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THE USE OF PARAMETRIC WORKFLOW ON TIMBER CONSTRUCTION AT SERVICE STATION TORGHATTEN

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ABSTRACT: This paper deals with the planning and design process of the service station Torghatten which should provide better tourism infrastructure for one of the Norwegian scenic routes. It describes parametric and automated workflows used across the various project planning phases and their benefits. Based on the project presented, it will also be shown how using these workflows makes it possible to combine modern design and complex geometries even with traditional construction methods.

KEYWORDS: Timber log structure, solid timber structure, complex geometry, parametric modelling

1 INTRODUCTION

The project 'service station Torghatten' is a collaboration between the architecture studio Atelier Oslo AS and Bollinger+Grohmann on behalf of the road authority 'Statens vegvesen' of Norway.

As part of the 'Nasjonale turistveger', the Norwegian scenic routes, the project has a prestige character within the tourism industry in Norway. The Norwegian scenic routes deliver a scenic alternative to the main roads and is suited for tourists who want to explore unique natural qualities such as fjords, mountains or waterfalls by car. To make these natural sights more accessible, each stop provides parking spaces, sanitary facilities, or information boards. The service areas aim to combine beautiful Norwegian nature with Nordic architecture and art.

Today, the Norwegian authorities established 18 scenic routes totaling more than two thousand kilometres. The new service station is part of the section 'Helgelandskysten' and situated on an island in Brønnøy commune. The connected natural sight is Torghatten, a geological formation of a mountain with a hole going through from one side to the other, shown in Figure 1.

Figure 1: *Photography of Torghatten by Atelier Oslo*

The project will be located at the foot of this mountain. It contains parking lots, benches, and rooms for sanitary, technical and exhibition usage. The rooms share one cantilevered roof structure made of timber. In addition, there is a steel stair structure planned, which leads up to the hole. This structure is not part of this paper.

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2 CONCEPT

The location of the service station forms a transition between the organised forecourt and the wild nature of Torghatten in the background (see Figure 2).

Three volumes where the cantilevered roof structure rests offer shelter and space for toilets and exhibition areas. The covered outdoor area below the canopy roof creates open spaces equipped with bicycle parking spaces and seating.

Figure 2: *Visualization of the service station by Atelier Oslo*

Except for the foundation, the whole building consists of solid timber beams arranged in layers on top of each other. The alternating overlapping of the layers of timber creates a log structure, which has a long tradition in Norway and is known as 'lafteverk'. This concept continues in the roof structure which is made of overlapping beams in several layers and irregular placement (see Figure 3). The construction method with its traditional roots represents a low-tech solution common in rural areas and differs from many high-tech solutions in urban construction. Due to this irregular placement of the timber beams and the glass roof around the structure, varied shadow plays can be observed throughout the day.

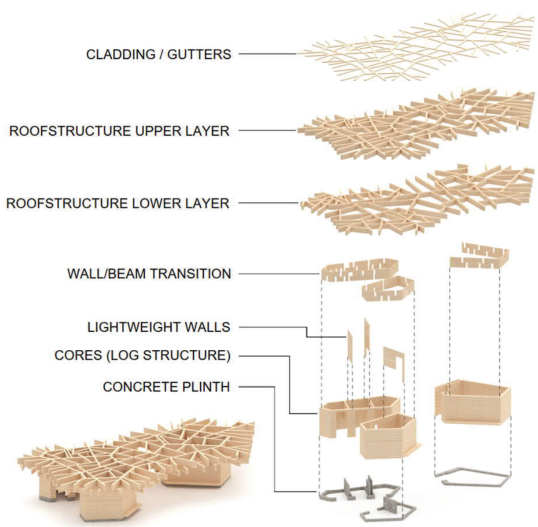

Figure 3: *Illustration of the service building components by Atelier Oslo (translated)*

The simple screw connections and the renunciation of glued timber connections allow the building to be easily dismantled at the end of its lifetime. Just in 2022 these regulations for the reuse of building materials were relaxed in Norway, making it easier to reuse the screws afterwards. A sustainable solution for the project could be found through the predominant use of renewable materials and consideration of the entire life cycle of the building.

3 STRUCTURE – WALLS

3.1 STRUCTURAL CONCEPT

The walls follow the traditionally used 'lafteverk'-concept, where each timber member is placed on top of the other. Each member interlocks on the top and bottom sides to create a horizontal shear connection between the layers.

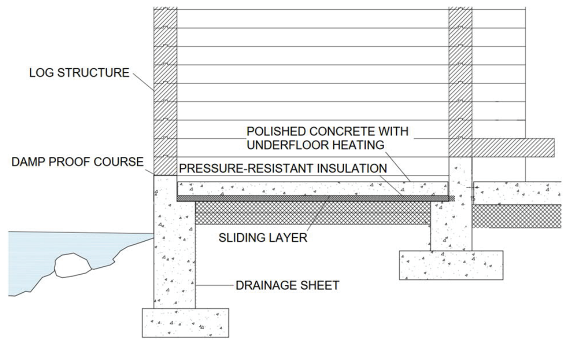

Figure 4: *Section through the service station by Atelier Oslo (translated version of an early presentation)*

In the intersections of two walls, the members alternately overlap in layers. This concept results in a structure of rigid wooden boxes that do not require any additional fasteners except for the door openings. Since the openings interrupt the interlocking principle, other timber dowels and vertical members were planned to ensure the stability of the walls.

3.2 ANCHORAGE/FOUNDATION

The cantilevers of the roof structure, the wind pressure from the passing wind underneath and the wind suction from above lead to uplifting forces that need to be anchored in the foundation. A detailed wind simulation was performed to estimate realistic values for the resulting wind forces that also take the blockage of the canopy roof into account (see Figure 5).

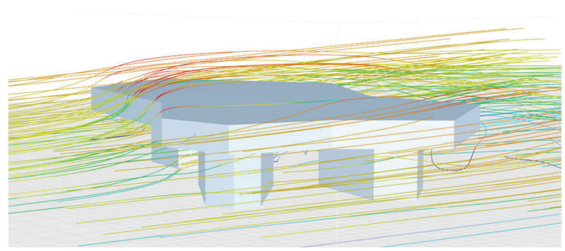

Figure 5: *Extract from the FE-wind calculation*

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The resulting uplift forces are transferred by screws from the roof structure into the walls. As shown in Figure 6, the three upper beam layers are screwed to the three lower beam layers screwed to the upper members of the walls. A threaded rod that goes through all wall members is anchored in the foundation and receives a steel plate inside an opening in the top member of the walls. Through this threaded rod, the anchorage of the building can be adjusted according to the long-term deformations of the walls.

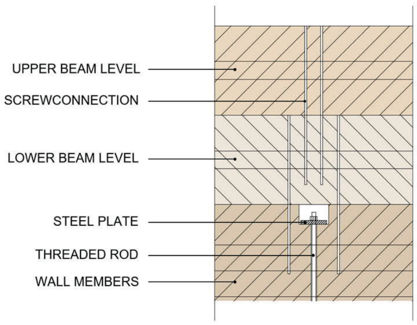

Figure 6: *Anchorage detail*

4 STRUCTURE – ROOF

4.1 STRUCTURAL CONCEPT

4.1.1 Lafteverk-concept within the roof structure

Like the walls, the roof structure also follows the 'lafteverk' principle. Each beam consists of three solid timber members, that are screwed together to create one stiffer member. In the intersections of two beams of the same level, the upper and lower layer of the primary beam (see Figure 7 in orange) continue. In contrast, the inner beam layer stops to give room for the inner layer of the secondary beam (see Figure 7 in green).

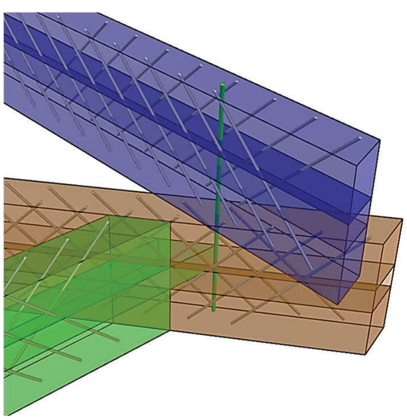

Figure 7: *Illustration of a connection of three beams*

This overlapping of the beam layers creates a vertical support for the secondary beam. This support is unsuitable for transferring moments, so it can be assumed to be hinged. To enable the cantilevers of the canopy roof, another level of beams has to be introduced (see Figure 7 in blue) to support the cantilevered beams that would be structurally unstable, with their only support being hinged. The beams must be placed so that every unstable secondary beam of one level can be supported by a structurally stable beam of the other level. This concept and the resulting structural systems are shown in Figure 8. As shown, it does not matter if a beam from the upper layer supports a beam from the lower layer or the other way around.

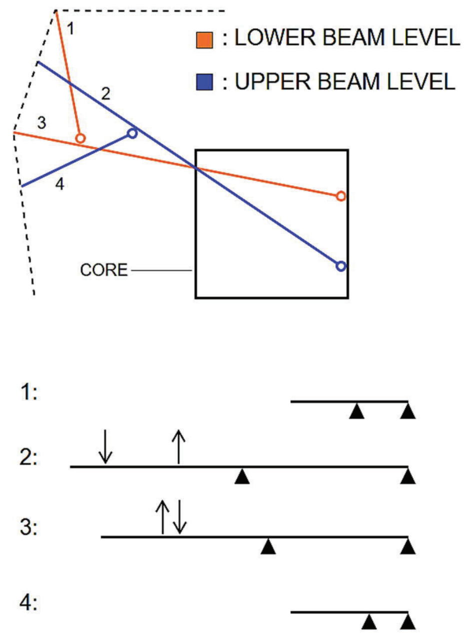

Figure 8: *Illustration of the structural concept of the roof*

Each level on its own would therefore be unstable. Only the combination of the two levels create a stable system where the acting forces travel up and down in the levels and end at the cores.

4.1.2 Form-finding

The architectural design showed the roof geometry as a disordered interaction of beams (see Figure 9).

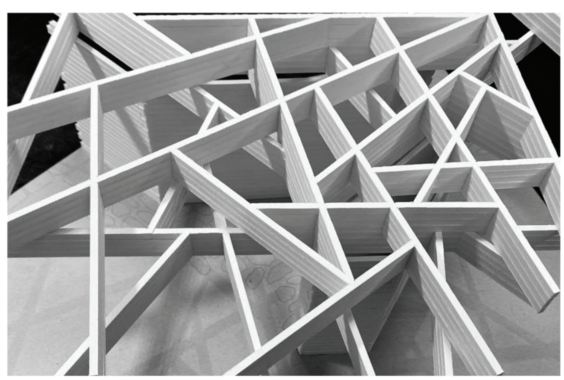

Figure 9: *Photography of an early model by Atelier Oslo*

The task was, therefore, to optimise the beam layout in a way that combines the architectural concept and an efficient structural design.

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First, a variation of beam geometries was created using Rhino 3D and its plug-in Grasshopper. For this purpose, short lines were generated along the wall supports defined as fixed positions. Each of these were given a ranking. The short lines were then successively extended in the order of their ranking. If the lines meet the defined building boundary or hit another line, they are not extended any further. In the next step, the lines' ranking varied, which led to endless new patterns. The principle is shown in Figure 10. This approach made it possible to obtain various beam layouts that always sit on the supporting walls.

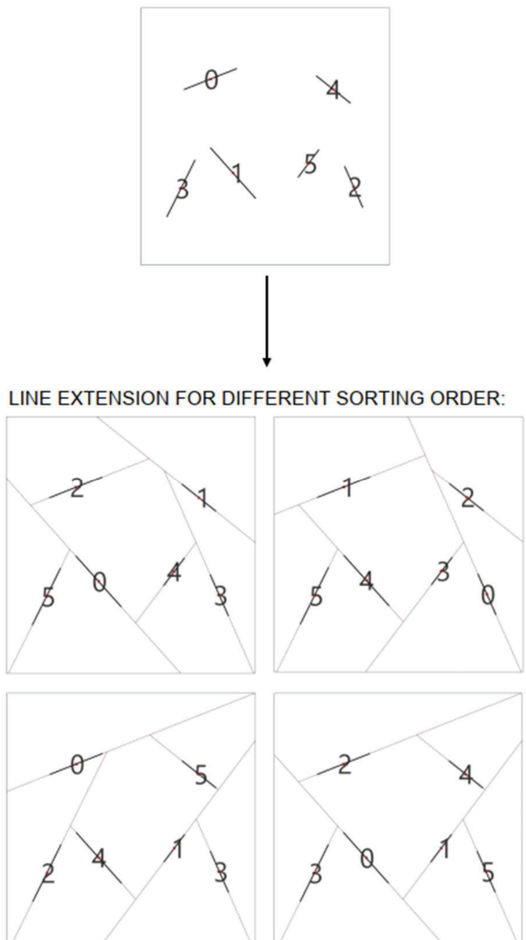

Figure 10: *Illustration of the form finding concept*

To get a tighter beam grid and to optimise the wall positions, additional lines and boundary conditions for the wall geometry were implemented.

In a further step, a structural analysis including FE-calculations was performed using the Grasshopper application Karamba in combination with a multi-objective optimization using the application Octopus. The results of the optimization were rated according to the three variation criteria "deformation", "deviation of the wall geometry" and "beam diversity". The architects used the optimisation variants (examples shown in Figure 11) as the basis for discussion and further development of the roof geometry.

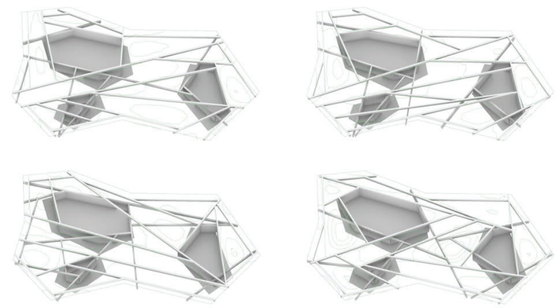

Figure 11: *Selection of results of the form-finding process*

The last adjustments, which led to the final geometry, were made in collaboration between Bollinger+Grohmann and Atelier Oslo based on more detailed FE calculation models using RFEM.

4.1.3 **Modelling**

The structural calculation model was created by using the FE-Software RFEM by Dlubal. The Eurocode refers to the gamma method in EN 1995-1-1 Annex B to model mechanically jointed beams. The gamma method is a simplified calculation in which the reduction factor gamma considers the resilience of the mechanical connection. This factor makes calculating an effective bending stiffness and the resulting deformation and inner forces possible. However, the calculation of the gamma values requires certain boundary conditions. For a mechanically jointed beam consisting of three members, the gamma values can be calculated as shown below:

$$\gamma_2 = 1 \qquad (1)$$

For i = 1 and i = 3:

$$\gamma_i = [1 + \pi^2 \, E_i \, A_i \, s_i / (K_i \, l^2)]^{-1} \qquad (2)$$

Ei Ai: axial stiffness

Ki: slip modulus

si: spacing between the fasteners

l: span

The shown equation (2) sets limits such as a uniform compound of the connection, constant cross-sections and simplified structural support conditions. Especially the last-mentioned limitation is hard to combine with the shown project. The span l can be defined as follows:

Single span beams with a span l: l = l

Continuous beams with a span l_i: l = 0,8 l_i

Cantilever with a cantilever length l_c = 2 l_c

Even though RFEM offers the opportunity to define mechanically jointed beams according to their gamma values, each beam would have a different gamma value because of the varying support conditions. Furthermore,

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the simplified structural systems used in the code to define the value for l are not feasible for more complex geometries like the roof structure. This premise meant that the gamma method was only used for preliminary calculations and as a plausibility check for individual beams.

A more precise approach was considered to model the stiffness reduction within the mechanically jointed beams, including the screws in the FE-model. The slip modulus of a mechanical connection influences the deformation behaviour of load-bearing systems. In addition, it directly affects the distribution of internal forces in the case of flexibly connected bending beams [1]. For this reason, each screw member had to be modelled according to its slip modulus.

Each combined beam's upper and lower beam layer was modelled for the calculation model according to their cross sections and material properties. Between these layers, the screws were added as spring members at a 45° angle and with a hinged connection to the beams. Each spring member was modelled with a capacity limit and a spring constant according to its slip modulus for the different limit states ULS and SLS and the time $t = 0$ and $t = \infty$. The resulting model acts as a truss system with realistic stiffness values. Additional vertical compression members, which fail if tension occurs, were added to simulate the beams laying on each other. As a simplification, the middle beam layer was only modelled as a load. To gain better control of the internal forces, every truss received a result beam that can show the combined inner forces of the upper and lower beam (see Figure 12).

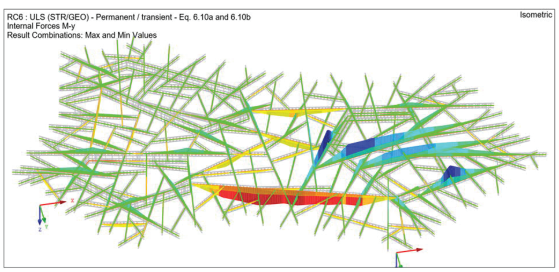

Figure 12: *Moment diagram of the result beams*

Figure 13 shows the FE model equivalent of a combined beam consisting of three individual beams screwed together.

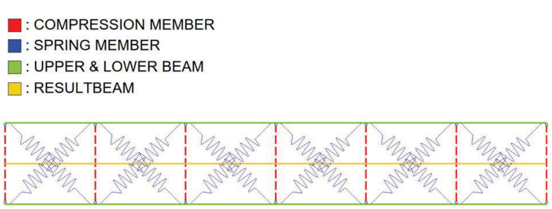

Figure 13: *Illustration of a beam in the structural model*

4.1.4 **Interaction between FE-calculation model and parametric model**

By having a representative member for each screw of the roof structure, the FE-model gained much complexity. To still react quickly and efficiently to changes in geometry or screwing, interfaces were created between the parametric 3D model and the calculation model.

The Rhino 3D plug-in Grasshopper made it possible to determine the centre lines of each beam for the calculation model from the architects' 3D model. Cross-sections and material properties could already be assigned to these centre lines. In a further step, the centerlines of the screws were generated, and for the screws fixed boundary conditions and variables were defined. One example for a variable parameter was the screw spacing. This made it possible to change the distances between screws in Grasshopper easily, and all the screw centre lines were automatically updated. Figure 14 shows an extract from the parametrically generated centre lines of the screws.

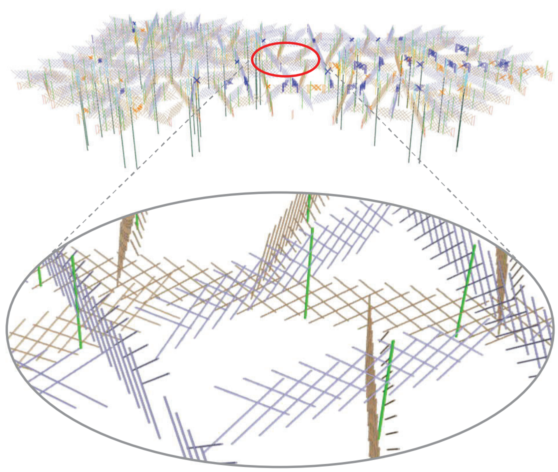

Figure 14: *Generated centre lines of the screws*

After the import into RFEM, only a few adjustments had to be made to get the results from the FE calculation.

5 PARAMETRIC COLLISION CHECK

The two super-positioned structural levels must be connected and also to the cores at particular points, thus creating constraints for the insertion of fasteners. Additionally, intertwining the beam layers within each level of the roof structure induces many potential clashing situations between fasteners and timber beam edges. Since the three beam layers of every level must create a stiff member, the density of necessary screws must be relatively high, increasing the complexity even further.

Over six thousand fasteners of at least eight different types varying in position, length, diameter, and angle had to be placed within this complex structure.

Some screws penetrate not only the three intertwining beams of one roof level but also those of the roof level beneath or the top layers of the walls. This posed a challenge for their modelling, but even more so for ensuring that all fasteners keep a minimum distance to each other and any other element, edge or opening.

By informing each element with a set of key and value properties, such as for the screws their type and beam affiliation, and for the beams their dimensions and beam group affiliation, they could easily be filtered and integrated into custom checks. For example, one review was to model a pipe around a set of screws, with the pipe's radius representing the minimum distance to other objects as defined in the code. Then, the pipe was used for clash detection towards another set of screws or towards beam or opening edges.

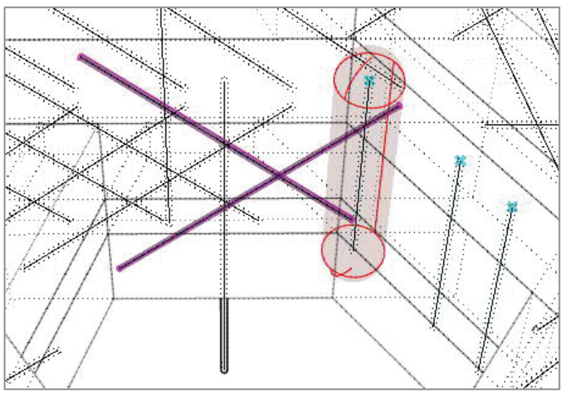

Figure 15: *Showcasing a collision check example*

Even with the 3-dimensional model at hand, it sometimes proved difficult to orient within the structure and avoid confusion. But without using both a 3-dimensional model and a parametric tool, this task for sure could not have been achieved within a reasonable timeframe.

6 PARAMETRIC SHOP DRAWINGS

By choosing a parametric workflow for this project, it was possible to automate almost the entire shop drawing process. This required setting up and maintaining a highly detailed, consistent, and data-informed 3D representation of the whole structure. Therefore, all structural parts, like beams, screws etc., were developed parametrically by Grasshopper scripts. Especially the complex intertwining beam layout proved to be an exciting challenge.

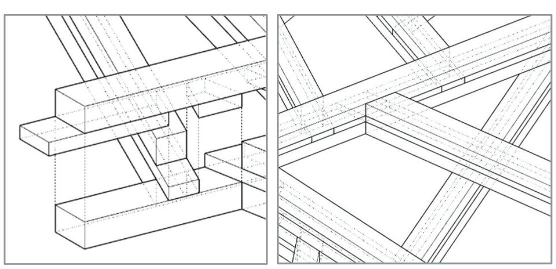

Figure 16: *Intertwined beam layers*

On the one hand, the beams were modelled as simple beams with rectangular plans, with each beam aware of its raw dimensions. On this basis, an excel sheet was exported containing all the necessary information to purchase the raw timber beams, since they had to be dried early on for the later construction process. On the other hand, the beams were also modelled in detail, with their heads cut according to their intersections to produce plans for their manufacture (see Figure 17).

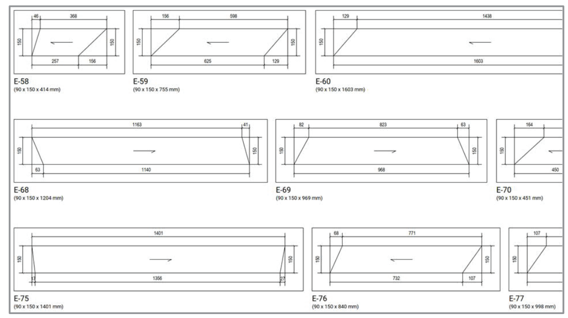

Figure 17: *Extract from the cutting drawing*

Since most elements for the drawings were extracted from or created based on the model, but also to enable an easy check of consistency between the 3D model and the 2D plans, they were made in 3D space at their actual location in the roof structure (see Figure 18). The geometrical elements of the drawing, dimensions, drawing titles, leaders and texts were generated in the parametric process. Once a set of elements was not supposed to change at a certain point in the design process, its final version was stored in the 3D model to reduce the number of elements in the scripting pipeline. To integrate them in the later stage plan production, they inherited the keys and values of their 3D parents and received new information on their purpose.

To conceive meaningful screw position plans, the almost one thousand beams making up the roof structure had to be sorted into roughly two hundred beam groups according to which beams were parallel and connected. Each resulting beam group received geometry and information from neighbouring groups, such as connecting beams and relevant screws that should be displayed along with themselves for orientation. Per beam group, one top view and one section plan were generated. For example, the model's 3D screw lines were transformed into 2D circles at their tips for the top views and to 2D offsets along their length for the sections. The diameter was retrieved from a table according to the screw type information each line contained.

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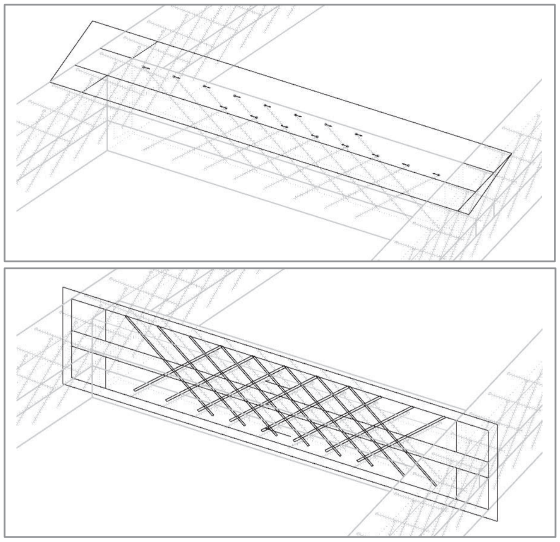

Figure 18: *'Raw' drawings at their origin within the 3D model*

In total, 16 A0 plans were produced for the beam cutting plans and 19 A0 plans for the screw position plans, plus a few more for overviews etc. Considering this number of plans and because every A0 sheet can contain up to one hundred beam cut drawings or up to twenty screw position drawings, it was a challenge to figure out a smart layout for each plan. Therefore, also this task was delegated to a computational tool: A nesting algorithm automatically distributed differently sized rectangles representing each drawing on A0 sheet boundaries, resulting in a spatially optimized layout (see Figure 19). The distributed rectangles contained information as to which drawing, they belonged, so the drawings could be placed on the A0 sheets accordingly.

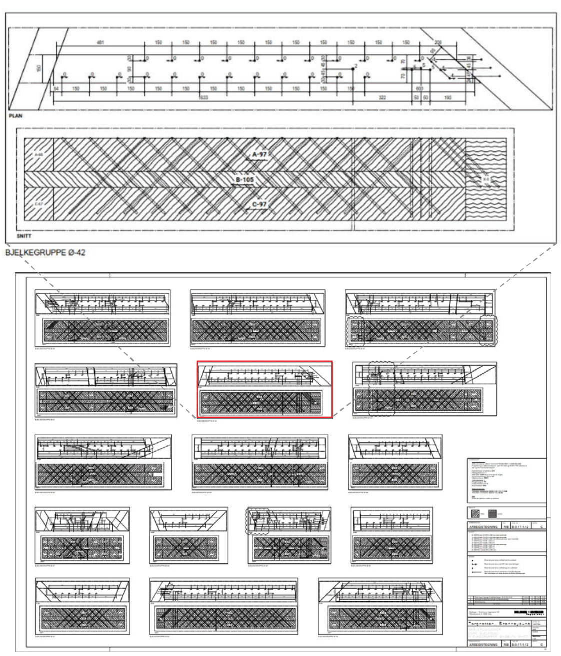

Figure 19: *Extract from the screw position drawings*

Since the entire workflow from modeling to plan production is parametric, changes to the structure or the drawings can be made relatively fast, and automated checks can be performed to enhance quality and oversight. Nevertheless, it was of course necessary to also double-check every plan manually in case of overlapping drawing elements or potential errors. These manual corrections alone proved to be so time-consuming due the number of drawings, that a manual production of all drawings in projects of this complexity can hardly be imagined.

7 CONCLUSION

The project 'service station Torghatten' presented several challenges for the planning architects and engineers due to its disorderly roof geometry and the chosen construction method resulting in an enormous number of fasteners. However, the successful course of the project showed how a parametrised workflow of the complex geometry in all project phases could help to overcome these challenges. The parametric form-finding process also made it possible to achieve an optimised solution in terms of costs, material consumption and sustainability. The interface between the parametric model and the FE software ensured that changes in the design could easily be imported into the analytical model. Custom scripts facilitated the handling of the geometry, for example, to automate edge distance control and collision checks of the screws. This led to more precise results and time savings. Thanks to the automated plan production process, hundreds of individual beams and thousands of screws could be transcribed with their exact position from a 3D model into 2D plans within a short time.

This project has shown that modern planning methods, such as the described parametric workflow, can give new input to traditional construction methods, such as the Norwegian 'lafteverk'.

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