The impact of the combined innovations at the Hungarian National Athletics Stadium steel roof structure construction

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Abstract –

The aim of the research is to discover the interrelation between Construction 4.0 technologies and Sustainable development Goals (SDG) in a complex project. The construction of the National Athletic Stadium in Hungary of the 25.000m^2 steel and cable membrane roofing structure demanded special innovations due to its uniqueness and its special geometry was used to explore these relationships. Construction 4.0 technologies such as Design for Manufacturing and Assembly (DfMA), Building Information Modelling (BIM), the combination of parametric-algorithmic design and large volume metrology (LVM) laser tracking have been applied to deliver the complex shape. Qualitative case study research methodology was applied to demonstrate that Construction 4.0 technologies can facilitate complex projects, increase collaboration, decrease risk and save significant time and money while contributing to the achievement of Sustainable Development Goals (SDG).

Keywords –

DfMA, sustainability, parametric-algorithmic design, laser tracking, construction 4.0, metrology, case study, SDG

1 Introduction

Industry 4.0 involves supporting relatively standardised processes with digital tools. However, in contrast to industrial production, a particular problem is that the type, location and size of construction projects vary with each investment by the companies involved, thus standardising processes is a particular challenge in the absence of modern technology and an unskilled workforce. The Construction Industry (CI) is transforming into a new cyber-physical ecosystem called Construction 4.0 that facilitates this problem. This cyber-physical ecosystem includes technologies, methodologies and concepts and strong collaboration in order to build in a more sustainable way[1]. To achieve this, it is simply not enough to apply innovations on a large scale, the combined impact of related technologies must also be taken into account throughout the whole value chain [2].

Despite the fact that sustainability has become a pillar of the transformative industry, there is still a research gap in the relationship between new construction technologies and the SDGs. Thus, the aim of the research was to answer the question of how the technologies used in a complex project affect the quality, time and costs of the project and how these relate to the achievement of SDGs. The case study introduces the construction and applied innovations of the National Athletics Stadium in Hungary of the 25.000m^2 steel and cable net structure. The special roofing of the service area was built by the KÉSZ Group and its member companies with the assistance of innovation partners and experts.

The design-manufacture and assembly teams worked together early in the design phase to realise the complex structure. The design was facilitated by Building Information Modelling (BIM) and parametric-algorithmic design which together founded the concept of Design for Manufacturing and Assembly (DfMA). DfMA is the strategy that considers the building element in the design phase for manufacturability and buildability in order to speed up construction processes and optimises material usage [3,4].

DfMA in combination with parametric design can reduce waste during manufacturing [5] and enhance the use of tight quality control and can infuse more innovation offsite [6]. This is particularly important during the construction of a special steel structure that demands a geometrical accuracy of mm. For this, large-volume metrology (LVM) laser tracking can provide a solution that can facilitate tens of mm over large objects. This technology has been successfully applied in many industries such as aerospace, automotive and shipbuilding in manufacturing processes [7–10].

The United Nations report shows that the CI is responsible for 37% of energy-related carbon emissions [12] due to its inefficiency and high-emission supply chain. Major changes are needed in the design and procurement phases also to achieve responsible consumption and production targets. Unfortunately, the most optimal solutions are still not brought to the design table [13]. Furthermore, the industry's raw material production 95% uses water [14] which has a great impact on the Earth's clean water. Technological infusion especially DfMA can directly support organisations to achieve SDGs [6]. Literature highlights sustainable cities and communities (SDG11), climate action (SGD13), responsible consumption and production (SDG12) and clean water (SDG6) as the four most important SDGs from the perspective of CI [11]. Climate action is the common goal for the whole society. [12][13][14]

2 Research Methodology

Qualitative research methodology was applied with a case study approach to prepare an explanatory case study. Explanatory case study aims to *"seek answer for presumed causal links in real-life interventions that are too complex for the survey or experimental strategies"* [15]. The preparation of the case study consisted of three different phases: the design of the case study, conducting the case study and analysis of the results [14]. A preliminary workshop was conducted with the KÉSZ Group management and project participants during the design of the case study. The workshop aimed to explore the innovations used in the construction of the Hungarian National Athletics Stadium. As a result of the workshop the participants agreed that the main innovation of the project was the application of the LVM technology. During this workshop, the sampling strategy was also agreed on how to conduct interviews for each phase of the project participants. In the second phase of the case study, further two workshops and four semi-structured interviews were conducted with a total of eleven people, each playing a different role in the four project phases to explore how the technologies were applied. The output of the second phase was the technologies effect for each project phase. Finally, in the third phase of the case study, the results were analysed in a matrix based on the project process to evaluate the results in terms of challenges, solutions and impacts of sustainability. At this stage, a literature review was conducted to clarify the sustainable impacts. The results were post-reviewed by the project participants. Table 1 illustrates each interviewee and their main collaboration phase in the project.

Table 1 Interviewee participants and their role

Number	Role	Phase
Interviewee 1	Contractor	Assembly
Interviewee 2	Contractor	Assembly
Interviewee 3	Designer	Design
Interviewee 4	Designer	Design
Interviewee 5	Manufacturing	Manufacturing
Interviewee 6	Manufacturing	Manufacturing
Interviewee 7	Quality Control	Manufacturing
Interviewee 8	Quality Control	Manufacturing
Interviewee 9	Quality Control	Manufacturing
Interviewee 10	Contractor	Assembly
Interviewee 11	Consultant	Cable tension

3 Case study

The implementation of a complex cable-tensioned steel structure required innovations that overcame the complex challenges of design, manufacturing and construction. This case study aims to demonstrate through the construction of the roof structure of the Hungarian National Athletics Stadium the impact of innovations and their interrelation with the SDGs on the implementation of an entire project and its interconnected processes during the design, manufacturing and assembly (construction) phases.

3.1 The challenges of the steel structure

The varying geometry in different construction stages required high dimensional accuracy, which was only possible with a quality control (QC) method capable of sub-mm accuracy during the manufacturing process. In addition, the manufacturer sought to achieve the structure with the most optimal use of materials, as the technical problems were exacerbated by the emergence of the pandemic that generated further problems in the supply chain.

During the design, the biggest challenge was the complex geometry as the different phases of construction formed different geometrical shapes. Furthermore, the complexity of the structure had to be taken into account by choosing the manufacturing and construction technology. Thus, the plans had to be prepared for four different service conditions:

1. Manufactured steel structure
2. Assembled steel structure
3. Tensioned cable structure
4. As-built steel structure

The geometry and structural complexity induced the tight tolerance problem. For the appropriate functioning of the structure, the structural 3 mm tolerance between the structural nodes, while the entire structure's 50 mm tolerance was specified for the entire length of the structure. In interpreting the tolerance specification, it is important to emphasise that tolerance was not defined as the tolerance of individual components, but as the sum of the tolerances of several manufactured components, which required quality control beyond the continuous inspection of manufactured components.

Thus, the steel structure was built with a higher execution class based on EN 1090 EU standard than required by the design. Execution class (EXC) refers to the level of quality and assurance controls needed to ensure a structure meets the engineer’s design assumptions. KÉSZ Group has applied the highest execution class, EXC4 for the steel ring due to having as much optimisation as possible. Thus, the carbon footprint had been reduced and the pandemic and the fragile supply chain were taken into account. Although the EXC quality control system specifies a number of requirements, in this case study geometric dimensional accuracy will be discussed in detail.

The tolerances and size also needed to be considered during the baseplate assembly installation during the construction phase. Since the tolerance had to be provided together with the manufacturing and placement defects of the base assemblies, the result of the design evaluation had to be taken into account in all cases until the base assemblies were pinned. The complexity was further induced by the reinforced concrete structure as it was built in pre-shift to the steel structure installation. Cable installation required a structure built with precise geometry and cables cut to exact dimensions. Table 1 summarises the challenges of steel structure construction.

Table 2 The challenges of the steel structure construction

Phase	Challenges
Design	Complex geometry had to be followed in the different stages of construction
Manufacturing	Consideration of installation technology, feasibility, materials 3 mm tolerance between the structural nodes and 50 mm tolerance in the entire structure Temperature Pandemic and supply chain problems
Assembly	Baseplate assembly installation and size
Cable tension	Cable and geometry accuracy

3.2 The solution

The complex structure demanded a technological solution for the problems of the design, manufacturing, assembly and cable tensioning processes together. In addition to the complexity, the feasibility was also a risk, therefore the concept of the technology was developed during the tender phase.

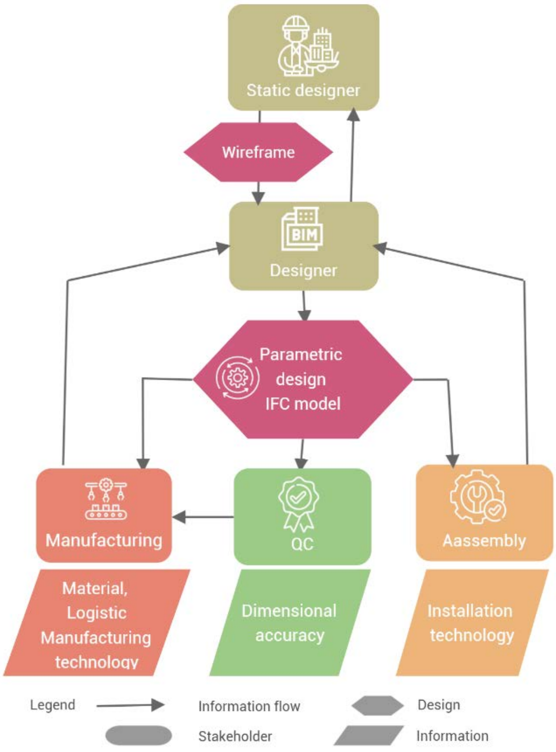

Figure 1 The design collaboration

This was facilitated by DfMA-oriented parametric-algorithmic design in combination with LVM laser tracking. The implementation of the four different geometries was facilitated by parametric design, which supported the design, manufacturing, quality control and assembly team collaboration in the design phase. Figure 1 illustrates this process.

The combination of Tekla Structure and Rhynoceros-Grasshopper software were the core tool for the parametric-algorithmic design. Based on the structural calculation, the steel structure's wireframe was created. Due to the change of sections and stiffness during the design process, and after counting in the material quality and availability, the possibilities of installation and quality control opportunities new structural calculations were made several times, which resulted in continuous changes to the wireframes. This continuous change was tracked by the Rhynoceros-Grasshopper algorithm, which generated automatically the 3D shop drawings of the entire steel structure in Tekla Structures. Finally, the model was converted to IFC to be able to use for all departments in Trimble Connect. The entire model of the compressing ring was regenerated in 1-2 hours and with final model checking was ready in 1-2 days due to the parametric design algorithm. Figure 2 illustrates the concept of the project process.

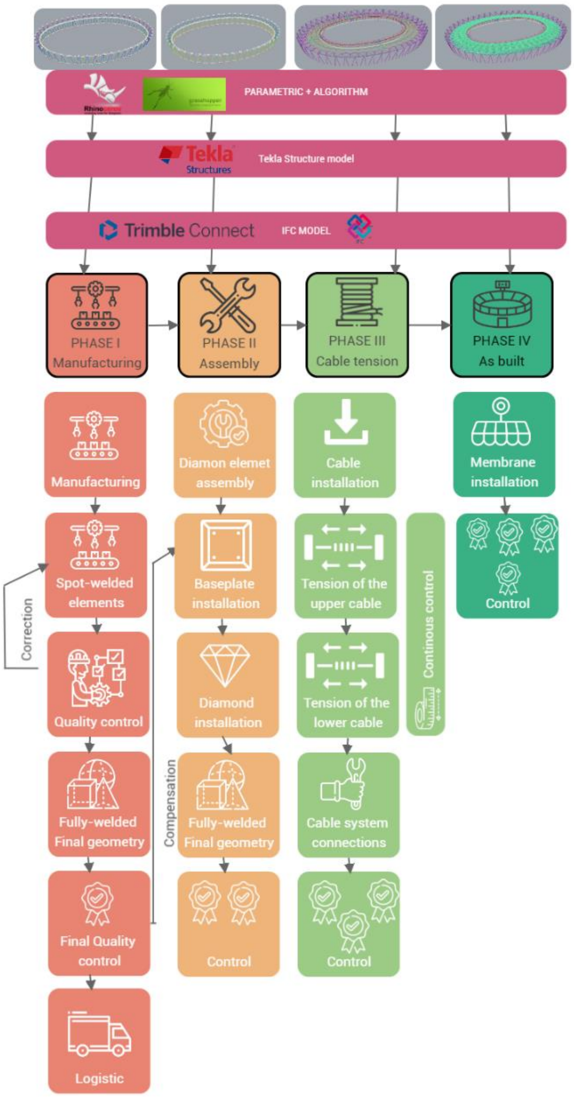

Figure 2 Concept of the project process

The entire process can be broken down into four main parts based on the geometry which represents the four service conditions: manufacturing, on-site assembly, cable tensioning and the built structure. These processes are described in detail in the following four subsections.

3.2.1 Phase I - Manufacturing

Based on the manufacturing, construction and logistical aspects, the steel structure has been divided into so-called diamond elements (Figure 3 red elements). The steel structure was made up of 48 diamonds, which were further broken down into manufacturing and logistical phases.

During manufacture, the required accuracy could only be ensured by LVM. Due to the dimensions of the structure, it was also necessary to take into account the prevailing structural temperature during manufacture and to compensate for the theoretical mean value when setting the length dimensions. The data was provided by the design team in a variety of file formats (IFC, DXF, XML, NC) from the Tekla model, according to the manufacturer's machines, which were then used by the programming technologists to set up the machines. The communication between the teams was supported by Trimble Connect.

Figure 3 A selected diamond in the IFC model

The dimensional accuracy was facilitated by LVM laser tracking during the QC. The technological solution was developed based on a previous project where FARO® Quantum Faroarm® & Scanarm series was successfully applied by the innovation partner called Geolink3D. However, for elements of several metres and sometimes more than 10 tons, it became apparent that this tool would not be sufficiently precise. Thus, VantageS6 Max Laser Tracker was applied. This Laser Tracker was finally suitable to measure the approximately 10m length manufactured elements with a dimensional accuracy of 0.01mm.

QC worked closely with the design and manufacturing team. From the model, data were exported to FARO Cam2 software and the measurement criteria were recorded in the software. Finally, coordinate geometry was used to check each completed element against the geometric tolerances specified by the design team. Calibration was the first step in the LVM process. To achieve the correct dimensional accuracy of the machine needed to achieve equilibrium temperature which took about 30-80 minutes to compensate itself and a further 10 minutes were taken by the calibration. Each measurement was preceded by calibration to three points in a given area.

The first phase of the QC was the manufactured elements in spot welded condition. The 360-degree angle of view of the machine allowed to measure on both sides of the production area, therefore the QC and manufacturing teams could work together continuously to correct tenth of millimetre geometry instantaneous. The surfaces of the joined structures were machined using the data obtained by processing the measurement results

A joined element was typically assembled within three rounds of measurement and machining and within the tolerances allowed. The spot-welded elements were welded for their final geometry (Figure 4). Further dimensional variations could have occurred during the final welding hence all joined elements were post-qualified. The measurement results were recorded on a rolling basis per joined element; therefore, compensation could be made for the closure defect of the previously manufactured elements during the manufacture of the next element. Figure 4 shows a detail of a measurement protocol in an intermediate state. The total quality control process for a sole node element took approximately one hour, while for a compression ring node approximately 2-3 hours.

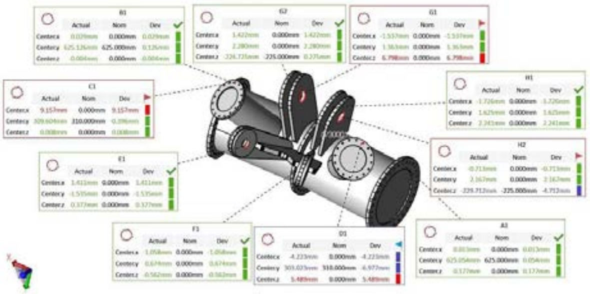

Figure 4 Compression ring node QC report

3.2.2 Phase II - Assembly

A diamond is made up of 10 sub-assemblies (c.f. Figure 3). Each diamond was thus assembled on site from 7 rods and a compression ring node and then inserted into 2 baseplate assemblies.

The baseplate node (Figure 5) was positioned and adjusted separately, as the vertical misalignment of the rods was compensated during the positioning of the baseplate. The positioning of the baseplates was a particular challenge due to the fact that each baseplate installation required the production of the connecting rods to be able to compensate their dimensional accuracy (final height coordinates), the accuracy of the reinforced concrete nest and the baseplate manufacturing defects. These challenges were solved by measuring from two positions during placement while taking each variable into account for the final compensation. During the alignment, the final compensation step was the correction of the baseplate node pin position, taking into account the resulting manufacturing defect of the connecting element series. The purpose of the baseplate node adjustment was to increase the geometrical accuracy of the compression rings on which the strained cables were loaded and to ensure that only forces in the direction of the actual rods would occur, thus the two rigid compression rings would be as close as possible to the originally designed geometry.

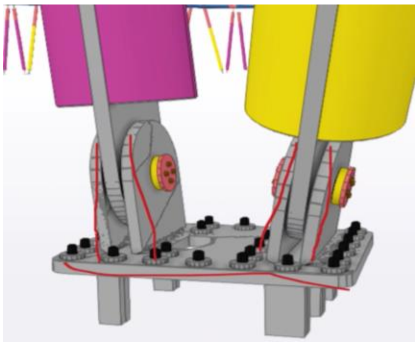

Figure 5 The base plate node in Tekla Structures

During this process, 3-4 baseplate assemblies were installed in one day and the 70 tons and 28m height diamond elements were assembled to this baseplate with the support of special crawler cranes that took further 3-4 hours per diamond. Assembly and installation were continuously carried out by two teams. The steel structure assembly followed the reinforced concrete structure in the compression ring direction.

3.2.3 Phase III – Cable tensioning

Computer controlled cable tensioning system was used to lift up the cable structure that spans 37 meters above the arena to cover the stadium. Once the cables were attached to the compression ring on-site (Figure 6) consisted of three steps.

Figure 6 The cables before the strain

In the first step, all the cables of the upper compression ring were prestressed by hydraulic jacks simultaneously, followed by the tensioning of the lower compression ring. The lifting process was controlled by a lifting sequence code, developed from finite element calculations of the lifting stages. This was a computer aided task. The goal of the process was to ensure a slide-free lift-off of the cable net from the scaffoldings, as well as to prevent the overstressing of the cables or the compression ring structure during the process (Figure 7).

Figure 7 The lifting process

The main input of the lifting process was the stroke sequence of the 96-strand jacking machines working simultaneously. The stroke distances were controlled by measuring the jack displacements as well as by direct distance measurements by a pull-wire system. As a third control instance, the forces in all cables were continuously measured from the oil pressure of the robot technology obtaining values within 2% of the design values during the lifting of the cable roof. Finally, the two-level cables were connected by the so-called flying columns. Flying column refers to the columns that were installed between two cables to keep the distance between the two levels (Figure 8). The final prestress applied by tensioning the lower radial cables to their pinning positions.

Figure 8 The flying columns

As a result, the surveyed deviations from the theoretical shape were of the order of mm (Figure 9) . The force measurements were also a verification of the cable and compression ring system manufacturing processes, as their geometrical precision directly governs the achieved prestress state.

3.2.4 Phase IV – As built structure

To achieve the final steel membrane structure, the membranes were placed on the prepared "spider mesh" cable structure, which was strained to their final state on-site using hand tools and the structure achieved the final shape. The final shape was created by tangentially joining 3 arcs of different radii and then segmenting the diamonds straight at their intersections.

Figure 9 The cable lifting final stage

3.3 Benefits of innovations

The world of Construction 4.0 is all about connecting technologies, methods and collaboration. The project team emphasised that feasibility could only be overcome and delivered on time and to the right technical standards through a combination of state-of-the-art technologies. Many research emphasises the isolated advantages of each technology however the authors here focus on the combined applications through the value chain.

First, in the tender and design phase, BIM created the opportunity for parametric, algorithmic design resulting in strong collaboration and more efficient solutions during the design, manufacturing and assembly phases than in the traditional solution. As a result, the team applied DfMA strategy during the project. The concept was developed during tender, therefore the costs of the technologies and the savings were taken into account in the quotation. Without a parametric design, the modelling phase would have taken at least four times longer and would have involved much more manpower, as the model was necessary for all four different service conditions. Thus, the design was significantly faster than without a parametric algorithm, leaving additional lead time for the manufacturing and assembly phases.

Second, as a result of the tight QC, the pre-assembly of the 48 diamonds in the factory was abandoned. The factory environment pre-assembly took two and a half days for the first diamond. The dimensional accuracy of this diamond has reached the required standards. For the further 47 diamonds this step was omitted, saving 47 times two and a half days. This equates to a total of 118 working days saving nearly six months. This time saving was particularly significant in the assembly phase to comply with the penalty period and to avoid another six months of project organisation costs on site.

Third, due to the detailed preparation the lifting of the cable net structure was completed in just over a month with the coordinated work of fewer than 20 people, and the forces measured during the lifting deviated on average by 1-2% from the preliminary calculations.

Last, according to the literature, the most important targets for the CI are SDG11-13, and SDG6 [11]. In addition to these objectives, this case study proves that the application of Construction 4.0 technologies also contributes to the following goals: Decent work and economic growth (SDG8) and Industry, innovation and infrastructure (SDG9). Novel SDG indicators were guided to determine the technologies contribution to the SDGs [16]. The enhanced design of the roof structure reduced the amount of steel required by almost a fifth due to the cable-tensioned steel membrane structure. The DfMA-oriented parametric-algorithmic design combined with tight quality control (application of LVM laser tracking) further optimised the design and the materials left over from the production process (templates of cut-out elements) were recycled, thus contributing to the circular economy. These steps were significantly reduced the carbon footprint and directly contributed to SDG12 and SDG13. The reduced and optimised raw material decreased the necessary water needed for raw material production contributing to SDG6. SDG9 was facilitated by BIM combined with parametric-algorithmic design, DfMA, LVM laser tracking and a computer-controlled cable tensioning system. In addition, background calculation indicates that the technologies used during the project brought significant cost saving leading to economic growth contributing to SDG8.

4 Summary and conclusion

Hungary has been lagging far behind the digitisation of the CI since the 1980s and the challenge of promoting Construction 4.0 in this market is much greater than in Western countries [17]. Nevertheless, this case study demonstrated that market players can take significant steps in complex projects to embrace innovation in recent years and the construction of the steel roof structure of the Hungarian National Athletics Stadium is internationally outstanding. Challenges include the feasibility of the project, technology and construction risks, short deadlines, the complex shape of the structure, dimensional accuracy, different geometries, pandemics and the fragile supply chain.

In this case study, estimations were presented, showing that parametric-algorithmic design saved four times in modelling time in the design phase. DfMA-oriented parametric design in combination with tight QC (LVM laser tracking) reduced the manufacturing phase by eliminating pre-assembly that lead to avoid another six months of project organisation costs on site and finish the project on time. The case study presented a literature gap so far [18] on how LVM can contribute to BIM and DfMA. As a result of these combined technologies computer-controlled cable tensioning system was successfully applied and resulted in 1-2% force deviations compared to the designed condition. Finally, the final shape of the complete compression ring at 806m ended up at 21mm tolerance compared to the allowed 50 mm. Even though sustainability was not a primary consideration in the project, the results demonstrate that the combined use of technologies contributes to the following SDGs: SDG6, SDG8, SDG9, SDG12 and SDG13.

Among the many barriers of Construction 4.0, management attitude is critical due to the lack of risk and return on investment calculations in the technologies [19,20]. This case study presents a great example for industry practitioners to overcome these barriers and presents the bottlenecks of technology implementation. In addition, it contributes to areas of SDGs impacted by these technologies that require further in-depth research to measure these contributions through key performance indicators. Thus, the authors will use the results for the development of the Construction 4.0 Maturity Model Ontology to explore in detail how to measure the relationship between technologies and SDGs.

In summary, the case study demonstrated that Construction 4.0 technologies can facilitate complex projects, decrease risk, increase collaboration and save significant time while directly transforming the construction to a more sustainable industry, thus, contributing to the achievement of SDGs.

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