Tampereen yliopisto

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ALGORITHM-AIDED PRE-DESIGN OF BOILER BUILDINGS

Faculty of Built Environment
Master of Science Thesis
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ABSTRACT

Janne Koivuniemi: Algorithm-aided pre-design of boiler buildings
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The aim of this master's thesis was to find out if the efficiency and speed of pre-design could be improved in boiler buildings using algorithm-aided design approach. For this purpose, an algorithm-aided design process was developed where some of the operations could still be performed manually. In addition, the algorithms needed for the process were developed. The algorithm-aided design process is based on an integrated design system, where one 3D product model of the structure is maintained in Building Information Modeling software. From the Building Information Model analysis models are generated using an algorithm. This design approach is not limited to boiler buildings, it can be used to design and analyze any structure modeled in Tekla Structures software. An algorithm for generating the Building Information model of boiler building was also developed.

The motivation for this thesis comes from the tight schedules in pre-design phases and the challenges in analyzing multiple optional structural frame options simultaneously and cost effectively. Most decision that affect the structural frame are made during the pre-design phase, so improving the pre-design process has a large impact on the realization of the whole project. By making the pre-design process more efficient the design options can be considered more comprehensively and thus, the comprehensive optimization of the design solution is possible. This generates savings in material and overall costs.

The algorithm-aided design process was found to be working as intended and the time savings achieved in the pre-design phase are significant. Boiler buildings are diverse in construction and geometry and it was found that the best way to perform the pre-design is to first generate a raw Building Information model using an algorithm. In this model the buildings geometry, details of equipment support and loads can be manually modified to answer the needs of the specific facility. Usually there is variation and exceptions that are difficult to fully handle with an algorithm. After the possible manual modifications an analysis model is generated from the Building Information Model using an algorithm, in which the parts that are included in the structural member design at the pre-design phase can be dimensioned. The same analysis model is used to determine foundation loads.

Keywords: Algorithm-aided design, boiler building, pre-design

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Janne Koivuniemi: Kattilalaitoksen algoritmiavusteinen esisuunnittelu
Diplomityö
Tampereen yliopisto
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Maaliskuu 2021

Tämän diplomityön tavoitteena oli selvittää, voidaanko algoritmiavusteisella suunnittelulla tehostaa ja nopeuttaa kattilalaitosten esisuunnittelua. Tätä tarkoitusta varten kehitettiin algoritmiavusteinen suunnitteluprosessi, jossa edelleen osa työvaiheista voidaan tehdä manuaalisesti. Tämän lisäksi kehitettiin prosessiin vaadittavat algoritmit. Kehitetty algoritmiavusteinen suunnitteluprosessi perustuu integroituun suunnittelujärjestelmään, jossa rakenteesta ylläpidetään yhtä 3D-tuotemallia tietomallinnusohjelmassa ja tästä generoidaan laskentamalleja algoritmiavusteisesti. Kyseinen suunnittelujärjestelmä ei ole sidoksissa vain kattilarakennuksiin, vaan sitä voidaan käyttää mihin tahansa rakenteisiin, jotka on mallinnettu käyttäen Tekla Structures tietomallinnusohjelmaa. Myös kattilalaitoksen esisuunnitteluvaiheen tietomallin generoimiseksi kehitettiin algoritmi.

Motivaatio työn tekemiseen muodostui esisuunnitteluvaiheiden tiukoista aikatauluista ja tästä johtuvasta erilaisten runkovaihtoehtojen samanaikaisen vertailun haasteellisuudesta. Suurin osa runkorakenteeseen vaikuttavista ratkaisuista tehdään jo esisuunnitteluvaiheessa, joten esisuunnitteluun panostamisella on huomattava vaikutus kokonaisuutta ajatellen. Tehostamalla esisuunnitteluprosessia voidaan näin ollen tutkia useampia rakenneratkaisuita ja valita mahdollisimman hyvä runkoratkaisu laitoksen tarpeisiin. Tällä tavoin voidaan saada aikaan materiaali- ja kustannussäästöjä.

Algoritmiavusteinen suunnitteluprosessi todettiin toimivaksi ja sillä aikaansaadaan merkittäviä säästöjä esisuunnitteluun kuluvassa ajassa. Kattilalaitokset ovat monimuotoisia ja epäsymmetrisiä kokonaisuuksia, joten käytännössä parhaaksi tavaksi suorittaa esisuunnittelu todettiin prosessi, jossa ensin luodaan rakenteen raakamalli tietomallinnusohjelmaan. Tämän jälkeen rakennuksen geometriaa, laitekannatuksien yksityiskohtia ja kuormituksia voidaan muokata käsin vastaamaan kyseisen laitoksen erityistarpeita. Näissä on usein vaihtelua ja poikkeuksia, joiden takia täysin valmiin rakennuksen mallintaminen algoritmilla on haastavaa. Tämän jälkeen tietomallista generoidaan algoritmilla laskentamalli, jossa voidaan mitoittaa esisuunnitteluvaiheen kannalta oleelliset rakenneosat ja laskea perustuskuormat.

Avainsanat: algoritmiavusteinen suunnittelu, kattilalaitos, esisuunnittelu

PREFACE

This Master’s Thesis is made for Sweco Structures Ltd. The aim was to enhance the design process of steel framed boiler buildings using algorithms-aided design methods. The research is focused on the pre-design phase in which the schedule is usually quite hectic but where the important decision affecting the structural frame (it’s costs, structural behavior and installability) are made.

I want to thank Professor Mikko Malaska of Tampere University and Ilari Pirhonen of Sweco Structural Ltd for guidance and support. I want to thank Sweco for providing me an interesting thesis subject. The subject was quite challenging for someone without prior programming experience but that also means I learned a lot about programming, visual programming, and algorithm-aided design in general.

I also want to thank all my colleagues in Tampere for their time and input in improving my knowledge of boiler buildings and steel structures in general.

Last and most I want to thank my spouse for taking care of our kids and tolerating me while I was focusing on this thesis and other schoolwork leading to my master’s degree.

“No tämähän on parempi kuin sata jänistä, nimittäin märät puut ei syty koskaan ilman syttöpaperia, aina täytyy olla syttöpaperia, se on yks asia mikä on varma tässä vaiheessa” – Kopiovastaava

In Tampere, 26.2.2020

Janne Koivuniemi

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AAD	Algorithm-Aided design
CAD	Computer-Aided design
BIM	Building Information Modeling
CNC	Computer numerical control, automated control of manufacturing machinery
IFC	Industry Foundation Classes, a standardized format for data transmission, used in architectural and construction applications.
FEM	Finite element method, a numerical method for solving partial differential equations
FEA	Finite Element Analysis, simulation of physical phenomenon using FEM
DWG	File format used by CAD software to store 2D or 3D design data, developed by Autodesk
LC	Load case
BFB	Bubbling Fluidized Bed, a boiler type
CFB	Circulating Fluidized Bed, a boiler type
API	Application programming interface
C#	C Sharp, a programming language developed by Microsoft

1. INTRODUCTION

Algorithm-aided design (AAD) has been on the rise within structural engineering recently when many companies and operators have found the new potential offered by AAD in making the design process faster and in handling design changes as well as modeling complex geometries. For these reasons many structural engineering companies are developing their own tools and practices for algorithm-aided and parametric design.

The algorithms used in this thesis were done using Grasshopper, an environment for visual programming. Grasshopper is a plug-in for Rhinoceros 3D CAD software. Rhinoceros itself was mainly used as a monitor to visualize the data and data flow inside the algorithms.

The produced algorithms generate structural model of the boiler building to Tekla Structures software, where it can be manually modified if needed. This model is then algorithmically exported into an analysis software, Autodesk Robot Structural Analysis Professional, where the building is analyzed, and the design calculations required at the pre-design phase are performed.

1.1 Background of the research

The schedule in pre-design phase of boiler buildings is usually tight and there is not enough time to consider different structural systems and solutions. The structural framing system is often chosen based on the solutions used in previous projects. This doesn't usually lead to the most optimal and cost-effective solution.

The pre-design phase is where the major decisions affecting building's frame are made, so this is the phase where making the design process faster and smoother can generate savings in project costs and overall better structures. In this thesis the algorithm-aided design is considered as a possible solution to these challenges.

1.2 Research aims and limitations

The aim of this research is to find out if it's possible to make pre-design of boiler buildings faster and more efficient using algorithm-aided design. The structural systems studied also include irregular geometry and framing. One aim is to find out which parts of the boiler building can be efficiently designed using algorithms and which parts are better left to be designed by traditional methods. The solutions aim to reduce the time required for manual operations so that the designer can focus on the actual design work. The research tries to answer how much the design process can be speed up by adopting algorithm-aided design approach. The algorithms necessary for this research are produced. Also, the usage and state of algorithm-aided design in the field of structural engineering is discussed.

The research scope is limited to the pre-design phase of boiler buildings with steel frame, where the boiler is hanged from steel structures with rods. Another way of supporting the boiler is from below with additional support structure, but this is uncommon in the larger boilers which are the ones mostly designed in Sweco. The boiler's supported from below require a whole different type of steel frame and thus it is not convenient to combine both in the same geometry creating algorithm. Boilers supported from below are not included in the scope.

Furthermore, only the main building of the boiler structure is considered, smaller buildings attached to the main building (such as fuel silo supports and stair towers) are not included in the scope nor are the equipment support outside the building.

1.3 Research methods

Research methods used in this thesis were literature study, survey study and case study. Literature survey is conducted to map the already existing knowledge of algorithm-aided design, focusing on improvements of efficiency and speed of structural design provided by adopting algorithm-aided approach to design. The special focus is taken because similar literature survey of algorithm-aided design in general is already available and it's still relevant while writing this thesis.

In the survey study, the state of algorithm-aided design in field of structural designing is being examined. The survey is directed to the structural designers in Sweco Structures Ltd that have been involved in algorithm-aided and parametric design. Open interviews of designers involved in boiler building design are also conducted during the development of the algorithms in order to get a working tool for pre-designing in practice. These interviews are directed to project managers and structural designers that have extensive experience in pre-design and final design of boiler buildings. From these interviews the information about framing system similarities and differences for different boiler types and what to take into consideration when developing the algorithms are investigated.

The case study is performed to test the developed algorithms and the algorithm-aided pre-design process. Case study is performed by making a new pre-design to an existing boiler building previously designed in Sweco by more traditional design process and comparing the time spent on the design and the foundation loads calculated.

1.4 Thesis structure

This thesis mainly focuses on pre-designing a steel structures of an industrial boiler building using algorithm-aided design methods. In chapter two the current design process is presented. The design process is studied through interviewing project managers and technical analysis experts involved in boiler building pre-design and going through projects previously designed in Sweco Structures Ltd. Also, different types of boilers are briefly presented, from the structural designer's point of view.

The theory and meaning of algorithm-aided design is briefly explained in chapter three. The study of these was conducted using literature survey on existing research. The focus on the chapter thought is in the usage and targets of algorithm-aided design today. This is researched using interview survey, the targets of the survey were the designers involved in algorithm-aided design in Sweco Structures Ltd.

In chapter four the workflow using algorithm-aided design in pre-design of boiler buildings is discussed. Chapter five consists of a case study where the algorithm-aided design process was tested in action. The target of the case study was a boiler building previously designed in Sweco Structures Ltd.

2. PRE-DESIGN OF BOILER BUILDINGS

2.1 Boiler buildings

Boiler building acts as a structural frame, and usually, but not always, as a weather shelter, for an energy boiler that produces high pressured steam which can then be used to generate electricity in turbine. In the structural engineer's point of view, considering the pre-engineering phase, the boiler has a few main parts that need to be supported from the building's frame, the parts vary a bit depending on a type of the boiler. This also means that the structural frame is varying depending on the boiler type. These main parts of the boilers are shown in the next subchapters where the different boiler types are introduced. In addition to these main parts every boiler has a feed water tank that is generally located in one of the service platforms, it adds a significant load to the frame, but it is quite simply supported from the platform beams. Boiler's also have various amount of other equipment supported from the frame, but these are not as heavy and significant as the main parts. Most of the main equipment are hanged from main support level with tension rods. The main support level consists of large welded box beams that are supported from the boiler columns, which are usually also welded box profiles. The layout of the boiler building is viewed in the direction of the steam flow and it is necessary to know which are the front, rear, left and right sides of the boiler building to be able to communicate with other designers involved in the boiler project. The layout direction is presented in Figure 1.

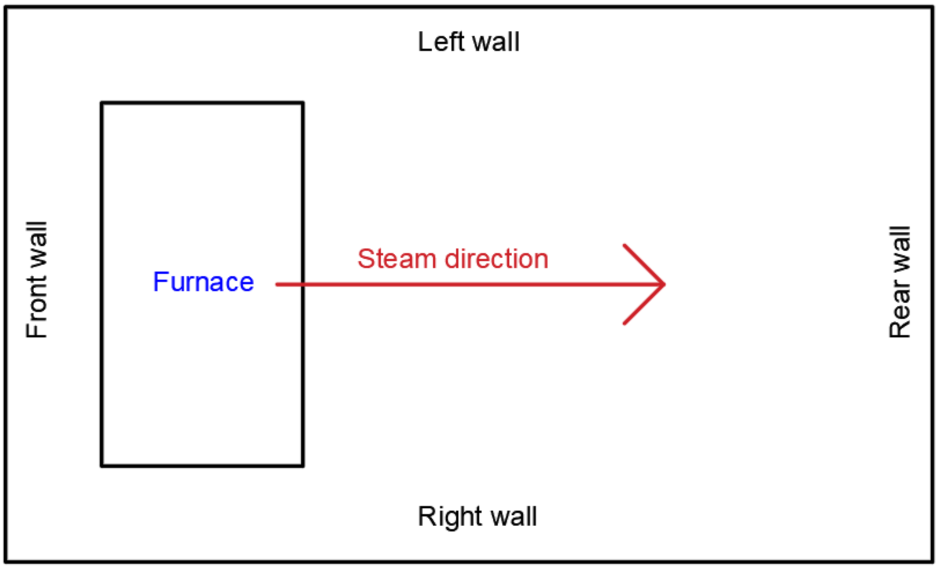

Figure 1. *Boiler building layout directions.*

Boilers can be roughly divided into three types according to the process they use to generate steam: Bubbling Fluidized Bed boiler, Circulating Fluidized Bed boiler and Recovery boiler. The steam generation process is not included in the introduction of the boilers. Seppälä has discussed the steam generation processes in his master's thesis (Seppälä 2010).

In the pre-design phase two documents are usually delivered. A foundation map, where the foundation locations and IDs are shown, and a table which contains the foundation loads. In the table the foundation IDs are shown and the resultants of each of the load cases. Usually the resultant of each of the load cases for the whole building are also presented. The foundation loads are delivered as NTE-loads (Not to exceed), which means that the final loads to the foundations, calculated when the whole structure is designed, should not exceed the given value even though the loads at this phase are usually preliminary and are going to be changed during the design cycle of the boiler building. This is achieved simply by using a factor to increase the loads, the factor is agreed with the customer, who also provides the structural designer with the equipment loads.

2.1.1 Bubbling Fluidized Bed Boiler

Bubbling Fluidized Bed (BFB) boilers are used to combust fuels with low thermal value and high moisture content, such as bark, wood chips, peat, different sludges, and other recycled products. Different kinds of fuel can be used simultaneously. (HYBEX boilers 2014)

In Figure 2 the main parts of the boiler supported from the building's frame are shown. 3rd pass includes economizer, the upper part, and air-preheater, the lower part, which are usually not hanged from the main support level but have their own supports.

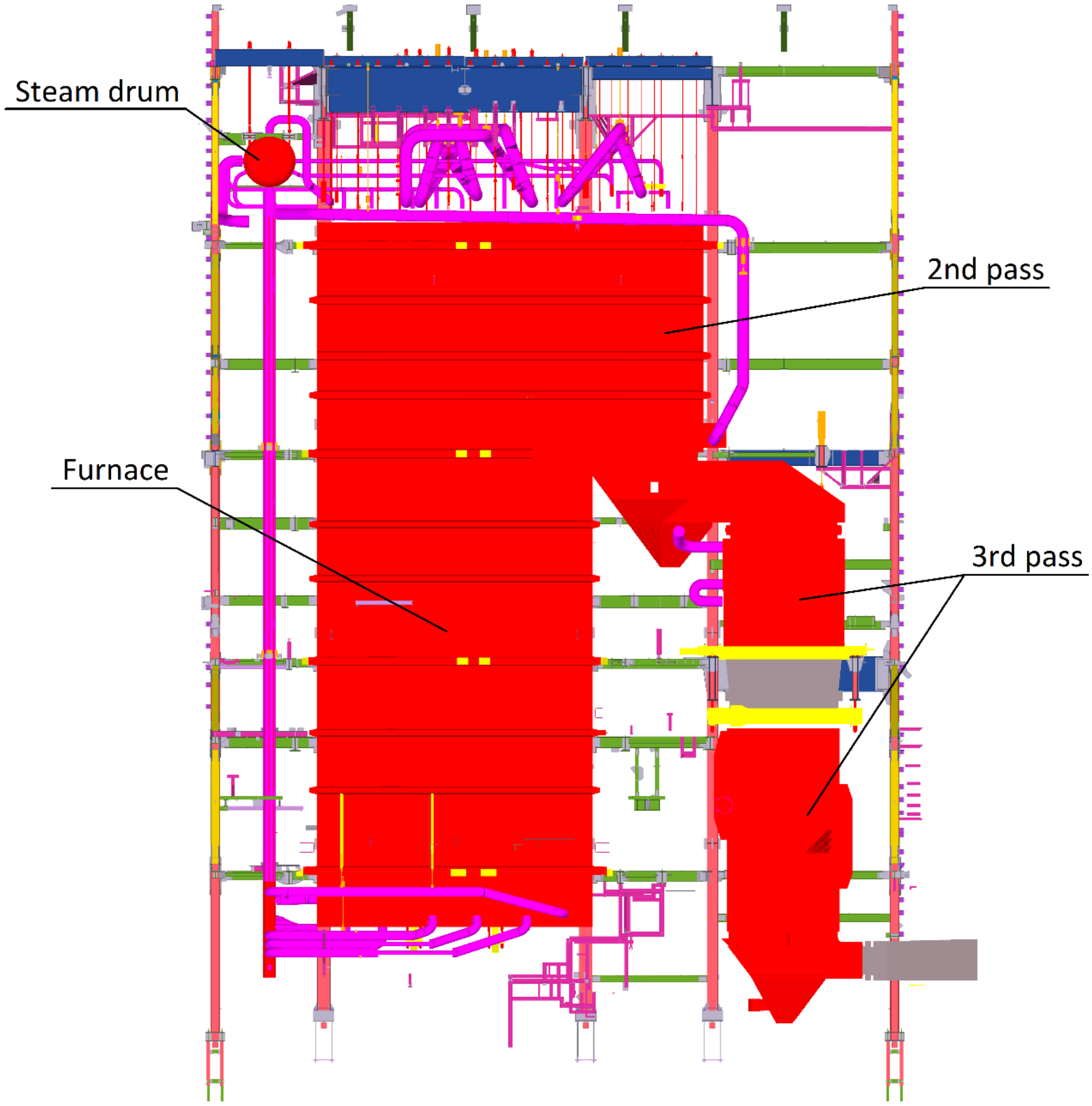

Figure 2. *Cross section of a BFB boiler*

2.1.2 Circulating Fluidized Bed Boiler

Circulating Fluidized Bed (CFB) boilers can be used combust coal, biomass, recovered fuel fractions or a combination of them. The thermal power output produced by CFB boilers is higher than of those produced by BFB boilers. (CYMIC boilers 2014)

In Figure 3 the main parts of the boiler supported from the building's frame are shown. 3rd pass includes economizer, the upper part, and air-preheater, the lower part, which are usually not hanged from the main support level but have their own support beams. The Catalyst is an optional part of the CFB boiler, and it is generally also not hanged from the main support level but has its own support beams. Depending on the size of the boiler there might be one or two cyclones. If there is only one cyclone, it and 2nd pass are eccentric to boiler's centerline, thus making the supporting frame unsymmetrical. This is a noticeable difference in the frame compared to other types of boilers.

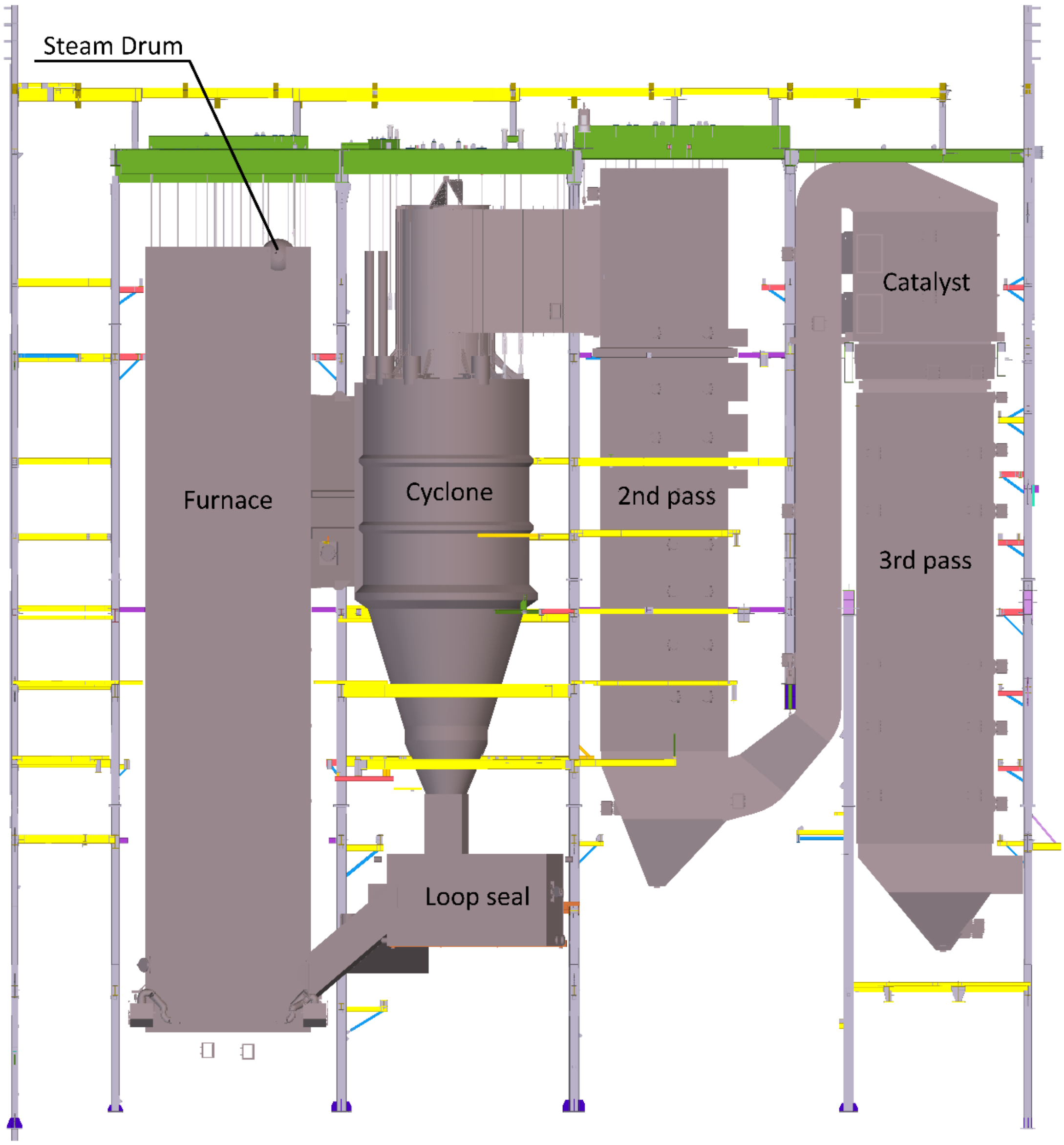

Figure 3. *Cross section of a CFB boiler*

2.1.3 Recovery Boiler

Recovery Boilers are used in pulping industry to combust concentrated black liquor, which is a by-product in pulping process. According to Vakkila the recovery boiler has three main functions in pulp mill: it combusts the organic material in black liquor to generate steam, it restores and recycles chemicals spent in making of black liquor and minimizes the waste production of the mill. In Figure 4 the main parts of a Recovery boiler are shown. (Vakkila 2005)

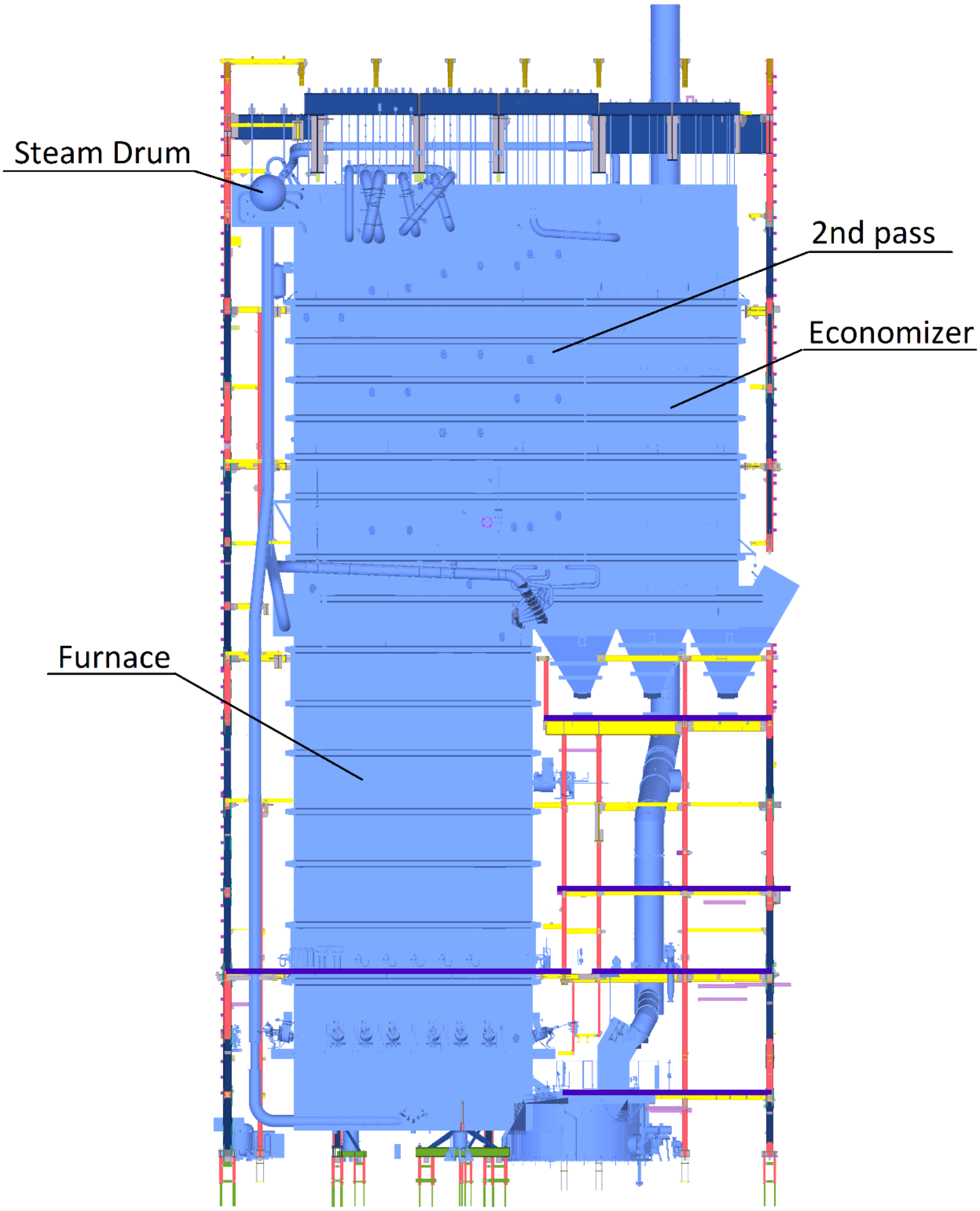

Figure 4. *Cross section of a Recovery boiler*

2.2 Pre-design process today

In this subchapter the pre-design process used in Sweco Structures Ltd. Tampere department is presented. The process might differ from the design process used elsewhere and according to the interviewed people it is not quite common practice. More often the structure's geometry is modeled with a Building Information Model (BIM) software and exported to a Finite Element Method (FEM) software, or the geometry is modeled straight to the FEM software, and after that different models are maintained separately and the data transfer between the models is done manually. All the definitions needed for the Finite Element Analysis (FEA) are done in the FEM software manually and if the geometry is revised during the pre-design it is must be changed manually to both software. This method is even less efficient than the one currently used in Sweco's Tampere department and this traditional design process is not discussed further.

The boiler building design process used in Sweco's Tampere department today can already be called algorithm-aided, as it includes running a few individual scripts, but it still includes a lot of manual work and it contains a few inconveniences. The algorithm-aided process created within this thesis is meant to lessen the amount of manual work and fix the inconveniences of the current process and also bring the automatization and usage of algorithms further.

After receiving the initial data, which usually includes the layout drawings of the boiler building, load drawing of the main support level and drawing of wall openings. The design of a boiler building starts with manually modeling the building to a BIM software, according to the received initial data. Tekla Structures is commonly used in steel structure design in Finland. In this phase only the main frame is rather roughly modeled, locations of platform beams and braces are going the be specified later in the design process. The important part is to get columns to the right positions, choose the locations for wall braces and get the loads to be divided as correctly as possible to the frame with the given information. The parts are modeled using the default profiles and they are changed later to the correct ones according to FEA. In addition to the building's geometry, loads are added manually to Tekla model. Later the equipment point loads can be added to the model by running a script, but the load data must be in Excel table for the script to work, which is usually not available at pre-design phase, so it cannot be used in this phase of the design. For columns connected to foundations an ID number is given in Tekla. This is to be able to connect the later calculated foundation loads to foundations presented in the foundation map.

Once the geometry and loads have been modeled to Tekla, an analysis model is created in Tekla. The parts and loads in Tekla form a physical model, which represents structure as it is going to be built. The analysis model is a structural model used for structural analysis and it includes all the information needed for FEM analysis: analysis parts, bars and members and their release conditions, analysis nodes and their support conditions, rigid links between these parts and nodes, and loads applied to the analysis parts. The analysis model is created from the structural model inside Tekla, both physical and analysis model are presented in Figure 5. (Trimble Solutions Corporation)

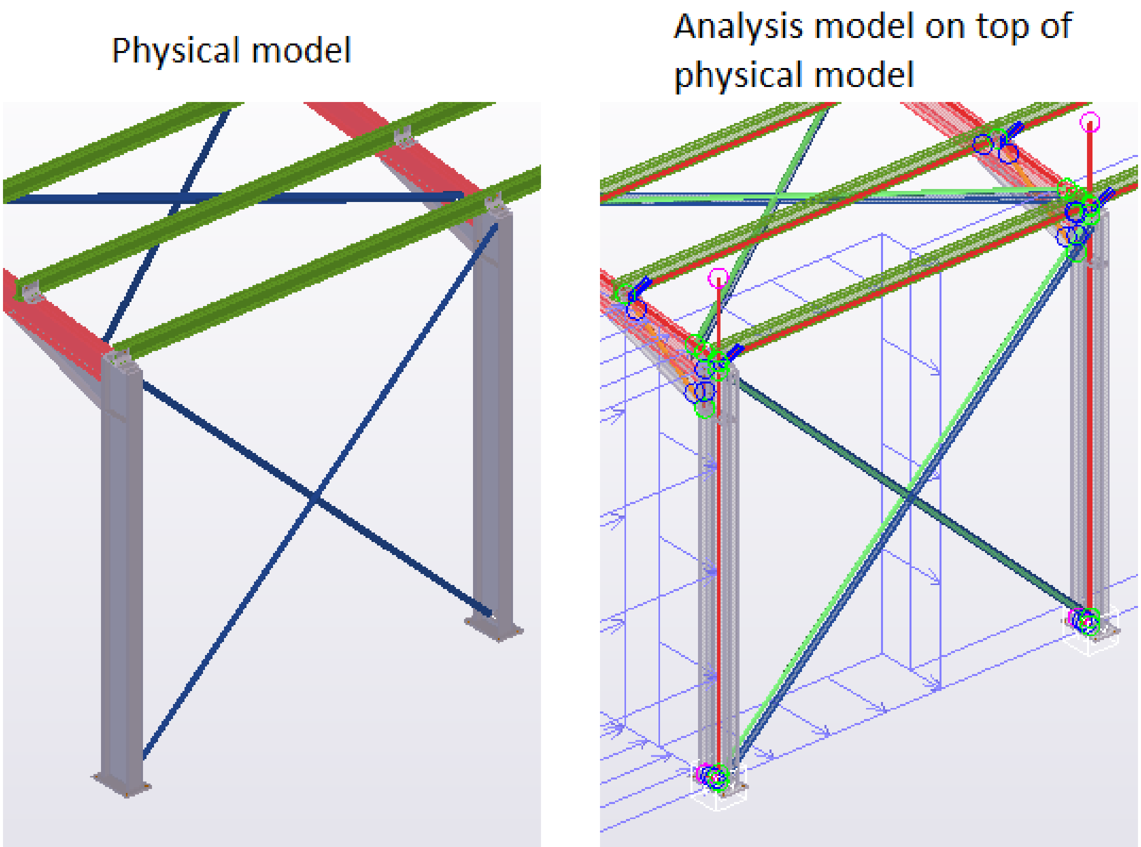

Figure 5. *Physical and Analysis models in Tekla (Trimble Solutions Corporation)*

After the analysis model has been created and the parts' settings adjusted as desired, the analysis model can be exported to a FEM software, typically Autodesk's Robot has been used in boiler buildings with steel frames, in which the structure's statics, deformations and support reactions are calculated. If the deformations and support reactions are within reasonable limits, the part dimensioning can be performed. For example, if the transitions are very large, the Tekla model is modified and re-exported to FEM software. Usually, in the pre-design phase, only columns and wall braces are dimensioned, as these have the most effect on the distribution of loads and structures behavior. The profiles of the beams and platform braces have a little relevance to the whole at this stage if they are within reasonable limits, so their dimensioning can be left to a later phase. When the desired parts are dimensioned, a stability analysis is carried out on the building and the deformations are checked to be within permissible limits.

When the user is satisfied in the FEmodel, the part profiles in Tekla are updated to match those in Robot. This is done using a script that has been made to compare the parts in the Robot with the Tekla parts and update the changed profiles to Tekla. A foundation load map can then be created in Tekla, in which the foundation IDs and dimension are shown. Since foundation IDs given in Tekla differ from Robot node numbers, ID — node mapping must be performed to direct the foundation loads to the correct foundations.

This is also done by running a script. Finally, the loads to the foundations are obtained from Robot, and modified to the final tabular format.

Since in the process the structural FEM model is exported from the Tekla model, special care must be taken in modeling. Modeling points and reference lines of parts and loads must connect, or else loose nodes will form in the FEM model and cause errors in the analysis. If the modeling was done negligently in the first place, it is quite laborious to fix these.

In this process, Tekla's analysis model and it’s exporting has formed as the main source of problems. When exporting the analysis model to Robot, data loss occurs and not all parameters given to the analysis parts transfer correctly, if at all, to the FEM model. Because of this, the FEM model needs to be corrected, to match the parameters given in Tekla. This is done by running individual scripts. Another problem with the Tekla’s analysis model has been the disappearance of the entire analysis model, but it seems that this issue has been corrected to newer versions of Tekla. It takes some time to re-create the analysis model, and especially for very large projects, it can take hours.

The algorithm-aided process shown in the chapter 4 completely avoids problems caused by the Tekla’s analysis model, as it is not used at all. Manual modelling can also be greatly reduced, since the basic geometry of the boiler building is generated using an algorithm, this also reduces the risk of inaccurate modeling as the algorithm models the geometry according to pre-defined rules and risk of miss clicks is avoided. Also defining some of the loads manually can be avoided by using the algorithm, as it can be programmed to generate these. With the developed algorithm platform loads, snow loads, and wind loads are generated automatically, especially calculating and modeling the wind loads manually can be quite time consuming. The Tekla model will still serve as the basis for the calculation model, so special care is still needed when manually modifying the model. In addition, the numbers of the foundation nodes in the FEM model produced by the algorithm are made to match the ID numbers of the foundations, thus avoiding unnecessary mapping and data editing.

3. ALGORITHM-AIDED DESIGN

Algorithm-aided design and parametric design have been subjects of many master's thesis studies lately. In these studies, the theory behind and the meaning of algorithm-aided design is usually presented, so in this thesis algorithm-aided design is only explained briefly. Algorithm means a series of tasks that are completed in a specified order. The purpose of an algorithm is to reach a certain goal by creating exact and unambiguous description of these task's content and order. Algorithm is originally a mathematical term but nowadays it's mainly understood as a term involved in programming. (Tanska and Österlund 2014)

Building Information Modeling can technically be considered as algorithm-aided design, because the BIM software's underlying algorithms include user-defined data (for example profile, material, orientation for beams objects) to objects that are manually modeled. Still this is not generally understood as algorithm-aided design as all the information is manually entered to the modeled objects. BIM is therefor considered as part of traditional design. (Boeykens 2012, 453-458)

In this thesis the term algorithm-aided design means a design process where the designer constructs a so-called recipe that generates new information from open parameters programmatically. This can also mean modifying existing data into new format or enrichening existing data with new information. The generation of new information programmatically, without the need of much manual labor, is the distinctive feature between algorithm-aided design and tradition design.

3.1 Literature study on algorithm-aided design

In his thesis Koski (2020) has done a literature survey of recent publications in the field of algorithm-aided design in general. When this thesis is being written this survey is still relevant and therefor similar study is not concluded. Thus, in this thesis, the literature survey is focused on finding out if algorithm-aided design has been successfully used in improving efficiency and speed of structural engineering.

Koski studied algorithm-aided design on precast balcony element systems and found that modeling with it was faster, more efficient and more accurate compared to traditional modeling done manually. He found algorithm-aided design process to be suitable for balcony element systems with certain limitations, main limitation being the variation on stacking balconies. (Koski 2020)

Erkkilä studied utilization of algorithm-aided design on precast concrete elements and found no unambiguous answer whether it was suitable or not. In his case study the algorithm-aided design process was not straight away applicable but with further development and solving the discovered issues it could be used to improve the efficiency of the design. In his algorithm an architects IFC model was used as input parameter and one of the issues was that the provided IFC model was not always free of modeling errors which were hard to detect and caused unexpected results in the algorithm. The detailing of the precast elements was also found to be to complex and developing an algorithm to handle the task was considered impossible. The link between modeling software (Tekla Structures) and the algorithm software (Grasshopper) also caused issues when the algorithm would run every time it was opened, on already detailed model this would cause the algorithm and the modeling software to get stuck and they had to be force closed. (Erkkilä 2017)

In his thesis Hirvikoski developed an algorithm-aided design process for creating stability models for tall concrete buildings in pre-design phase. He found algorithm-aided process to be efficient and suitable method for creating the stability models. The stability models were created to RFEM, using manually prepared 2D plan drawings presenting the structure as geometrical parameter and key-value pair data as non-geometrical parameters. In this study no BIM model is created. One important thing pointed out in his study was that the software chosen to be used alongside algorithm-aided design should have programming interface that provide good control over the software's functionality. (Hirvikoski 2019)

Mäenpää studied algorithm-aided structural engineering of steel framed warehouse structures and found out that modeling structures with repetitive geometry is fast and efficient but if the structure contains nonrepetitive elements, developing an algorithm for modeling these is quite slow and requires a lot of work. For analyzing the modeled structure Mäenpää has used Karamba3D, a plug-in of Grasshopper, that performs FEM calculations and can be used to dimension steel structures according to Eurocode. He found out that the calculation results for some of the steel members deviate from results given by RFEM and hand calculations. In his thesis Ketola (2019) has come to the same conclusion about Karamba3D. For this reason, Karamba3D was not used in this thesis. (Mäenpää 2018)

According to these studies it is possible to improve efficiency and speed of structural design using algorithm-aided approach. However, structures with inconstant geometry and exceptions were found to be difficult to handle algorithmically. The structures where algorithm-aided design was tested in these publications differentiate from boiler buildings quite drastically so a clear answer for the research aim of this study cannot be drawn from these.

In these studies, the whole process after inserting the parameters is tried to be finished algorithmically with no manual work in between. For simpler structures and smaller entities this is a valid and efficient way of making algorithm-aided design. However, boiler buildings are usually quite complex and don’t always follow a specific pattern and thus creating an algorithm that could take into consideration all the possible variations of the structure is difficult. For this reason, the approach to algorithm-aided design is a bit different in this thesis and manual actions are done in between tasks performed by algorithm.

3.2 Interview study on the user experience of algorithm-aided design

For this thesis a short survey was conveyed to find out about algorithm-aided design in the field of structural engineering thus far, the type of projects it has been used on and its benefits. For this survey designers of Sweco Structures Ltd who have been involved in algorithm-aided design were interviewed. Thus, the survey is limited to employees of Sweco Structures Ltd. The questions asked in the survey were:

1. In what kind of projects have algorithm-aided design been used?
2. What was done with the algorithms in these projects?
3. Where do you see most benefits in using algorithm-aided design in the future?

The participants also had the opportunity to make free-form comments. In the following subchapter the results of this survey are presented.

3.2.1 Results of the survey

While searching for the interviewees it was found out that as of now algorithm-aided design is adopted by small group of designers, but the interest is on the rise and more and more people are showing interest and are starting to learn how to boost their efficiency with algorithms.

Algorithm-aided design and visual programming was first commonly used among bridge designers where it was used to create the BIM models and analysis models of the bridges. Bridges with challenging cross section geometry and / or bridges that follow a road center line that is a nonlinear curve are difficult and laborious to design manually but can be done much more easily using algorithm-aided process. Handling complex shapes and decorative structures was one point that rose on most of the interviews, these can be difficult and time consuming to design manually, whereas they can be rather simple tasks for an algorithm, and thus good targets for AAD. In timber structures where manufacturing automatization is rather far it was seen as a huge potential for AAD to be able to produce design for complex shapes that would be manufactured using CNC machinery.

One type of projects involving complex geometries, done using AAD are the class dome igloo structures in Lapland, where the steel structures were designed using algorithm to match the structure to different dome sizes. AAD has also been used for creating diagrams for timber roof trusses with complex roof shapes.

Usually when working with complex geometries the geometry must be rationalized and simplified so that the structures following this geometry can be manufactured, while still following the original shape as closely as possible. One such target was the new canopy for Olympic stadium in Helsinki, Figure 6. The canopy is a steel structure of complex shape, where each of the trusses are unique and had to follow the planes of inconstant shape determined by the architect. Algorithm-aided design was used in simplifying the geometry of the trusses' curved chords into straight parts and arches with constant radius, thus making the manufacturing possible. AAD was also used in detailing the truss connections. The canopy was also the winner of Steel Structure of the Year award in 2019. (Teräsrakenneyhdistys 2019)

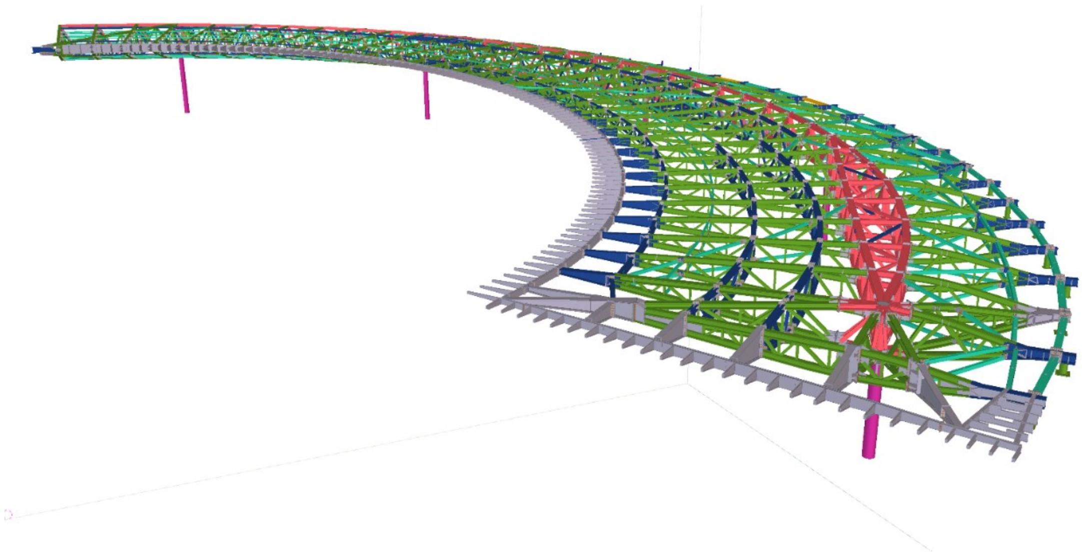

Figure 6. *Screenshot of Olympic stadium canopy from Tekla Structures.*

Another great feature of AAD is the ability to adapt to changes. If the initial data changes, the parameters of an algorithm are updated and the product changes accordingly. This is especially effective when working with complex shapes, for example when creating roof trusses for a complex roof shape. If the trusses are designed manually and the roof shape changes during the design, the design work must be started over. Whilst when using AAD, the input parameter, an IFC model from an architect for example, can be updated and the trusses change accordingly, and no design work is wasted. This also makes interlaced design process possible where different designers need initial data from other designers, such as structural engineer needs initial data from an architect. With AAD the designers can work on their algorithms that will produce the final product even without final initial data, as long as the format on which the initial data will be delivered is known.

A lot of the projects where AAD is used are of structures that follow a recurring pattern and thus once the algorithm is developed it can be used over and over multiple times. The structures are of varying scale and difficulty, such as electrical masts, conveyor bridges, truss structures, service platforms for industrial buildings and insulated measurement rooms. With these kinds of structures, depending on the complexity of the structure, it is usually reasonable to make the algorithm quite detailed and perhaps even able to produce finalized products. The more detailed product the algorithm is made to produce the more time it takes to create the algorithm and usually it is quite fast to develop an algorithm that produces simple raw geometry. For this reason, AAD is also used quite often to produce the initial model of the structure which is then manually detailed. Because of the ability to produce simple geometry fast and the ability to handle changing initial data AAD is extremely useful in the pre-design phase of most structures.

Yet another aspect of AAD in structural designing is the possibility to build an integrated design system, where structure model is created and maintained in just one software, usually a BIM software. The analysis model is created from the BIM model using an algorithm. During the creation of the analysis model it is also possible to generate loads and other information needed for the analysis. This also enables the transfer of the analysis data back to BIM model and the automated connection design and modeling using the information from both BIM model and analysis model. When applied to pre-design phase, where the whole structure is algorithmically produced this also enables efficient comparison of different structural solutions based on analyzed data.

AAD has also been used to automatize simple repetitive tasks such as detailing concrete elements and steel assemblies, transferring data between design software and transforming data from 2D drawings and tables to BIM data.

One possibility made available by AAD is the optimization of structures by using optimization algorithms. This is not yet widely used in practice in structural design but could provide cost savings and reduced environmental effects on construction.

3.2.2 Survey summary

As the result of the survey the main benefits of algorithm-aided design were identified as: the possibility to handle complex shapes and geometries, the ability to handle changes in the initial data, the automation of simple repetitive tasks, efficiently designing structures that follow recurring pattern, ability to create raw geometry fast and creating an integrated design process where the product model and analysis model are build and maintained at the same time. Most of the projects where AAD was used reflect these main points.

Algorithm-aided design is still used by a small minority of structural designers and usually new targets for AAD are discovered when these people start new projects where they identify needs and possibilities for AAD.

4. UTILIZING ALGORITHMS IN PRE-DESIGN OF BOILER BUILDINGS

Boeykens compares BIM (Building Information Modeling) with Parametric Modeling and describes Parametric Modeling as a system where geometric information (points, curves, surfaces, etc.) are being generated from input data using mathematical formulas and functions. Whereas in a BIM system, the model is constructed by manually modeling objects that use underlying algorithms to limit the amount of direct modeling. The BIM model contains a lot more information in addition to pure geometry. (Boeykens 2012, 453-458)

In this thesis, the used algorithms combine both Parametric Modeling and BIM. While also generating a pure geometry to Rhinoceros 3D, shown in Figure 7, the boiler building is also modeled as a BIM model to Tekla Structures, shown in Figure 8. The algorithm generates points according to given parameters, presented in subchapter 4.1 and connects lines to these points. From these lines the Tekla objects are created, thus making sure the reference lines and the modeling points of the parts are connected. All the necessary information for pre-design phase are inserted to the modeled objects in the generation. The creation of BIM model was done using Grasshopper-Tekla Live Link, a plug-in for Grasshopper that is available from Trimble Solutions Corporation. Some of Tekla's utilities are not included in the Live Link, for example adding loads to Tekla model is not possible using the Live Link. For such tasks Grasshopper's C# scripting component was used, where the Tekla-model was modified using Tekla's API. The issues with Tekla – Grasshopper link presented by Erkkilä (see chapter 3.1), were solved by adding a Boolean switch that enables and disables the Tekla components of the algorithm, by default it is set to false and thus the Tekla components of the algorithm don't run when the algorithm is opened.

Information required for verifying the strength and stability of the constructed structure are also inserted to the model (for example, each of the columns contain information about their buckling lengths, support conditions and end releases). The algorithmically produced BIM model also contains information about the load cases used in the project, the information to which parts uniform loads such as wind, snow and platform loads are considered, and the equipment point loads.

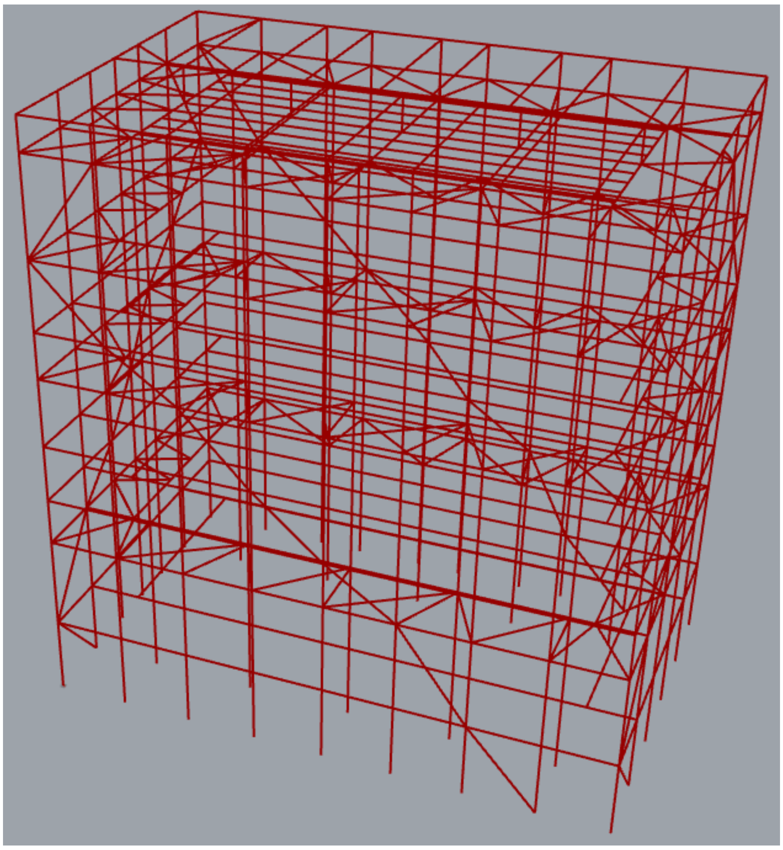

Figure 7. *Boiler geometry lines created with the algorithm in Rhinoceros 3D.*

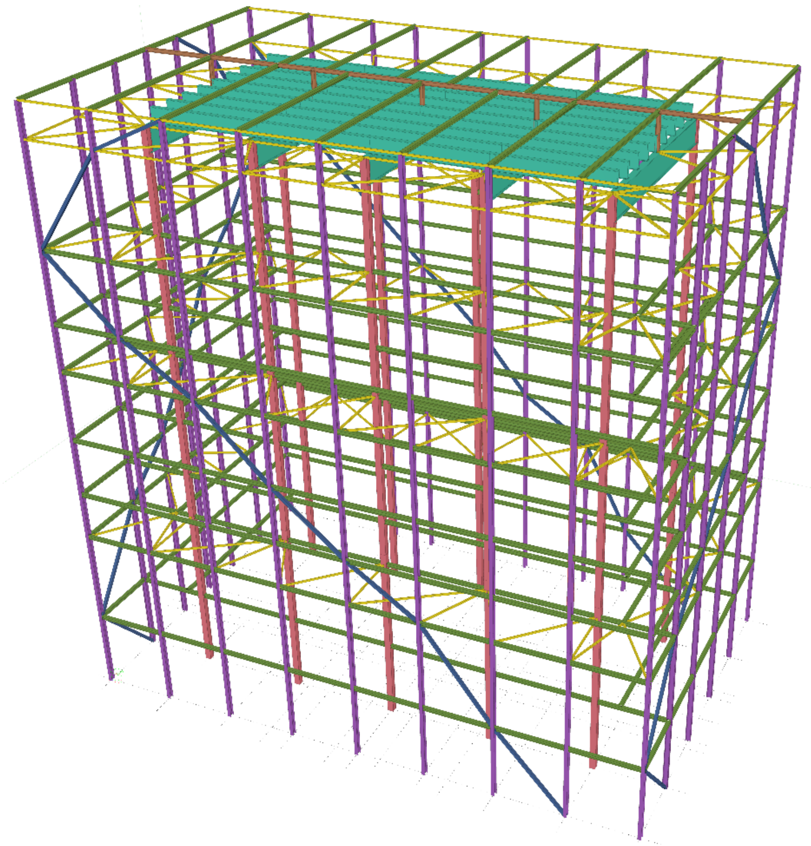

Figure 8. *Boiler geometry created with the algorithm in Tekla Structures.*

The algorithmic process is divided into two parts and thus two different algorithms are developed for this thesis. The first algorithm constructs a BIM model representing the structure to be designed and the second algorithm generates FEM model based on the data transferred from the BIM model and open parameters defined in an Excel sheet. The design process is show in Figure 9 and further explained below.

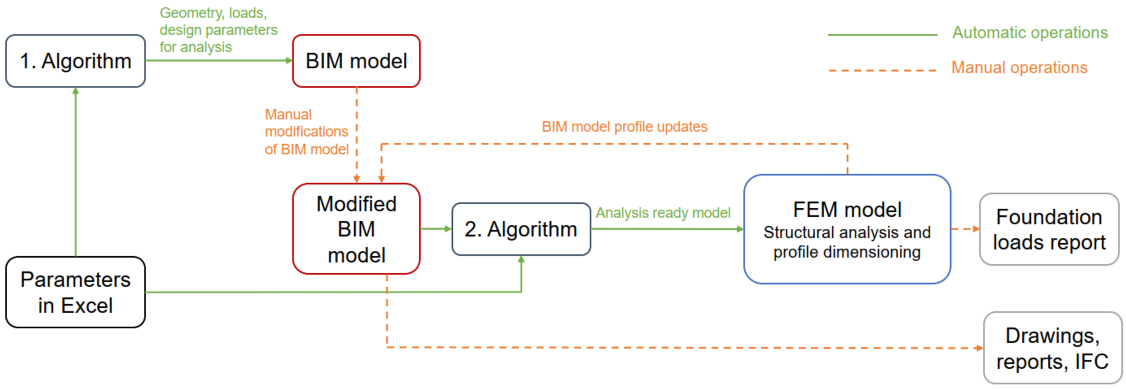

Figure 9. *The design process chart using algorithm-aided design developed in this thesis*

In the first algorithm, the BIM model is created to Tekla. After it is created, the model acts as a data bank containing information required for further calculations and analysis. The BIM model can then be manually modified and enhanced. For example, if there are other structures connected to the main boiler building, they can be added using traditional modeling methods. The geometry creation was intentionally limited to the main building and left to produce quite raw geometry which can then be modified manually, or by using different algorithms made for it, to match the requirements of the project in case. One such algorithm to further enhance the Tekla model is an algorithm that reads drawings that are in DWG format and contain information about equipment loads. The algorithm adds these point loads to Tekla, the loads are placed in correct positions and added to their respective load cases. Intensity and direction is also according to the drawing. The geometry creation was made like this because in practice the boiler buildings do not follow a standardized geometry and layout and defining an algorithm that could handle all the exceptions would be really difficult and time consuming, perhaps even impossible. Also, the additional structures tend to vary too much to be effectively added to the algorithm. As it is, the geometry algorithm can produce a finalized geometry for the pre-design phase if the layout of the boiler building is symmetrical and follows a certain pattern.

In the second part, after creating and possibly modifying the BIM model, structures and loads are read to a second algorithm. The algorithm reads the lines of the Tekla parts and the information added to them and creates FEM members of them that include all the design parameters needed for FEA and profile calculations according to Eurocode.

The design parameters of parts have default values according to part's name in Tekla, but each of these can be overwritten to enable handing exceptions. The overwriting is done by modifying the part in Tekla. Algorithm also divides members into different sets that are operated on inside the algorithm. The algorithm generates platform loads to the beams that in the BIM model are marked as platform-supporting beams, increased platform loads to platform beams marked to be located in hatchways, snow loads to beams marked as roof beams and wind loads to columns marked as wall columns. For the area loads the algorithm measures the distances to next load bearing members when defining the load width of the member and creates line loads to the bearing members. For wind load bearing columns, it also detects their position and to which wind zone the column belongs in each wind direction, as well as the elevation of the column so that a correct velocity pressure can be used to generate the wind line load. Also, all these load widths and positions can be overwritten in Tekla to allow handling of exceptions. The algorithm calculates wind loads according to Eurocode (SFS-EN 1991-1-4 2011) and user defined parameters, such as terrain category. The algorithm also creates imperfection loads as horizontal point loads from the vertical loads using a user defined coefficient. For this the line and trapezoidal vertical loads are first created as equivalent nodal forces to the ends of their bearing members and then modified to horizontal loads using the coefficient.

The algorithm converts the above-mentioned data into a specific format that can be exported to a FEM software for structural analysis. For this conversion a special Grasshopper plug-in developed in Sweco was used. The development of this link between Grasshopper and FEM software is not part of this thesis. During this thesis the Grasshopper — FEM link development is still underway and not all the features are yet available. For example, defining earthquake spectrums is not yet implemented and therefor earthquake analysis cannot be performed using the algorithm.

The FEM software used for the algorithm was Autodesk Robot Structural Analysis Professional, but with just minor modification the algorithm can be modified to export the model into a different software. In Figure 10, the boiler building in Robot is shown with the generated wind loads, when wind blows to one side of the building. After the exportation the FEM model is calculated and structural analysis is performed to parts necessary for the pre-design phase, which usually means columns and wall braces as those have the most impact to the building's stiffness and to the distribution of forces. The structural analysis and profile dimensioning are done manually using Robot's user interface or scripts, but no modification of the actual model is required, other than changing the profiles according to calculations. The information about the calculated profiles of the parts can then be imported back to BIM model and the existing parts modified.

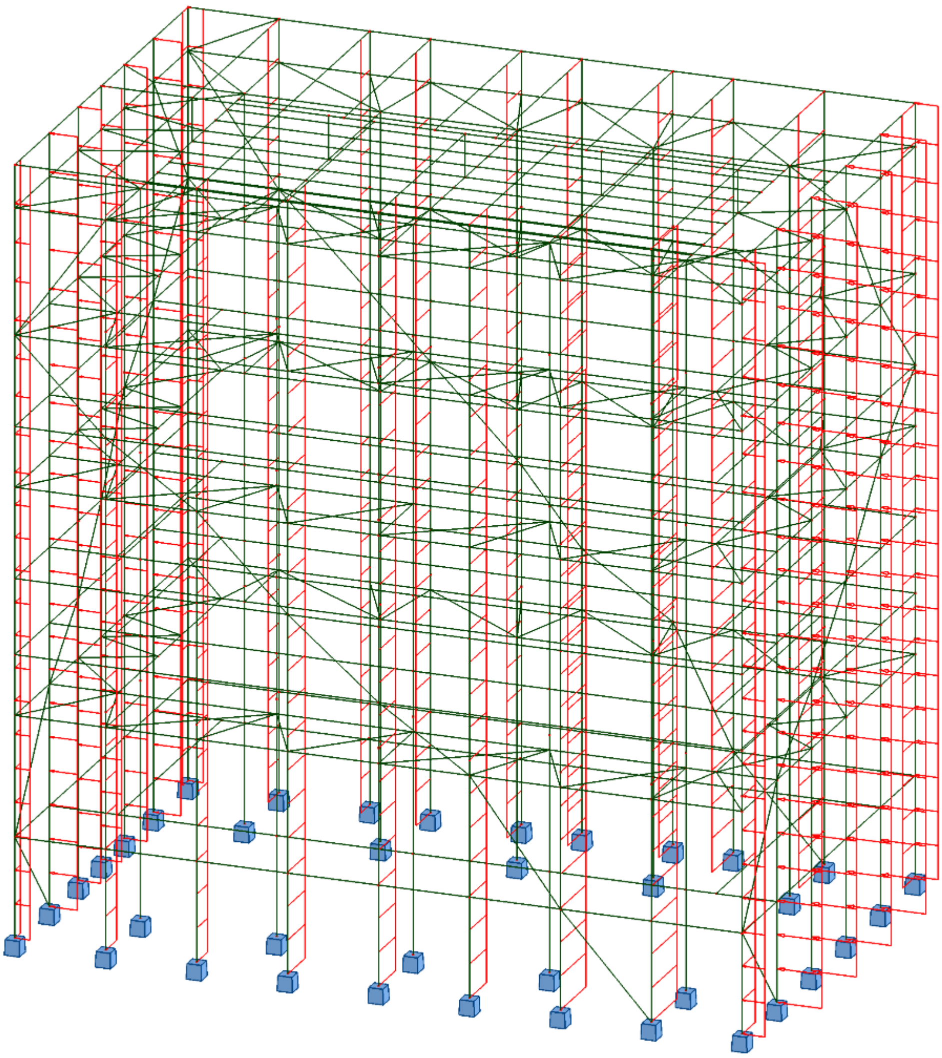

Figure 10. *Generated boiler building in Autodesk Robot Structural Analysis Professional, showing the wind loads when wind blows to the right gable-end.*

The documents required for the pre-design phase can then be created from the models. Foundation map drawings can be created from the BIM model and foundation loads are obtained from the FEM model.

After the pre-design phase the BIM model can be further enhanced to support the needs of more detailed design and it can be used through the whole design process up to creating workshop and erection drawings. Also, the second algorithm can be used to export the BIM model to FEM model at any phase of design for structural analysis and calculations.

4.1 Parameters of the algorithms

The input parameters for the algorithms are read from an Excel tables. For the first algorithm, parameters include all the dimensions needed to create the geometry, these geometry parameters are visualized in Figure 11 and Figure 12, as well as the load point coordinates, and load intensities of equipment loads and other point loads. A common parameter for both algorithms is the information about load cases, which include case number and name.

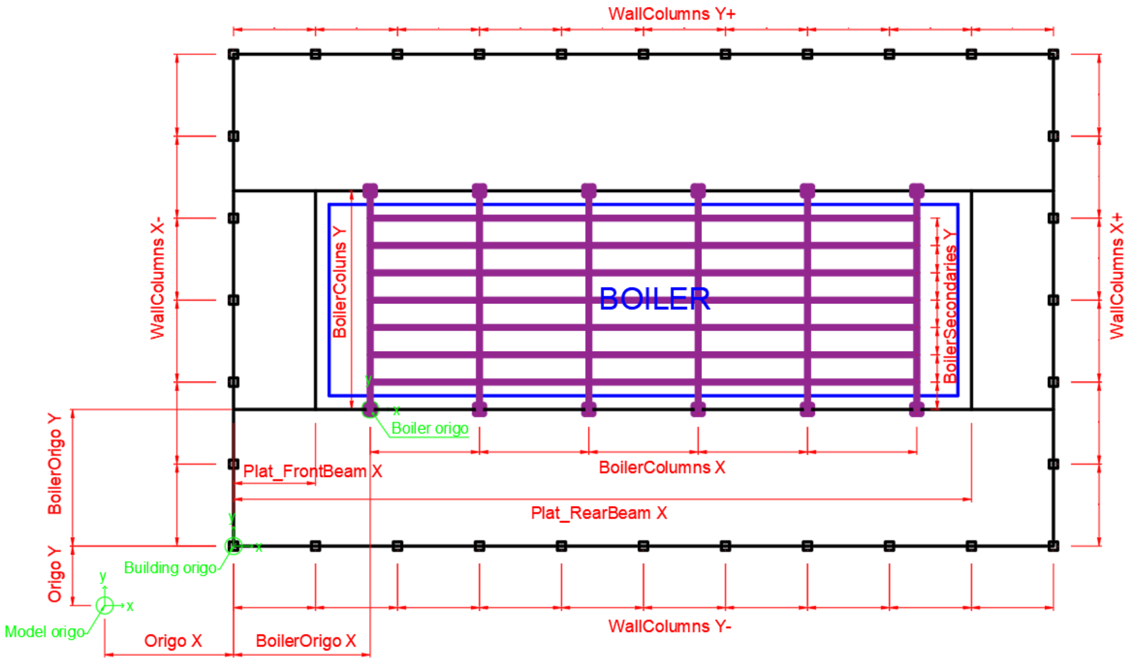

Figure 11. *Geometrical parameters for the first algorithm, plan drawing*

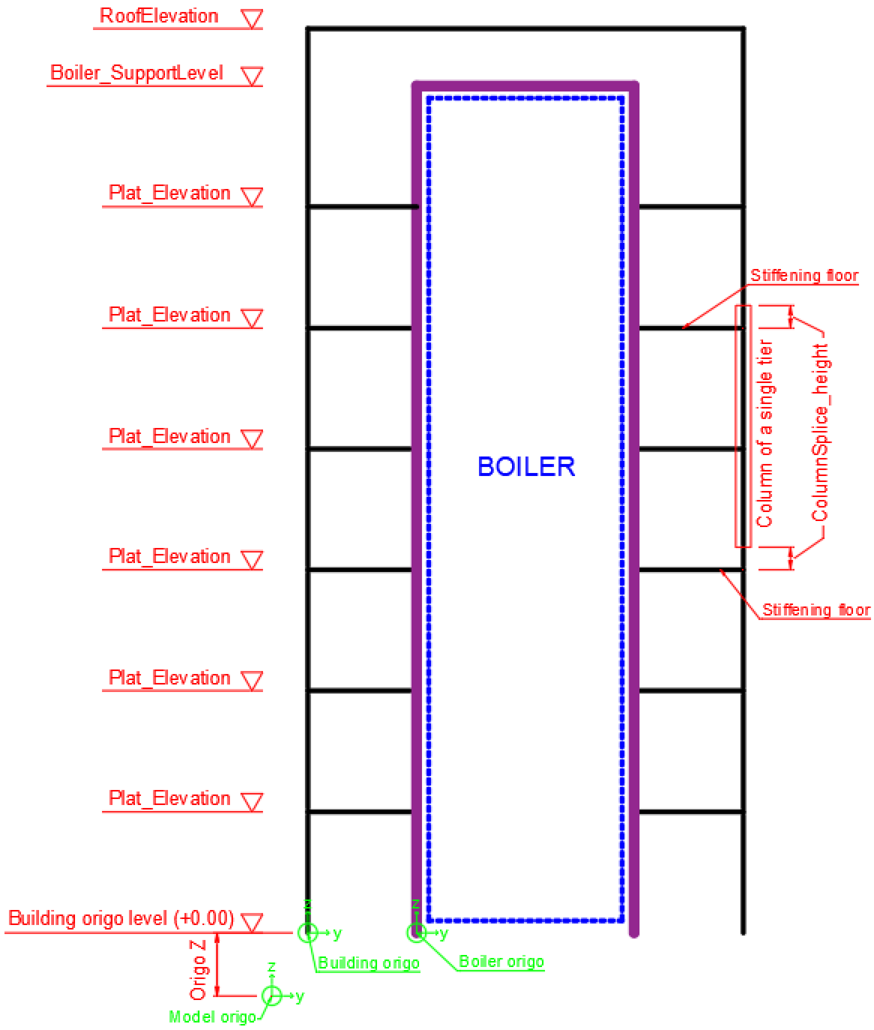

Figure 12. *Geometrical parameters for the first algorithm, section drawing*

For creating the wall braces, a user-interface was created where the walls were shown as sets of rectangles. The rectangles are created by wall columns and beams, and for each rectangle the user could define bracing from a predefined list of options. The options were: no brace (the default option), from bottom-left to top-right, from top-left to bottom right, X type bracing or inverted V type bracing. Each of the options and the result of these inputs are shown in the Figure 13. The platform bracings are automatically generated to stiffening platforms and boiler level. This is done so even though it is realized that the platform bracing won't be accurately placed according to final design. The location of individual brace in the platform has minor effects to the structure as whole and the stiffness of the stiffening platform is correct enough with this approach. The final positioning of the platform braces is left to be done after the pre-design phase when the final design of the structure is performed.

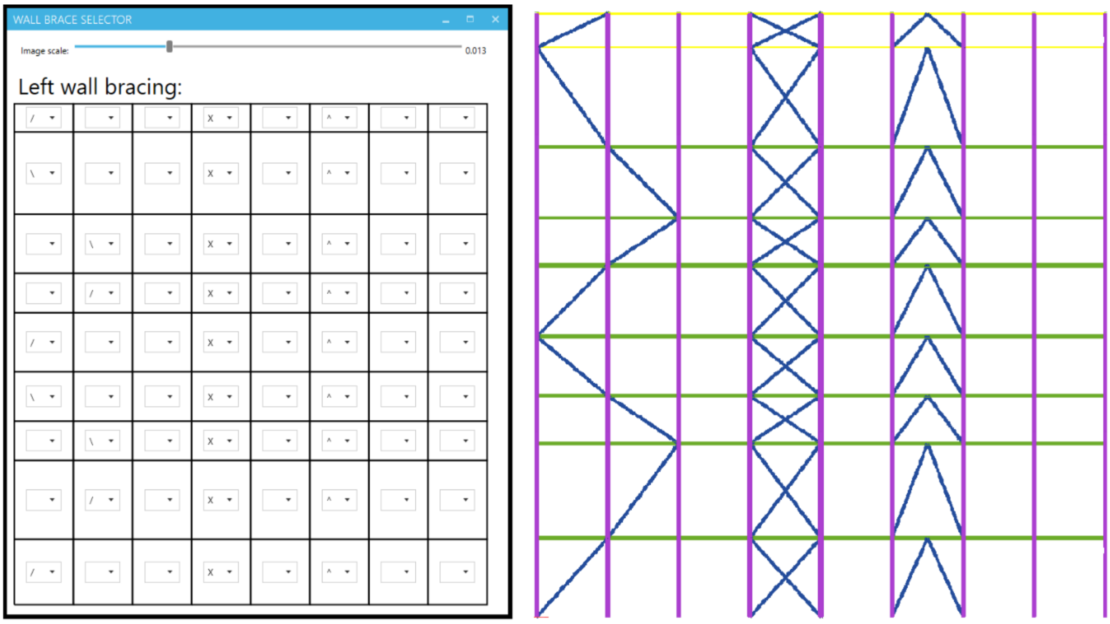

Figure 13. *User-interface for creating wall braces and the output of the selection from Tekla Structures.*

For the second algorithm the primary parameter is the Tekla model which contains most of the needed information, in addition to the this, parameters include the intensities of uniform loads (platform dead and live loads, hatchway loads, roof dead and live loads, snow loads), terrain category for wind load calculations, load factor for generating imperfection loads, the numbers of the load cases that imperfection loads are generated from and load combinations. The load combinations can be read from an Excel table or written in a text box in Grasshopper using a specified syntax.

4.2 Outputs of the algorithms

When the algorithm-aided pre-design process is finished the following outputs are created:

- The pre-design phase BIM model in Tekla, from which the necessary drawings, preliminary bill of quantities reports and other information such as IFC-models can be produced. These can then be delivered to the customer as the result of pre-design. This model can later be used for the final detailed design of the structure by enhancing it further. Throughout the whole design process the second algorithm can be used to generate FEM models for analysis and separately maintaining an analysis model is not needed, as the BIM model and the algorithm contain all the necessary definitions for structural analysis.
- The pre-design phase FEM model in Robot, from which the most important results of the pre-design phase, the foundation loads, can be reported. This FEM

model is supposed to work as single time usage and new model is exported every time the structure is modified, and further analysis needed.

With these outputs the whole pre-design phase can be finished and premise for further design of the boiler building is established.

4.3 Approach change of the algorithms during the work

The initial idea was to produce an algorithm that would create the geometry, loads and everything needed for FE analysis straight to Robot. With this method the foundation loads could be obtained fast without much manual labor. The calculated data would then be exported to Tekla Structures to create a BIM model for creating foundation map drawings for pre-design phase and for further use.

While this study was ongoing, the still unfinished algorithm was tested in two projects, both of which were pre-design assignments. The first one was typical CFB boiler building and the other was a gas boiler of which structural geometry was quite different from a typical boiler building. The algorithm worked quite well for the first project's main building but there were also stair towers, external duct stands and a support for fuel silos attached to the main building. Some of these structures also contributing to the structural behavior of the main building so the result from the algorithm was unsatisfactory. Also, in the main building there were some places that the thus far produced algorithm couldn't handle well enough, one such place was the geometry of the main support levels beams supporting the boiler. The boiler beam geometry was quite irregular and would have been difficult to include in the algorithm. In the second project the geometry was too different from a typical boiler building that the algorithm was of no use.

After these notices, several old projects were reviewed and experienced boiler building designers were interviewed and it was found out that the boiler building structures tend to vary even more than originally expected. The column layout is far from standard and some of the columns might be cut from the middle to allow placing of ducts or other equipment necessary for the steam production process. In addition to this, inside the building there are varying number of different small equipment that need to be supported from the frame. These can be handled in the pre-design phase by dividing the loads to the nearest structural members, but it would be useful to have beams under these loads already in this phase, which also allows more accurate distribution of the equipment loads.

Based on the findings reported above the algorithm was divided in two separate parts. First part creates the geometry and loading data to a Tekla model and the other one reads information from the Tekla model and exports it to Robot. This arrangement allows the manual modification of the Tekla model between the two algorithm-aided operations. This approach would be much more efficient in practice. This also allows the designer to create as detailed model straight in the pre-design phase as wished. This division also allowed the second part of the algorithm to be used in the second project, where the entire BIM model was done manually. The second algorithm can also be used in any kind of structure that is modeled with Tekla, thus providing an integrated design system where all the modeling and modifying of structures and loads can be done in a BIM software and the need to maintain separate model for analysis purposes is not needed.

Yet another point supporting this approach to the workflow was that in a typical boiler building project, the geometry was usually mostly decided before the pre-design assignment thus leaving only little room for modification. Column locations, platform levels, and even sometimes the locations of the stiffening floors were given in layout drawings leaving only the wall bracings as a major contributor to buildings structural behavior and force distribution open for variation. The initial approach would be more efficient if used earlier in the process when the geometry is more open for modification and when entirely different structural frames could be compared. This would mean that structural designer should be involved earlier in the design process of the whole boiler building.

After these experiences the first algorithm was further enhanced so that it includes creation of all the necessary information for FE analysis to the Tekla model, minimizing the manual labor needed for pre-design. The algorithms were finished and made to work as told before in chapter 4. While writing this thesis the produced algorithms have already been used in a couple of different projects and the feedback has been highly positive. Especially the second algorithm that can be used on any kind of steel structure modeled with Tekla has been found extremely useful. After the modifications the algorithms were also successfully used in the projects where the issues with the initial approach were found. In the first project, both algorithms were used and in the second project the second algorithm was used to generate the FEM models from the manually prepared BIM model.

For future a further development of the algorithm-aided design process could be done using the initial approach where the customer could have access to the algorithm through an online interface. The process of this approach is presented in Figure 14. The customer, the party designing the actual boiler, could then insert parameters and vary the structure as they wished, and the algorithm would construct the geometry, perform analysis of the structure and dimension profiles. The structure analysis and profile dimensioning can be done interactively by using Karamba3D and Shapediver, Karamba3D is a FEM plug-in for Grasshopper and Shapediver is a platform that offers cloud applications for Rhinoceros and Grasshopper. After that it would provide the user with a BIM model and preliminary bill of quantities. The structural weights at this point would be quite rough estimates as it might be impossible to include all the boundary conditions of the structure to the algorithm, but correlation between different structural solutions could be compared easily. After the customer would be satisfied with the frame, pre-design order could be sent to a structural designer that checks, and modifies if need be, the structure and performs the final analysis and calculates the foundation loads. Reaching this state needs quite a lot of further development for both the algorithm and the customer interface. This approach would be used in really early stage of the design and for it to be possible the handling of loads, especially the equipment loads, and the structure itself should be simplified radically. Because of this simplification Karamba3D should provide accurate enough results even thought it is reported that the results differ a bit from hand calculations and calculations performed by other FEM software.

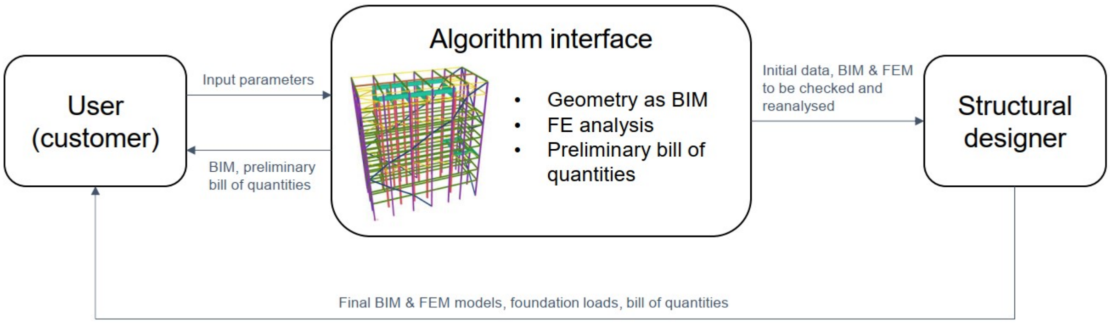

Figure 14. *Pre-design process using online interface for the algorithm.*

5. CASE STUDY: RE-PRE-DESIGN OF A BOILER BUILDING

The algorithm-aided pre-design process was tested in a case study, where a new pre-design was made to a boiler building previously designed at Sweco. The aim of the study was to find out if it would be possible to produce accurate enough foundation loads for pre-design phase using algorithms produced for this thesis. And if the design process could be made more efficient so that designers could have more time for the actual design work instead of doing a lot of manual labor, which could be made by a computer. To perform this case study the initial data from the pre-design phase of the boiler building was searched and using this information a BIM model was created to Tekla, FEM model was created to Robot where the foundation loads were calculated and foundation ID-map was created in Tekla. The foundation loads calculated were compared to the foundation loads calculated in the original pre-design. Also, the time spent on both pre-designs were compared together, for the parts where information from the original pre-design was available. The software used for this case study were Tekla Structures 2018i, Autodesk Robot Structural Analysis Professional 2019 and Rhinoceros 6 with its Grasshopper plug-in.

5.1 Case introduction

For the subject of this case study a CFB boiler building built to Finland was chosen. The pre-design was originally done in 2014. The dimensions (width x length x height) of the boiler building were 16 m x 34 m x 40 m to which a support structure for four silos was attached, dimensions of the silo support structure were 16 m x 9 m x 6 m. Attached to the boiler building's frame were also two stair towers which were left out of this case study. The support structure of the silos is located next to the front wall of the boiler, above an electrical building made of reinforced concrete. The concrete structure is not included to the scope of pre-design of the steel frame so that also left out of the case study. The beams supporting the silos are connected to the boiler building's front wall from one end. From the other end the silo beams are supported by columns from the electrical building's roof. The silo support structure columns have pinned connections to the concrete structure and foundation loads for these columns are also provided. The rest of boiler building's columns have rigid connection to the foundations. All beams have hinged connections to each other or to the columns and all wall and platform bracings are considered as truss elements, so they only transfer axial forces.

As the initial data for pre-designing, the customer provides the designer with Layout drawings that usually contain plan drawings from each of the service platforms and roof, and a section drawing of the entire building and its main equipment. In the Layout drawings column locations, elevations for service platforms and roof, and locations for hatchways are presented. Also, the loads for the equipment, pipes and hatchways are presented. At this phase the locations and scale of the loads are preliminary and there are usually some changes to these while the project goes forward to final design. In addition to the Layout drawings, a line load drawing of the main support level is provided by the customer. In this drawing the main equipment locations, loads and elevations are shown. These also include the 3rd pass, which in this case is located near the back wall of the boiler building and supported from the elevation +15,290. +0,000 being the start elevation of columns and +35,500 being the elevation of main support level. This is the initial data accessible in this case study and in addition to it, it is most probable that there has been discussion about the initial data between the designer and the customer, but unfortunately it is impossible to access this information.

5.2 Design process using algorithm-aided workflow

The design process started with the search of initial data. Once the information that was available at the pre-design phase was found from the project folder the actual design could start. First the dimensions affecting the boiler building's geometry were found out from the Layout drawings and these were inserted as parameters to the geometry algorithm. In about an hour a BIM model representing the boiler building's structural frame is made to Tekla Structures, the output from the algorithm, without any manual modifications, is show in Figure 15. In addition to geometry the Tekla-model already contains a lot of information needed for the structural analysis, following information is already included when creating the model with the algorithm:

- Columns contain the information about how they are supported from the foundations, as default the support is considered as rigid. Columns connected to the foundations also have a foundation ID numbers. This ID number links the foundations to supported nodes in FEM model, when the FEM model is created the supported node numbers match the ID numbers in Tekla. These ID numbers are also presented in the foundation map drawing produced later in the process.
- Columns also contain the information about their buckling lengths. Boiler columns are laterally supported from the stiffening platform levels as are non-corner wall columns in their strong-axis direction. Wall columns in their weak-axis direction and corner columns in both directions are laterally supported from each of the

platform levels. This is because all the platform beams located between the wall columns are connected to the buildings bracing system. The buckling length of a column is the maximum of the following two: distance between supporting levels, or if the column is connected to the foundation the distance from foundation to the first supporting level multiplied by 0,8 factor. 0,8 is chosen because the foundation connections are not ideally rigid, and some elasticity is to be expected.

- The wall columns have information on which walls they are located. This information is used when generating wind loads while exporting the FEM model.
- All parts are named according to certain rules. These rules dictate how the bar releases and element types are handled when exporting the FEM model from Tekla. Columns are beam elements, with no end releases, which means all column splices are considered as rigid. Beams are simply supported beam elements where torsional rotation is fixed in one end and free in the other end. Wall and platform braces are considered as truss elements.
- Platform beams also contain information that they are supporting service platform and all the platform loads are automatically generated when exporting the FEM model. Same is applied to roof beams bearing snow loads.

All the above-mentioned design parameters can be manually overwritten to Tekla for each member to ensure that special cases can be handled.

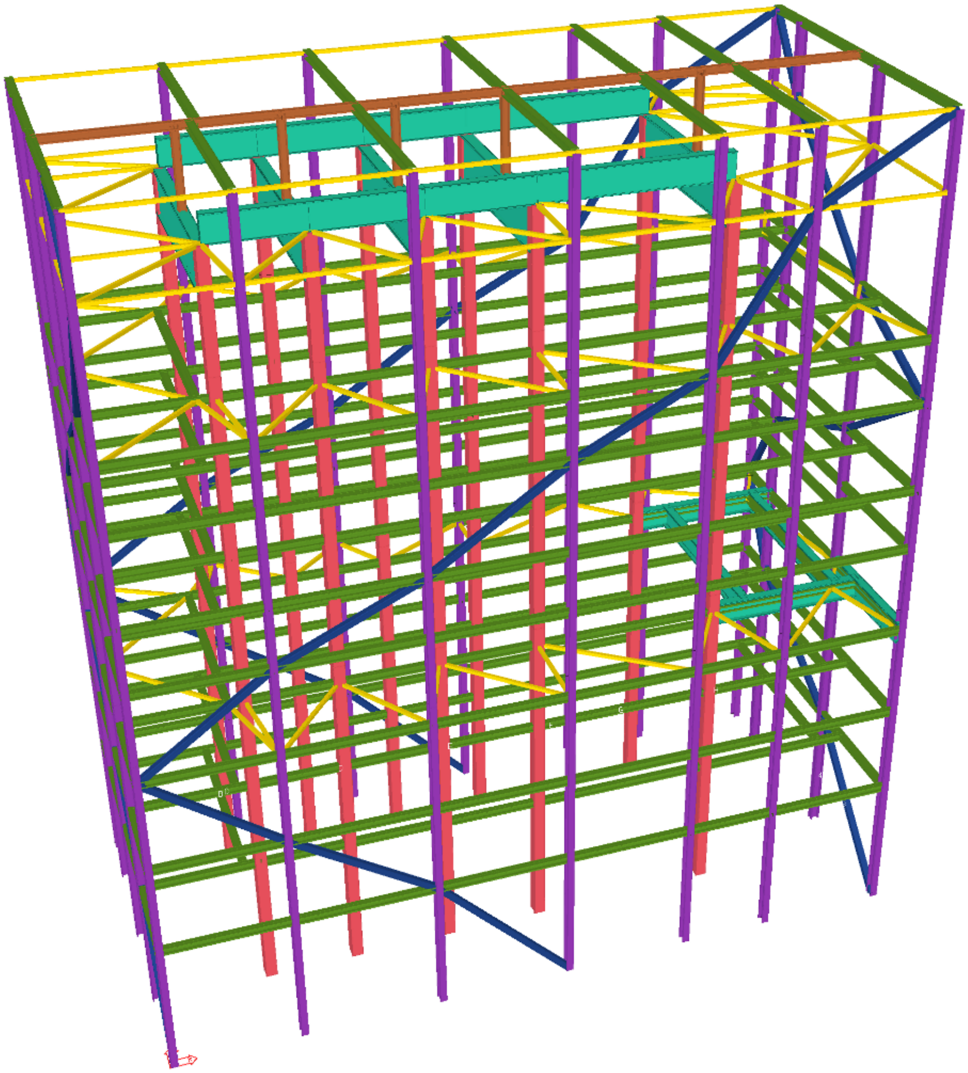

Figure 15. *Boiler building's frame in Tekla as it comes from the algorithm.*

Because the subject of design was a CFB boiler with one Cyclone, the main support level and thus the boiler column locations are eccentric. Handling this eccentricity in geometry was not included in the algorithm, so at this point manual modification of the Tekla model is needed. Two of the boiler columns are moved inwards and the boiler beams are modified according to the Line load drawings. To the front wall of the boiler, a support structure for the silos and a so-called compensation structure that represents the actual silos are modeled. The upmost part of the compensation structure is modeled to the silos' center of gravity and all the loads acting to silos are later modeled to this point. This way the moments caused by the wind loads are taken into consideration. The compensation structure is exported to FEM model with its own material that has all the properties of structural steel expect that its weight is 0. The compensation structures are filtered out when creating the final product model. When manually modeling new parts the design parameters needed for FE analysis have also to be added. The modified frame, with compensation structures are shown in Figure 16.

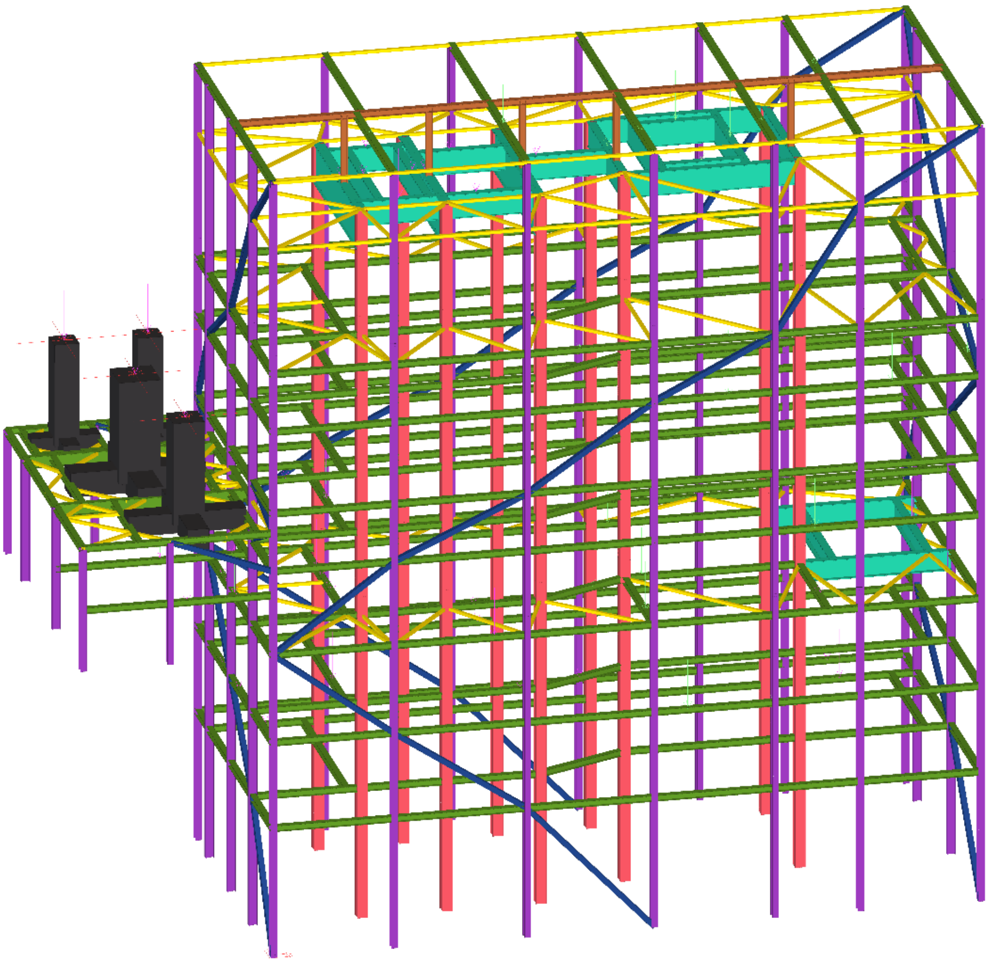

Figure 16. *Boiler building's frame after manual modifications.*

Once the frame was modeled to match the Layout drawings, the equipment point loads presented in these drawings were added to the Tekla-model. This could be done manually, but here the layout drawings were edited to specific format using Autodesk Autocad, so that the loads could be identified using a different algorithm. The algorithm finds the location, intensity, direction and load case of the loads from the drawing and imports them to Tekla. This algorithm is not part of this thesis, but it is developed alongside of this thesis to support algorithm-aided design process. Modifying the layout drawings containing the equipment loads was purely manual work, but hopefully the initial data will in the future be in a format that can be read with the algorithm. The load cases need to be specified in Tekla before adding loads to the model, the geometry algorithm adds these according to information specified in an Excel file. Typical load cases for boiler building pre-design are included in the Excel, but these can be manually modified to match the needs of the project. The Excel also contains load combinations, which are used as parameter for the FEM model generating algorithm later.

After all the necessary parts and information were modeled to Tekla the second algorithm produced for this thesis was used. This algorithm creates a calculation ready FEM model to Autodesk Robot Structural Analysis and generates wind loads to columns, snow loads to roof and platform loads to platform bearing beams. The algorithm uses data read from Tekla and user defined values for natural load (snow, wind) calculation, and for platform load intensities as its parameters. After the parameters are defined the algorithm's export function is executed and a calculation ready Robot model is produced, this model is illustrated in Figure 17. After the model is exported it is checked for possible issues, if something is found, the issues are corrected to Tekla-model. The algorithm's Tekla parameter is refreshed, and a new Robot model is exported. If everything is correctly modeled to Tekla, no manual modifications to Robot model is needed and calculating and member analysis can start. In this case study only the building's columns and wall braces were dimensioned. This is common practice in pre-design phase as these parts have the most effect on how the loads are distributed to the foundations. After dimensioning the column and wall brace profiles the model is calculated again and the before dimensioned profiles are checked as the force distribution changes when the profiles are changed. If needed, corrections to the profile sizes are made. Once the profiles are correct, the updated profiles are synced to Tekla using a script. This script is not part of this thesis and it has been made and used prior to this, here the already available tools are just used. After the Tekla model is updated a foundation map drawing can be produced in Tekla, where column locations and foundation IDs are presented.

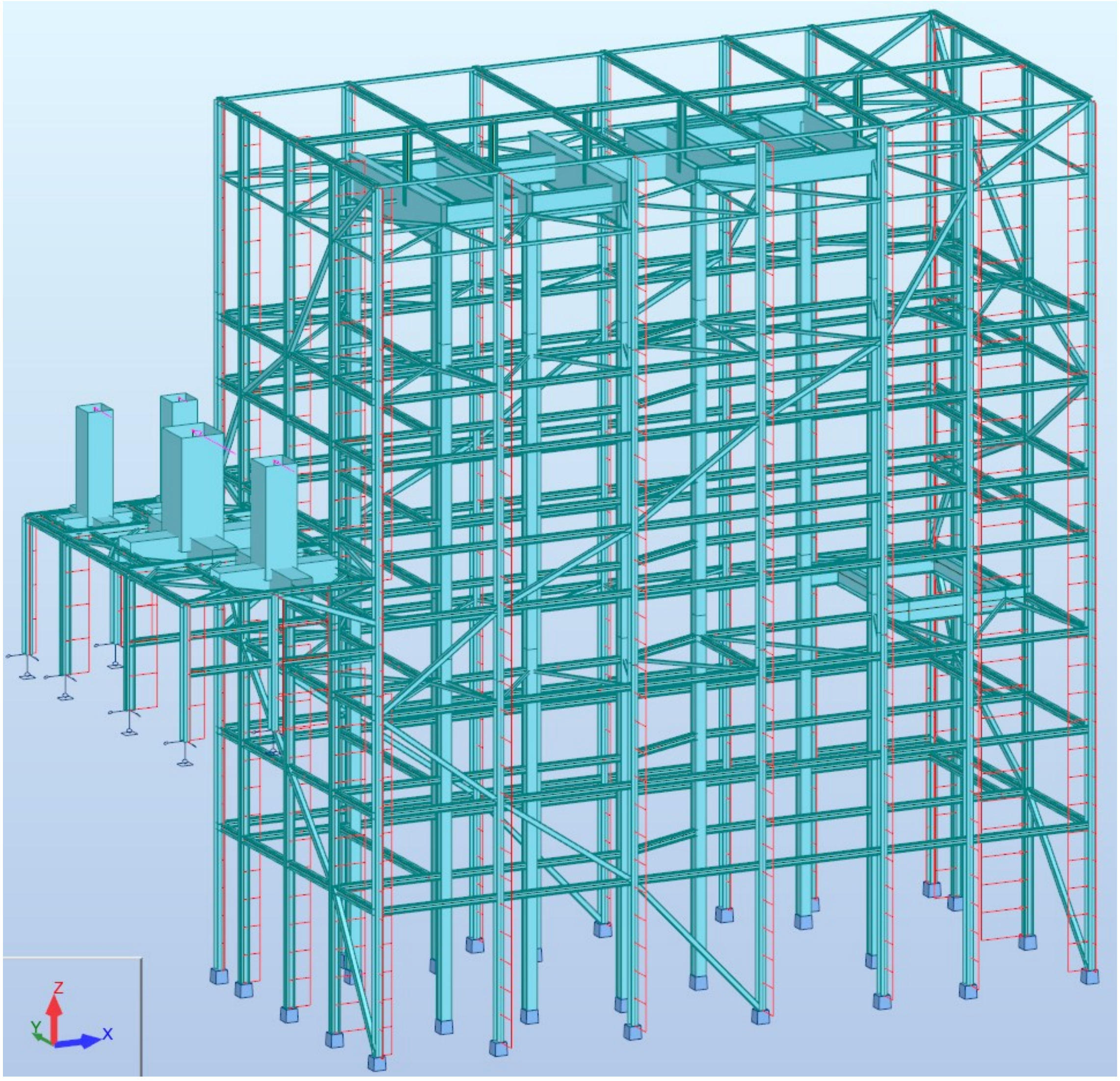

Figure 17. *Boiler building's frame in Autodesk Robot Structural Analysis as produced by the algorithm, also showing wind loads to Y+ direction.*

After the analysis is done the calculated support forces for each of the load cases are extracted from Robot and copied to an Excel table. The load cases used in this case study are presented Table 1. In the Excel the support forces are modified as foundation loads by changing them to their opposite numbers.

Table 1. *Load cases used in pre-design case study.*

LC No	**LC Name**	**LC Description**
1	DeadLoad_str	Dead load of the steel structures
2	Platform_DeadLoad	Dead load for platform levels 0,5 kN/m^2 (including grating, secodary beams and railigs). 1 kN/m^2 in hatchways. Also in-cludes dead loads for roof structures 0,5 kN/m^2 and wall structures 0,4 kN/m^2
3	Equ_DeadLoad	Equipment dead load

4	Platform_LiveLoad	Live load for platform levels 2,5 kN/m^2 including small small installations (pipings etc.) 0,5 kN/m^2. 10 kN/m^2 in hatchways.
5	Equ_LiveLoad	Equipment live load
6	SnowLoad	Snow load, s_k = 2.75 kN/m^2
7	Wind_ext_X+	External wind pressure, wind direction X+
8	Wind_ext_X-	External wind pressure, wind direction X-
9	Wind_ext_Y+	External wind pressure, wind direction Y+
10	Wind_ext_Y-	External wind pressure, wind direction Y-
11	Wind_int_+0.2	Internal wind pressure, c_{pi} = 0.2
12	Wind_int_-0.3	Internal wind pressure, c_{pi} = -0.3
13	Imperfection_X+	Horizontal imperfection load, direction X+
14	Imperfection_X-	Horizontal imperfection load, direction X-
15	Imperfection_Y+	Horizontal imperfection load, direction Y+
16	Imperfection_Y-	Horizontal imperfection load, direction Y-

Usually the foundation loads are further modified by increasing them with agreed increment factors. These factors are necessary because the initial data on pre-design phase is still subject to changes and equipment loads and locations can change after the pre-design is done. Still, the foundation loads presented in the end of pre-design are so called NTE-loads (Not to exceed), which means that they should not increase during the project. The increases applied to this project are show in Table 2. After the foundation loads were modified the foundation load document was prepared.

Table 2. *Foundation load increase rules for this case study.*

Load type	**Increase**
Self-Weight Dead Structure Dead Equipment	No increase
Live	Max (+ 20 % or + 50 kN), load min 200 kN.
Live Equipment	Boiler columns: max (+ 10 % or + 250 kN), load min 250 kN. Other columns: max (+ 20 % or + 75 kN), load min 250 kN.
Wind	+ 10 %
Snow	No increase
Imperfection	No increase

5.3 Case results

Results of this case study are divided into two parts. In the first part the calculated foundation loads are examined and compared to the loads calculated in the original pre-design. In the second part the efficiency of the design process is evaluated by comparing the times spent on both pre-designs.

5.3.1 Foundation loads

The foundation loads calculated in the new pre-design are show in Table 3. In the foundation loads originally calculated for this project, stair towers and equipment support located outside of the boiler building were included. These structures not included in this case study have been filtered out of the of the originally calculated foundation loads and the filtered loads are show in Table 4. The filtering was done by removing unwanted nodes and their loads from the original foundation load Excel table and calculating new resultants.

Table 3. *Foundation loads calculated in this case study.*

LC No	LC Name	Fx	Fy	Fz	Mx	My	Mz
1	DeadLoad_str	0	0	3949	19	13	0
2	Platform_DeadLoad	0	0	2978	20	20	0
3	Equ_DeadLoad	0	0	15097	11	5	0
4	Platform_LiveLoad	0	0	10253	67	44	0
5	Equ_LiveLoad	0	0	18086	130	20	0
6	SnowLoad	0	0	1819	13	9	0
7	Wind_ext_X+	-1029	0	0	-8	-750	0
8	Wind_ext_X-	1028	-2	0	-24	807	0
9	Wind_ext_Y+	67	-2278	0	2353	74	0
10	Wind_ext_Y-	-49	2278	0	-2367	44	0
11	Wind_int_+0.2	0	0	0	5	-8	0
12	Wind_int_-0.3	0	0	0	-8	12	0
13	Imperfection_X+	-286	0	0	1	-184	0
14	Imperfection_X-	286	0	0	-1	184	0
15	Imperfection_Y+	0	-286	0	234	6	0
16	Imperfection_Y-	0	286	0	-234	-6	0

Table 4. *Original foundation loads of the boiler building and silo support structure.*

LC No	LC Name	Fx	Fy	Fz	Mx	My	Mz
1	Self Weight	1	1	4176	34	20	0
2	Dead Platform	4	-5	3320	34	27	0
3	Dead Equipment	2	4	13955	34	15	0
4	Live Platform	6	-5	9692	34	29	0

5	Live Equipment	-3	18	20199	34	20	0
6	Snow	1	1	1940	34	15	0
7	Wind +X	-950	-28	0	34	-1214	0
8	Wind -X	932	-33	0	34	1170	0
9	Wind +Y	223	-2161	0	34	528	0
10	Wind -Y	266	2177	0	34	524	0
11	Wind +Int	51	7	0	34	111	0
12	Wind -Int	-76	-10	0	34	-167	0
13	Imperfection_X+	-168	2	0	68	-221	0
14	Imperfection_X-	168	-2	0	-68	221	0
15	Imperfection_Y+	4	-174	0	68	5	0
16	Imperfection_Y-	-4	174	0	-68	-5	0

The comparison between these foundation loads is presented in Table 5. From this comparison the internal wind pressures are left out. This is because in theory the internal wind pressures should summarize to 0. Having the internal wind pressure something else than 0 is typical in the boiler building projects where the calculation model is quite large. This is caused by the small defections in the model. In the new calculations the internal wind pressures result to 0, which would indicate that the model is working as intended.

Table 5. *Foundation load comparison.*

Loads in z-direction [kN]					
LC No	**LC Name**	New	Original	Difference	Difference %
1	DeadLoad_str	3949	4176	-226	-5,4 %
2	Platform_DeadLoad	2978	3320	-342	-10,3 %
3	Equ_DeadLoad	15097	13955	1142	8,2 %
4	Platform_LiveLoad	10253	9692	561	5,8 %
5	Equ_LiveLoad	18086	20199	-2113	-10,5 %
6	SnowLoad	1819	1940	-120	-6,2 %
	SUM:	**52266**	**53282**	**-1099**	**-2,1 %**
Loads in x-direction [kN]					
LC No	**LC Name**	New	Original	Difference	Difference %
7	Wind_ext_X+	-1029	-950	-79	8,3 %
8	Wind_ext_X-	1028	932	96	10,3 %
13	Imperfection_X+	-286	-168	-119	70,8 %
14	Imperfection_X-	286	168	119	70,8 %
Loads in y-direction [kN]					
LC No	**LC Name**	New	Original	Difference	Difference %
9	Wind_ext_Y+	-2278	-2161	-117	5,4 %
10	Wind_ext_Y-	2278	2177	101	4,6 %
15	Imperfection_Y+	-286	-174	-112	64,5 %
16	Imperfection_Y-	286	174	112	64,5 %

It can clearly be seen that there are quite some differences in the foundation loads. Some deviation was to be expected as there was only access to the official layout drawings. Usually during the pre-design process, dialog between the customer is held where the structural solutions, equipment location and loads, and many other things affecting the frame are discussed. To some places it might be agreed to add extra loads as reservations because of the incompleteness of the initial data. Also, in the original pre-design the modeling and load insertion was done manually, which causes some things to be more detailed and other things to be more simplified.

Upon more detailed inspection it can be seen that the live load for service platforms generated by the algorithm is 5,8 % higher than the original. This can be explained by the simplification of the service platform geometry used in the algorithm versus the manually modeled platforms. The simplification in geometry causes some additional platform loads. The difference is not too big however and during the actual design phase the initial data for platform geometry is usually further specified and so will be the loads. Even though the live load for the platforms is bigger than the original, the dead load is smaller, by 10,3 %. In the platform dead loads case also the dead loads of the roof structure and walls were included which explains some of the deviation between the differences. Most probably there has been some differences when calculating the dead loads for the walls or the roof. One possible explanation is also that during the original pre-design, more of the platform area are considered to have tear plate on top of the grating than what is shown in the layout drawings. The tear plate doubles the area load for the platform's dead load. On the other hand, typically tear plates are placed in hatchways where the live load is also increased.

The difference between the structural dead load is explained by the fact that the whole structural frame is not dimensioned at this phase of the design as mentioned before. So, a lot of the steel profiles for members are purely initial guesses and might be different. Also, when doing the design manually, the platforms might be more detailed and include more platform supporting beams than when doing the design using the algorithm. Even still, the difference remains quite small. A bigger difference can be found from the equipment loads, which seem quite interesting. The equipment dead load in the new pre-design is 8,2 % higher than the original while the equipment live load is 10,5 % smaller. After inspecting the calculation model generated in this case study and the inspecting the layout drawings and line load drawing for the main support level that contain the equipment loads, it can be noted that all of the presented equipment loads are taken into consideration. The increases were also checked, and no issues was found. The only explanation for these differences is that in the original pre-design some additional information was available that couldn't be found during this case study.

In the wind loads some differences can also be seen. The new wind loads are thoroughly bigger than the original ones but, in the x-direction the difference is significantly higher. Partly this difference can be explained by the stair towers which are connected to the buildings stiffening system. The stair towers also have their own bracings and the towers are oriented so that that they are much stiffer in x-direction. The stair tower locations are shown in Figure 18. Thus, some of the wind loads in the x-direction are distributed to the foundations of the stair towers. In y-direction the stair towers play an insignificant role in distribution of the wind loads when considering the boiler building. Other than that, the differences are probably explained by the simplifications made when generating the wind loads with the algorithm. The simplifications are made to be on the safe side, which causes the wind loads to be slightly bigger. For example, the wind load for a column, according to its height region is always considered to be according to the higher region if even some part of the column is in that region.

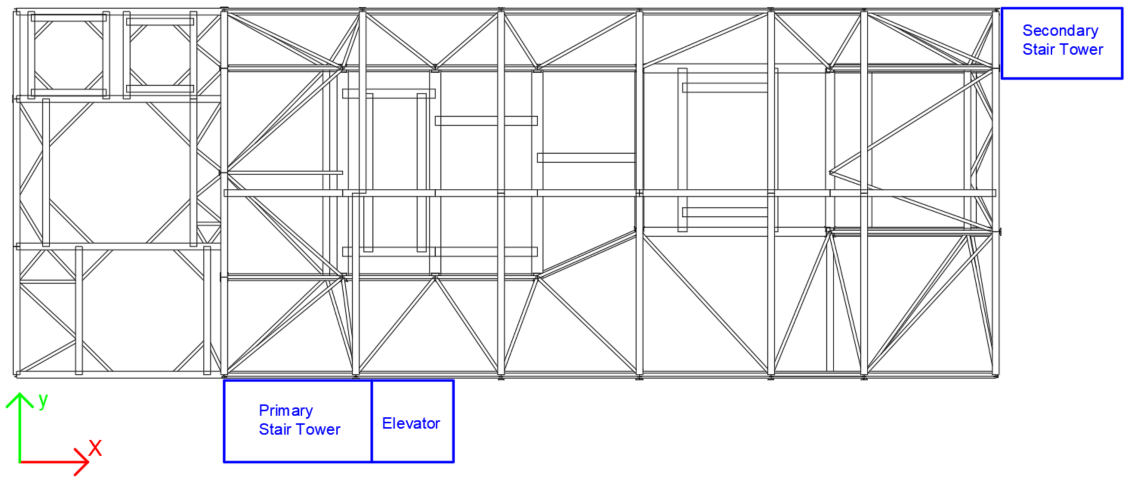

Figure 18. *Building layout including stair towers.*

Snow loads are 6,2 % smaller than in the original. This is probably caused by snow drift loads. In the algorithmically generated snow loads only the snow drift at the roof of the silo support structure, next to the boiler building front wall is taken into consideration. In reality, there is also snow drifts next to the silos and the stair towers, as the stair towers are higher than the boiler building. These extra snow drift loads should be manually added to the Tekla model.

There is a huge difference in the imperfection loads, but these loads play only a minor role when considering the entity of the structure and its loads. Calculating imperfection loads manually is laborious work and as these only have a minor impact to the structure these are usually radically simplified. Then again, as algorithm doesn't care about these kinds of issues, all the vertical loads in the wanted load cases are separately taken into consideration when calculating the horizontal imperfection loads. The line loads on beams are generated as horizontal equivalent point loads in the ends of the beams. In the original process the horizontal imperfection loads were added only to stiffening platforms. The difference is almost certainly caused by this different approach to imperfections.

When taking into consideration some vagueness of the initial data and the simplifications made for this case study, it can be noted that the new foundation loads calculated do not differ too much from the original foundation loads regarding pre-design phase.

5.3.2 Time spent on pre-design

For this case study's pre-design, three workdays (7,5 hours a day) were spent by one person, the researcher. This also included deleting and reinserting all the equipment loads, re-generating of the FEM model and calculating new foundation loads, as the difference in the foundation loads was huge after the first calculation. The explanation for this was found eventually as during the original pre-design a revision for the layout drawings was received. This new revision included many equipment not shown at all in the first issue of the layout drawings. In addition, the increases to the foundation loads were left out. After these changes the foundation loads presented before were calculated. The revision of the equipment loads was made quite easy by the algorithm-aided process as the old point loads could simply be deleted from the Tekla model and reinserted using the algorithm mentioned before.

The original pre-design took approximately from two to three weeks from two employees (which both had more experience in pre-designing of boiler buildings than the researcher). Sadly, no accurate data of spent working hours for the original pre-design was available. This pre-design period also included the pre-design of the stair towers and the equipment supports located outside of the boiler building, so there was some additional work to be done that was left out from this case study. Nevertheless, it can be stated that with the aid of algorithms a significant amount of time can be saved from the manual stages of the work. Thus, the designer has more time to spend in designing and thinking the different structural solutions and discuss the buildings layout and its possible improvements with the customer.

5.4 Case summary

Even though there were differences in the foundation loads compared to the originally calculated ones, the new foundation loads are reasonable and accurate enough for the pre-design phase. The exact reasons for these differences are impossible to find out because of lack of information about all the initial data that was used in the original pre-design but it is very likely that the differences can be explained with small differences in the initial data and the approximations that are used in manual design and algorithm-aided design. In both approximations are necessary to get the work done. The approximations used are different because some things are easily done much more accurately while doing them manually, for example modeling the service platforms. There is large variation in the platform layouts in boiler buildings and to get this done with algorithm some approximations are needed. On the other hand, things that require a lot of raw calculations are more easily done accurately by algorithm while it would be really time consuming if done manually. A good example of this are the horizontal imperfection loads, as discussed earlier. Also excluding the stair towers from this study has a minor effect to the boiler buildings foundation loads.

The time saved in the design process was significant, even though no exact amount of saved time could be presented, especially on the manual modeling and load inputting. This releases time for the designer to do the actual design work, discussing the frame and layout with the customer and focusing on the key points of the frame.

Thus, the result of this design study is that with algorithm-aided design and the algorithms produces it is possible to produce accurate enough foundation loads, enhance the efficiency of the design process and overall make better quality pre-design, as long as the time saved using this kind of workflow is not cut from the already tight pre-design schedule.

6. CONCLUSIONS

6.1 Summary

The purpose of this thesis was to find out if it would be possible to do faster and more efficient pre-design to boiler buildings using algorithm-aided design process and produce these algorithms. A literature study was performed to find out if algorithm-aided design had been successfully used in boosting efficiency and speed of structural design in other subjects.

Case study on a previously pre-designed boiler building was used as a research method to test the algorithm-aided process and find out if the design process would be more efficient and faster. This was measured by the time saved from manual tasks, and thus the time can be spent for studying different structural solutions and concentrating on challenging parts of the structure.

Also, a short study on the state of algorithm-aided design in the field of structural engineering was conveyed.

6.2 Results

As the result of this thesis two algorithms were produced, one to generate a Building Information Model to Tekla Structures software representing the structural steel frame of a boiler building, and one that exports the information in the Tekla model to a Autodesk Robot Structural Analysis software, where the structural analysis of the structure can be performed. The second algorithm also calculates and generates some of the typical loads to the frame. The second algorithm also provides an integrated design ecosystem, where it is no longer needed to maintain separate analysis model and BIM model for the same structure. All modifications to the structure can be done in a BIM software, which is intended for modeling purposes. This model can then be easily exported to FEM software for analysis. This approach works on all kinds of structures and is not limited to boiler buildings.

The approach of having a design process where algorithm-aided and manual design is combined was found to be most efficient in practice as boiler buildings are quite massive and complex structural entities. Having the process fully automated requires too much simplification to the whole structure for it to be useful in practice as the definitions of the algorithm would be really difficult or even impossible to produce so that they could handle all the exceptions and exceptions to exceptions. The parts that require most manual work are the additional structures connected to the main building, such as framing for silos and stair towers. Also, the main support level's boiler beam arrangement varies in different boiler projects and usually requires manual actions. In addition to these there is often irregularities in equipment supports and their locations as well as in the main structural frame itself, for example in some projects some of the columns can't be continuous from foundations to the roof because they have to give way to ducts and equipment.

The algorithms were tested in action on a case study and found to be working as intended, the outputs of the algorithms were trustworthy and clear. The foundation loads calculated using algorithm-aided process were close to the original foundation loads that were produced using more traditional design method. The time saved on the pre-design of the case study subject was significant, even though based on this study exact amount of time saved can't be reported. Still, it can be stated that if the time saved is not taken out of the pre-design phase by tightening the schedule even further, it is possible for the designer to study different structural solutions (for example the bracing locations of the stiffening system) and base decisions to analyzed data, rather than just relying on rule of thumb type decisions. Thus, making the pre-design better. Also, the reaction to revisions in the initial data is made easier compared to traditional design as seen in the load revision noticed in the case study.

During the literature survey it was found out that AAD can be a powerful tool for boosting efficiency and saving time in the design, but in complicated, nonrepetitive structures it might also be difficult or even impossible to perform all of the modeling and analysis tasks algorithmically.

In a survey where people involved with algorithm-aided design were interviewed about the state of AAD in the field of structural engineering, it was found out that AAD is not yet very common among structural designers, but the usage is on the rise and more and more people are interested in it. Algorithm-aided design is mostly used to either perform simple repetitive tasks or challenging single tasks which would be difficult to perform manually, such as creating complex geometries.

6.3 Further research

There is still lots of need for further research on algorithm-aided design of boiler buildings. As this thesis only focused on the pre-design phase where most of the structures inside the building are left incomplete. Generating service platforms and their supporting beams is something that could be made much more efficient using algorithms, as well as modeling and analyzing equipment supports for all the different equipment and pipes included in a boiler building. Also, an algorithm to produce the stair towers that are usually included in boiler building design scope would probably prove to be efficient. Yet one aspect for large steel structure projects would be the algorithm-aided design of connections between steel members. Connection design usually takes a lot of time and most of the connections could be made using previously designed typical connections. With the developed integrated design system the connection forces could be read from the FEM model and used in the connection design algorithm.

As for further enhancing the pre-design, the BIM algorithm produced for this thesis could be modified so that the wall bracings would be automatically generated using certain rules to avoid collisions with openings in the walls for ducts and other equipment. Also, utilization of optimization algorithms in the positioning of the wall bracings would further enhance the algorithm. In the FEM algorithm the generation of seismic loads is something that would need further research. Overall, the algorithm-aided design process would be more beneficent if the structural designer would be involved earlier in the project when the structural frame is still more open for changes.

While writing this thesis the produced algorithms were already used in few projects and they proved to be useful and time saving. The geometry algorithm is only useful for boiler building projects, but the FEM algorithm has been used in different kinds of projects and proved to be useful. Basically, any project that is modeled using Tekla can be exported to Robot and analyzed there without the need of maintaining two models of the same structure. As Tekla is a software intended for modeling structural elements it is convenient to build and maintain the model in Tekla and when needed, export the structure to analysis software.

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