Dabous, Alkass 2008) The underlying provision of the method is that an overall goal is attainable by reaching subordinate goals, which lead to obtaining the main goal. Alternative solutions are considered, which – to a different extent- satisfy the expectations. How a given decision option fulfils the overall goal depends on the degree to which it satisfies the main criteria and, appropriately ranked, sub-criteria. Decomposition of a problem facilitates our evaluation and is the essence of the AHP method.

In this method, a problem is solved by going through three stages (steps), arranged in an integrated and logical sequence:

1. presenting the problem's structure and constructing a hierarchy model (determination of criteria),
2. evaluating the criteria on a nine-point scale by pairwise comparison and construction of an assessment matrix ***A*** (analysis of the matrix, determination of vectors of priorities),
3. evaluating and arranging the variants by setting the priorities (main weights), including the analysis of sub-priority vectors.

When applying the method, the number of criteria compared on the same level should be limited to just a few comparable ones so that it is possible to construct a cohesive matrix of comparisons. It is also necessary to assume some degree of simplification in modelling the analysed problem, to collaborate with experts and to review references as well as opinion surveys.

During the evaluation, all the criteria on a given level are compared in pairs and their mutual relations are established; thus, a decision must be made which of these criteria and to what extent will be more important for the execution of the planned project. The evaluation is achieved using an evaluation scale elaborated by Professor Thomas Saaty, which is presented below in a tab. 6.

Tab. 6. AHP fundamental scale *Source: (Saaty 1990, 1994)*

Score	Specification
9	Predominance of one criterion over the other is absolute and proven to the highest degree
7	One criterion is very strongly preferred to the other and the preference is proven in practice
5	One criterion is preferred to the other
3	One criterion is slightly more preferred to the other
1	Both criteria contribute to the same degree to attaining the goal
2,4,6,8	Intermediate values, used only when necessary

Source: (Saaty 1990, 1994)

The number of pairs creating the matrix and submitted to analysis depends on the number of defined criteria (tab. 7).

Tab. 7. Number of nodes a_{ij}

Number of criteria	1	2	3	4	5	6	7	n
Number of nodes	0	1	3	6	10	15	21	$\frac{n(n-1)}{2}$

Source: (Saaty 1990, 1994)

The next step involves construction of a comparison matrix ***A***, in which we place the scores determined while evaluating the criteria. (Saaty 1990, 1994) The matrix has certain specific features: the diagonal consists of values equal one because it contains a comparison of each criterion to itself, $a_{ij} = 1$ for i=j; the elements a_{ij} are a reciprocal of the elements a_{ji}. Logically, all $a_{ij} > 0$. When the preferences (a_{ij}) are established, we can calculate elements a_{ji} $a_{ji} = \frac{1}{a_j}$. The pairwise assessment and establishment of other elements enables the user to construct a preferences matrix. Below, a matrix constructed for 4 criteria is shown.

$$A = \begin{vmatrix} a_{11}=1 & a_{12} & a_{13} & a_{14} \\ a_{21}=\frac{1}{a_{12}} & a_{22}=1 & a_{23} & a_{24} \\ a_{31}=\frac{1}{a_{13}} & a_{32}=\frac{1}{a_{23}} & a_{33}=1 & a_{34} \\ a_{41}=\frac{1}{a_{14}} & a_{42}=\frac{1}{a_{24}} & a_{43}=\frac{1}{a_{34}} & a_{44}=1 \end{vmatrix} \quad [7]$$

In this case, for the number of criteria = 4, the number of nodes = 6.

The literature contains calculations formulas for the subsequent steps leading to the calculation of the value of a priority criterion.

These are:

Calculations of the value of a normalised matrix:

$$\overline{w_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad [8]$$

Determination of the value of the vector of sub-priorities:

$$\overline{w_j} = \sum_{j=1}^{n} w_j a_{ij} \quad [9]$$

where:

$$w_j = \frac{\sum_{i=1}^{n} w_{ij}}{n} \qquad i, j = 1\ldots n \quad [10]$$

To verify whether the above procedure has been correct, we determine:

- the matrix's own maximum value:

$$\lambda_{\max} = \frac{1}{w_i} \sum_{i=1}^{n} a_{ij} w_j \quad [11]$$

- value of the consistency index:
-
$$C.I. = \frac{\lambda_{\max} - n}{n-1} \quad [12]$$

- consistency ratio:

$C.R. = \frac{C.I.}{R.I.}$, where the CR should reach a value <10%

R.I. - random index whose value depends on the 'n' number of compared components (tab. 8).
Tab. 8. Value of the random index (RI).

n	1	2	3	4	5	6	7	8	9	10
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: (Saaty 1990, 1994)

Conclusions

In the civil engineering practice, there are many ways of completing construction investment projects. Each construction can be built in a number of ways, which enables architects and designers to prepare different variants of planned buildings. The requirements set in front of building constructions, described above, show how wide is the range of analyses concerning the discussed solutions. The model construction can be made as a steel or monolithic ferroconcrete structure. The description of the construction given in this article demonstrates how differently the individual criteria are satisfied by the two technological variants. Analysis of the criteria could be a starting point for further analyses and, depending on the investor's expectations, either of the analyzed solutions can be implemented. Traditional methods have been amended with a calculation method which belongs to multi-criteria methods, namely the AHP approach. This is the method which – owing to its specific attitude to comparisons of analyzed criteria – enables us to see the problem via determination of advantages of one solution over the other, and can be successfully used in comparisons of the type dealt with in this paper.

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