The Usage of Iterative Methods of Implementation of Complex Civil Engineering Projects Based on Stadium Canopy Large-Scale Spatial Structures

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Abstract. The term iteration (from the Latin „iteratio” - repetition) deals with actions based on repeating a specific process as a method of achieving the desired objective. The iterative approach is used in computer science in creating programming algorithms. The iterative method is based on the assumption that a complicated program is created as the sum of individual iterations – separate steps that are increasingly detailed. The implementation of civil engineering projects is often indicated by computer science theorists as an example of not using the iterative methodology to solve complex problems. This is justified by the necessity to create a plan of realization for subsequent, different actions based on a previously prepared interdisciplinary design. However, there is an entire group of large-scale spatial structures whose characteristics point to the possibility of using iterative methodology both during the design phase, as well as in its implementation. Such facilities are oval stadium canopies based on using a repetitive spatial element in the construction structure, which in determining a clearly dominant architectural form constitutes a separate iteration also in the temporal sense. Testing the accuracy of the above-mentioned thesis is based on analyses of selected examples of stadium canopies as far as layout forms, as well as the principles of the functioning of constructional structures, exceptional due to extensive span and force. It is necessary to conduct an analysis of the characteristic features of these facilities, their structures, as well as the relationship between the spatial shape with the algorithms used and types of repetitive components. The implementation methods based on prefabrication of the elements of the constructional structure, as well as repetitive production and assembly schemes, should also be tested. In the tested multi-scale spatial facilities with clearly defined, often rhythmical structures such as stadium canopies, there are algorithms made up of clear iterations. Both singular, as well as sequential iterations, are used, the latter being a consequence of adapting the layout shape to the functional system of the stadium in case of facilities on the plan of an ellipse. In the facilities based on the plan of a circle, there is an algorithm with one type of an iteration with a scale resulting from the assumed constant constructional rhythm. The iterative approach is an immanent feature of designing and implementing large-scale oval stadium canopy spatial structures. The iterative method also concerns the process of constructional optimization of each individual element of the structure. Facilities created with the use of the iterative methodology are characterized by purity, honesty, and clarity of the synthetic architecture which corresponds in full to the thoroughly optimized construction. In addition, the postulate of the unity of function, form, and construction in architecture is also fulfilled.
1. Introduction

Iteration is a term encountered in computer science. The iterative approach is used there as a method of creating algorithms in computer programs. In a more general sense, the use of iterations encompasses activities that are based on repeating actions or a process to achieve the desired objective. In computer science, the iterative method used is based on the assumption that a complicated computer program is created as a sum of individual iterations – steps separated in time which become more and more detailed. The use of the iterative approach in a design or task in civil engineering occurs very seldom. The completion of civil engineering projects is shown by computer scientists as an example of not using the iterative methodology to solve complex problems. [1] This is justified by the necessity to create a detailed plan of completion of subsequent, differing from one another tasks.

1.1. Searching for iterations in architecture - theory

In times predominantly dominated by digital technologies, it may seem surprising to question the presence of iterations in architecture. However, architecture as an activity set on the verge of technology and art is largely governed by its own rules. Its complex nature can change the image of a design to such an extent that simple logical sequences are hidden, blurred in the maze of all rules. Additionally, these rules cannot be simply defined. An experienced architect, while drawing a line, decides on several design aspects at once. A significant part of these decisions results from his individual experience and his own interpretation of general principles. So it is not difficult to get an opinion rejecting iterations in architecture among professionals from similar professions.

Today, more and more aspects of work are shared by architects and IT professionals. These include software, modelling, technical infrastructure. Both of these professions are in their cores connected with designing and observing reality. The IT approach imposes the necessity of accurate observation and precise defining as well as the unambiguous assignment of data, variables and process structures. IT is based on ideal and accurate solutions (including model solutions), and it does not need the real world to exist or check the correctness of solutions. Its product can be a purely virtual creation and function very well beyond reality (i.e. Virtual Reality - VR, games). Despite this "facilitation", the performance of operations on values and variables still faces problems related to technical limitations (i.e. computational power), interpretation of real-world observations, or lack of full mapping capabilities (no data or too much data). A program is a multi-level structure which is a representation of reality, and its basic components are iterations. The professions of architecture and computer scientists have more and more points in common. They are similar to each other on a certain level, and on another level, they are very different. In architecture, we encounter problems similar to those of IT specialists. These are often associated with a large amount of data and a difficulty in reproducing or interpreting them. To solve such problems we use simplifications and models. A model in its basic definition is a simplification of a real situation. It can present only a selected issue of the problem, simplify a process with a high data amount or high implementation costs.

A model can represent an image of the designed object. Such models (mock-ups) are made in order to show and examine the form of a yet non-existing object. Despite possible model simplifications, the architectural and urban design aims to realise a more or less complex structure in the real world. Even with a lot of professional experience this can be difficult to do and requires tools to check results (models, calculations, etc.). If a "new path" is being followed, it may turn out to be even impossible and requiring research. Physical models, mock-ups, are very useful, yet digital models are increasingly used in the architectural design process. This is because digital design techniques allow creating multi-variant solutions and thus gain time and reducing research costs. In some complex cases, they can even give the possibility of implementing a model. An IT-based approach to design (including architectural design) is nothing new. Algorithms of the design process describe it in great detail. However, it is possible to describe the whole design process with a very general scheme. Its construction will depend on how we define the design process itself. Based on the definition of improvement of an existing state, which is the basic aim
of designing, or the definition of changing of a non-standard relative situation into a standard one the design process can be generalized as a process of identifying and solving problems (figure 1).

Figure 1. Block diagram of the problem solution process - own study

As the diagram above shows, this process is an iteration. Depending on the profession or the problem to solve the tools and methods change, but the process itself is a loop. It can be repeated a specified or indefinite number of times. At this level of generalization, it can be assumed that most of the human activity is the same. It is the identification of a problem and its solution together with the path leading to this solution. Only by going into details and considering their subsequent levels, we can see how many differences arise (similarly to comparing the professions of architects and IT specialists).

An iteration is the repetition of the same operation in a loop. Some definitions (e.g. Wikipedia) add information about repeating the loop a predetermined number of times (let's describe such iterations as full, and iterations with indefinite repetitions as simple). The existence of loops in nature is undeniable, which is shown by scientists analysing fractals observed in nature. This natural fractal "disorder" is also used where nature is imitated or serves as a source of inspiration. After all, even parametric textures used by architects are based on these equations. Similarly, when we hear about the work of the NOX group or other architects, we can realise that thanks to the designers' use of counting machines, iterations become an integral part of the design process.

The design process usually starts by identifying the problem. [2] We start with many questions and few answers. During the process, we uncover more and more answers, which allow us to modify and choose the best course of action in order to achieve a solution. Despite the fact that the whole process can be saved in one complicated algorithm (containing iterations), there is still a high probability of many complications during its implementation. These may be due to the combination of this process, or rather its effects, with the chosen location, i.e. the real world. Moreover, during the project process, there may occur unpredictable circumstances which are connected with the participants of the whole process. Since we cannot fully guarantee the effect we will achieve by repeating the loop a certain number of times, it may be impossible to achieve full iteration in the design process.

In times of digital machine dominance, a computer-based approach to the profession is becoming increasingly important. The ability to organize and record data in a computerised way is a highly valued skill. However, this is not an easy task, also for students who are at the beginning of their adventure with architecture. One of the subjects of the architectural studies at our University called "Model Design" includes works that fit very well into the subject of iteration. Design exercises in this subject do not have a predetermined final effect in terms of form or function of the object. Their aim is rather the search for
a solution to a given problem. The designed object is based on themes from the borderlands of architecture. The classes consist of an attempt to create a model for a selected issue, evaluation of its operation, analysis of mistakes made, drawing conclusions and correcting the initial model. In this exercise, iterations appear spontaneously, and yet they are not an end in themselves. The program of the subject is based on a simple scheme placed below, and resulting directly from the essence of the design described in the iteration. In addition, one of the tasks is to describe the conducted design process in an algorithmic form. The topic of the task is selected so that it is possible to repeat the steps leading to finding a solution several times. As a result of this exercise, we receive works containing iterations revealed in the form of an object and in different arrangements. Among others, there are halls consisting of repeating a single segment solution a certain number of times. In order to achieve the desired visual effects, changes are made to the form or complexity of the repeated element (figure 2).

Figure 2. Paper models as an example of linear iteration creating the form of an object - photo by Cezary Wawrzyniak

Changing the guideline for a repeating element into a circle or an ellipse also results in interesting solutions (figure 3).

Figure 3. Iteration in a working model of roof construction (model by Janusz Rożek) - photo by Cezary Wawrzyniak
Iterations also appear in the vertical arrangement of the object. Especially in the case of high-rise buildings, where the middle core is reproduced precisely (in terms of form and arrangement) and each subsequent storey (also reproduced in terms of arrangement) gains an additional parameter of rotation in relation to the vertical axis of the core (figure 4).

![Figure 4. Vertical iteration in the form of an object. Change in appearance depending on the change of one parameter - Cezary Wawrzyniak](image)

Despite such interesting visual results, there are problems with the IT approach to modelling. Often the mere collation of results or division of data is already difficult to do. In the case of block diagrams, even 50% of participants make mistakes. The errors of the scheme are serious and its evaluation is difficult because it should be evaluated only in a zero-one system (correct or wrong). Any miscalculation due to iteration, and consequently (positive) feedback, will generate a colossal error. The most common errors are: not closing the schematic gaps and generating multiple endings, looping without obtaining a solution, combining levels of detail in one run, trying to fit one's own process into a sample schema - the latter can be rejected as a lack of understanding of the command. Unfortunately, mistakes are also made by professionals. It turns out that for architects themselves, as well as for graduate students the existence of iteration in architecture is not obvious, and the translation of everyday activities into the language of IT is a difficulty.

Although iterations may be invisible, they certainly occur in architecture and design. The problem arises when we include the repetition of an instruction "a predetermined number of times" in the definition of an iteration. This is also the case in architecture, but it should be limited to the final stage when there is enough information to give specific quantities on the designed object. Full iterations are easier to find in the execution process itself. After the finished design process, we know the exact quantities of specific elements and are able to determine their repeatability in the realization of the construction project.

It is difficult to notice the occurrence of iterations in architecture, but they certainly do, if not in the full sense (as in IT), then at least in the form of general iterations. Iterations occur not only in architecture as a whole process, but also in the design process itself. We can use them both consciously and unconsciously. We can arrive at solutions that contain them, but we are not always able to translate this path into computer language. This can explain the frequent errors made in the block diagrams. Iterations in architecture are clearly visible in the case of objects with a particular function or form. In which the design requires repetition of the same actions according to a specific rule or principle.

In civil engineering, there is a whole group of facilities whose characteristic features allow for the possibility of using the iterative methodology, both in the design phase, as well as during the
implementation. In case of specific, large-scale spatial facilities such as canopies of halls, stadiums or sports arenas the iterative method can successfully be applied. Furthermore, such an approach is, by all means, beneficial and helps in the programming, designing as well as the completion of such structures. It can also be a condition (sometimes unnecessary or insufficient) of the creation of rational, interesting and aesthetic structures.

2. Historical structures with iterative elements (antiquity)
The iterative approach to planning and construction does not have to correspond to using contemporary, advanced methods of facility design and implementation. It is also not a sign of our times or an example of technological progress in civil engineering. This progress rather manifests itself in very daring and spectacular implementations which seem to be characterized by breaking off from the established canons, crossing the dimensional boundaries and experimenting with form and material. An analysis of characteristic historical structures which have been preserved until today, allows us to conclude that one of their principal characteristics is the repetitiveness of form and construction. One may even pose the thesis that it was specifically the iterative approach and methods of realization that to a large extent contributed to their longevity. In these structures, the experiences of previous generations of builders come together as far as the method of construction, selection of materials and their processing, method of assembly and connections. The way that the ancient masters worked cannot be justified by optimization based on the results of systematic calculations. Rather, we are dealing with intuition and careful observation as well as the imitation of nature. Apart from that, structures such as e.g. classical temples, aqueducts, and ancient arenas constituted a significant challenge as far as scale in relation to the advancement and level of the technology of those times. Significant height and large construction span was a challenge in every aspect. Yet, these structures were constructed and survived not only attempts at destruction by the hand of man but the systematic destructive forces of nature and the elements as well. Their present-day condition is often proof of the original use of the appropriate methods and means. In every such case, we are dealing with the systematic use of a certain spatial and constructive algorithm, sometimes multiple algorithms. At the same time, this algorithm is used in a consistent manner without the flexibility to adapt it to possible changeable conditions of the location. The hierarchy of structures if there are rational premises occurring as well as the logic of the solution is quite visible. All this confirms the fact that iteration of such archetypical structures is their immanent feature and the condition of their longevity.

All Roman amphitheatres are an example of the iterative approach to the completion of exceptional civil engineering structures. This principle lets us assume that this method constituted an effective measure of overcoming construction problems resulting from their enormous scale. Many amphitheatres have been preserved in a relatively good condition until the present day, despite the fact that they are nearly 2 thousand years old, while the dimensions of the oval views are over one hundred meters. They are an example of the application of spatial sequences of construction iterations of the hierarchical character. Suspended linear constructions were also used in Roman amphitheatres to mount light material awnings the so-called velarium. The radial system of ropes mounted on pillars above the last story and connected with an internal tension ring created a regular structure with obvious iterative features.

3. Contemporary facilities with iterative elements
The search for contemporary facilities that exhibit distinct features indicating the use of iterative methods of design and realization shows that relatively few facilities fulfil the criterion of repetitiveness and coherence in function, form, as well as construction. The functionality system as the most important and original feature, which is seldom based on multiple and exact repetitiveness of the same sequences is of particular importance. An exception to this rule is sports facilities designated for disciplines with a large number of fans. Therefore, criteria of the evaluation of a facility belonging to this category were formulated in order to search for examples, while their analysis allowed for the specification of characteristic and common features such as: sequentiality of function and construction, unity of
functional and constructive rhythm, the repetitiveness of construction spatial elements as well as the resulting solutions of architectural and construction details. In contemporary public space, large-scale spatial structures have appeared which fulfil the above-mentioned criteria. Their characteristic features indicate using the iterative approach both in the design phase as well as the realization phase. The most representative examples of such civil engineering facilities are oval stadium canopies based on using a repetitive spatial element in the construction structure, which constitutes a separate iteration. The test for the iteration of selected examples of stadium canopies is based on conducting analyses as far as the view of the form as well as the applied principles of functioning of the construction structures, which are exceptional due to the occurrence of significant spans and forces. It is also necessary to conduct an analysis of the characteristic features of the selected facilities by comparing the algorithms used with various types of repetitive spatial components. Methods of realization, often based on the prefabrication of structural elements of repetitive character are also tested.

In the examined large-scale spatial facilities such as stadium canopies with clearly defined structures with repetitive features, there are iterative algorithmic sequences. In most cases, the sequence iterations used are a consequence of the established goals of adapting the shape of the view to the functional system of the stadium e.g. on both sides of the symmetrical axis in case of facilities on a plan of an ellipse. In specific structures based on the plan of a circle, there is an algorithm with one type of iteration with a scale resulting from the established construction rhythm. The iterative character of the structure of canopies defines or more appropriately determines the construction structure, which thanks to this is subject to the same principles and becomes a logical, repetitive design task. Apart from programming the entire system, the designers must also solve a number of problems on various levels of specification in a way that can be called design prefabrication across all industries. Designing a model, partial iteration for multiple applications in the entire facility, with only slight modifications due to oval shape facilitates and simplifies the whole process. All this means that in the rationalization of the construction itself prefabrication widely used in such facilities plays a vital role. On one hand, this is a condition sine qua non, on the other – a consequence of the iterative approach. The architectural form is also a result of such an approach as it is bereft of all unnecessary elements and becomes genuine and pure.

4. The stadium in Chorzów (Poland)

4.1. Case presentation
The Silesian Stadium in Chorzów was built in 1956. This multi-function sports arena able to accommodate 100,000 fans was designed and stabilized by an earthen rampart with the basin accessible by two tunnels on a longitudinal axis. The design of the canopy along with the partial reconstruction of the stadium was created by the GMP Architekten (architecture) and SBP (construction) consortium in 2008 and finally completed in 2017 (figure 5).

Figure 5. Silesian Stadium in 1956 and a simplified model – drawing and model by Jan and Maciej Muszyński
4.2. Location conditions
The design of the roof of the Silesian Stadium in Chorzów was a specific task due to the dimensions of the stands as well as the necessity to mount a new structure in place of already existing cubature of the stadium’s auxiliary facilities as well as the differences in the height of the surrounding areas. The designers decided to give the stadium canopy a form directly resulting from the construction system while solving the issue of the differences in elevation using modified technology of monolithic reinforced concrete pillars. In this way using the iterative approach to a designing task a pure and simple spatial load-bearing structure, bereft of any elements not connected with the construction functions was created.

4.3. Construction criteria – original construction
The idea of a spatial load-bearing structure (main construction) is based on the principle of the construction of a bicycle wheel. [3] It consists of compressed external rings, tension spokes as well as internal tension ring. The geometry of the view is adapted to the shape of the existing stadium basin as well as the arrangements of the stands, while the external rings take on a form of an oval mesh basket with two radii. The entire structure is divided into 40 sections, constituting similar iterations both spatial and flat (figure 6).

![Figure 6. View of the roof and perspective of the singular iteration of the main structure - photos by Jan Muszyński](image)

4.4. Construction details
The external compressed rings built of steel box profiles are connected by pillars (spacers) of the same structure. The whole closed structure rests on 40 reinforced concrete pillars with roller supports. The length of the whole construction equals 334.71 meters, while its width is 275.23 meters. The segments of the compressed rings have the shape of an arch for architectural reasons (figure 7).

The internal tension ring is made up of 8 steel wires with a diameter of 120 mm. The external and internal rings are connected with flat linear trusses made up of an upper suspension cable with a diameter of 100 – 130 mm and a lower tension cable with a diameter of 70 – 90 mm, between which there are hangers to attach the secondary load-bearing construction (structures of the canopy). The girders were connected to the internal ring wires using two-dimensional connectors with a double T-profile equipped with cast beam pockets. At the ends of all steel cables, there are cast steels with pin mounts (figure 7).
4.5. Secondary construction
The suspended (secondary) load-bearing construction of the canopy consists of a system of girders and similarly to the original construction has a repetitive character. Eight ring rafters from welded double T-beams were connected with radially running ribs from rectangular profiles. The roof sheathing from polycarbonate sheets combined into easy to transport cookies was placed on such scaffolding. The flexibility of the shield provided by the roof surface is ensured thanks to articulated connections. (figure 8) The geometry of the roof is adapted to the curvature of the lower tension cables, which enables water removal in the direction of the lower compressed ring.

4.6. Supporting structure and realization methods
Due to the existence of cubature and engineering facilities as well as the geometry of the area, 5 types of reinforced concrete pillars were designed with a height of 27.35 meters. Some of them go through the existing stadium auxiliary facilities. The necessity to ensure independent functioning of the supporting construction as well as for reasons of fire safety forced the designers to leave spaces around the reinforced concrete pillars as a separate fire safety zone in the form of vertical chimneys crisscrossing all stories (figure 9). The process of raising and stretching the entire spatial linear structure (the so-called big lift) is based on the simultaneous and strictly coordinated stretching of the radial cables with the use of winding machines mounted on both rings in the axis of each pillar and ends with the insertion of the pins into the pockets welded onto the external rings.
4.7. Spatial expression

The body of the Silesian Stadium, which is the largest linear structure of its type in the world, is located in a specific space. The surrounding park compromised to a large extent of an old-growth forest stand is a graceful background for the applied solutions. At the same time, there are numerous interactions: the park is a place for observing the stadium from various elevations but is itself observed by users from various levels of the stadium. The scale of the buffer zone allows for the preservation of the appropriate distance and the complete perception of the body. Despite the enormous scale the surroundings do not seem to be dominated by the stadium. Thanks to maximum transparency and the geometry of the structure connected with the subtlety of the connecting elements it appears to be extremely light and in places even petite. From a distance, the "basket" of the stadium seems to be flowing in a sea of lush greenery. (figure 10)

5. Conclusions

Large-scale and repetitive functional sports facilities with a distinct spatial character constitute a significant designing and realization challenge. The iterative approach to the designing process and completion of these facilities seems to be the appropriate strategy and methodology of action. Iterative
activities may encompass the functionality system, spatial system, construction principle, and even
details. They also concern the optimization process of repetitive constructions of the structural elements.
Applying the iterative methodology in the design and completion of large-scale sports facilities of
specific and universal character leads to the creation of very functionally clear structures and thus user-
friendly. They are characterized by a distinct and pure architectural form strictly connected with the
spatial system. The synthesis of form which corresponds to the optimal construction is very rational
from the economic point of view as well. This, in turn, in the contemporary world, is very desirable due
to environmental factors. Iteration of these structures also ensures the desired effect of creating room
around the facility corresponding to its important role in the public space. All the above-mentioned
features of the examined structures allow us to conclude that the iterative approach may help in the
search for architectural beauty, and in a broader context for the principal objective – the truth.

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