LUT UNIVERSITY

LUT School of Energy Systems

LUT Mechanical Engineering

Tuukka Harju

PORTAL CRANE LAYOUT OPTIMIZATION FOR PULP MILL WOODYARD OPERATIONS IN SOUTH AMERICA AND EUROPE

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TIIVISTELMÄ

Tuukka Harju

Sellutehtaan portaalinosturikäyttöisen puukentän pohjapiirustuksen optimointi Etelä-Amerikan and Euroopan markkina-alueilla

Diplomityö

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99 sivua, 26 kuvaa ja 32 taulukko

Tässä työssä etsittiin selluteollisuuden käytössä olevien puukenttien optimoinnissa käytettäviä muuttujia markkina analyysillä, FEM laskennalla, ja työkalun kehittämisellä. Andritzilla on vuosien kokemus portaalinosturien kehityksessä, mutta haluaa lisätä ymmärrystä ja osaamistaan uudesta nosturirakenteesta ja sen kyvystä kohdata uusien markkinoiden haasteet. Tämä työn päätarkoitus on tuottaa dataa ja työkaluja tarjousprosessiin mahdollistamalla tarkempia alkuarvauksia ilman raskaita laskuja.

Markkina-analyysiosiossa tarkasteltiin muuttujia ja ominaisuuksia, jotka tekevät Etelä Amerikan ja Pohjoismaiden markkinoista sekä ainutlaatuisia että samankaltaisia. FEM laskennalla testattiin nosturin uuden poikkileikkauksen rajoja ja kykyä kohdata uusien markkinoiden haasteita. Tietojen pohjalta kehitettiin konseptityökalu, joka mahdollistaa tarjousprosessille tarkempia alkuarvauksia pienemmällä laskentamäärä kuin prosessi perinteisesti vaatisi.

Tässä työssä tunnistettiin Etelä American ja Pohjoismaiden tärkeimmät ominaisuudet ja tämän tiedon pohjalta syntyi perustieto lopputyölle. Laskentaosuudessa osoitettiin, että uudella poikkileikkauksella voidaan käyttää ainakin 90 jalkaisia ulokepalkkeja nosturirakenteissa. Lisäksi, todettiin että pylonivahvikkeilla voidaan mahdollistaa vielä pidempien ulokepalkkien käytön. Viimein, työssä kehitettiin onnistuneesti konseptityökalu, jonka avulla voidaan tehdä tarkempia ja nopeampia alkuarvauksia kuin perinteisellä metodilla. Työkalua käytettiin onnistuneesti oikeassa tarjoustilanteessa.

ABSTRACT

LUT University
LUT School of Energy Systems
LUT Mechanical Engineering

Tuukka Harju

Portal crane layout optimization for pulp mill woodyard operations in South America and Europe

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M.Sc. Ossi Viiala

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This thesis set out to discover the key variables in layout optimization of pulp mill woodyards through market analysis, FEM calculation, and tool creation. While Andritz has decades of experience developing portal cranes, it would like to further develop its understanding of the new portal crane design and its capabilities in meeting the challenges of new markets. The key reason for this whole process is to develop the quotation process by providing data and tools with which to improve the quotation process by providing better initial approximations.

This thesis uses market analysis to determine key variables and characteristics that represent both the similarities and unique characteristics of the target regions of South America and the Nordics. FEM calculation is used to test the limits of the new cross section and its ability to meet new challenges presented in new markets. Finally, a proof-of-concept tool will be developed to aid the quotation process by providing initial approximations more quickly and accurately, while limiting the heavy calculation work that is traditionally required.

This thesis identified market trends and characteristics in South America and the Nordics that help to provide a database from which to base the further work of this thesis. The calculations showed that the new girder cross section is capable of handling span and cantilever beam lengths of up to 90 ft. Additionally, pylon reinforced cantilever beams further increase the potential length of the cantilever beam relative to the span length. Finally, a proof-of-concept tool was created with which quick approximations that are much faster than using the previous method are possible. The tool was tested in a real-world quotation successfully.

ACKNOWLEDGEMENTS

LIST OF SYMBOLS AND ABBREVIATIONS

$A_{grapple}$	Grapple cross section size $[m^2]$
a_{truck}	Truck receiving hours $[hours/week]$
b_{infeed}	Infeed operating hours $[hours/week]$
b_{pile}	Average pile width $[m]$
C	Net lift capacity [tons]
h_{pile}	Average pile height $[m]$
IC	Infeed capacity $[tons/day]$
L_{Log}	Average log length $[m]$
L_{pile}	Average log length $[m]$
$S\%$	Average minimum flow thru as percentage of total flow [%]
T	Storage turnover time $[days]$
$W_{Storage}$	Total storage tonnage $[tons]$
ρ_{wood}	Wood green density $[kg/m^3]$
$\varphi_{Grapple}$	Grapple void factor $[unitless]$
φ_{pile}	Pile void factor $[unitless]$

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1 INTRODUCTION

1.1 Background

In the modern world, the pace of market changes and the speed at which new and emerging technologies are moving from idea to practice has been accelerating over the past several decades. While computers were merely a niche and expensive application used in large scientific laboratories and massive corporations only half a century ago, today everyone has not only one but several personal computers many times as powerful as the first computational machines. Although consumers now have access to smart devices and computers capable of much more than could have been realized by even the most capable institutional super computers just decades ago, institutions still have an, albeit different, advantage that they leverage every day.

Automation using algorithms and neural networks has been gaining steam in the previous decade and continues to do so at an exponential rate. This has led to a new battleground in which competitors vie for position as the market leaders of their field or specific niche. For example, when it was no longer reasonable for cell phone manufacturers to compete based on hardware specs and capabilities, they started to compete with their ecosystems, software ecosystems and ease of use, all with the same end goal of providing maximum practical functionality and utility for both personal and business use, in other words they essentially optimized the device to automate many menial tasks that would otherwise take up time. More prominently perhaps is the trend of creating larger and larger automated systems in the same vein as self-driving cars. While in the past decade automation has been mainly applied to electronic devices and software packages, the next phase of automation is moving forward at a fast pace. A new sort of competitive edge is desirable in the form of reducing overhead costs and increasing efficiency by reducing the human element and minimizing the number of machines and creating fully automated machinery.

However, applying automation to heavy machinery carries an increased risk in comparison to software automation. Beyond the obvious safety concerns that arise, other considerations like reliability concerns and a larger investment must also be accounted for. Additionally, automating heavy machinery requires an additional layer of assurances and convincing of

the customers to take a leap into a new era of manufacturing and production. Increasingly, the empirical evidence continues to mount, and calculations of increased productivity and profitability allow for customers to justify the investment more easily despite initial apprehension.

Increased efficiency, sustainability, and safety go hand in hand in the case of Andritz portal cranes, with the end goal being efficiency and sustainability through the reduction of fossil fuel-based loaders, a smaller woodyard footprint, and reduction of moving parts in the woodyard. All these things in tandem produce a more efficient and productive woodyard with fewer greenhouse gas emissions.

1.2 Scope and Focus

This thesis will focus mainly on the pulp industry and their associated woodyards. This can mean anything from a pulp mill that produces all kinds of pulp to integrated production plants in which products are developed from the pulp itself. While particle board and board production are left out entirely, satellite woodyards that provide wood for pulp mills should be considered regardless of their main function. Furthermore, this thesis will focus entirely on portal cranes, specifically an intermediate model for the currently existing product line of Andritz pulp and paper. Of course, loaders will be considered as support vehicles for the portal cranes as it is a necessary backup but no detailed investigation regarding their application and use will be conducted beyond the scope of a support role or comparison. The core of this thesis topic will revolve around Andritz portal crane operated pulp mill woodyards and their layout optimization.

1.3 Objectives and outline

The main objectives of this thesis are threefold: first the market and potential customers for an intermediate portal crane solution will be researched, including general needs and production volumes that are required to estimate initial design values. Secondly, using the data and constraints that are provided in the market research phase, general layouts and their ranges will be created for which initial strength and fatigue calculations will be conducted on the structure itself. Finally, using all the previously gathered data, a tool will be created to aid the salesforce in determining the capabilities and production ranges that can be promised customers. This tool should be easily usable by persons without an extensive

technical background regarding portal crane design and serve as a reference tool with which to consider product capabilities.

1.4 Research Problem

The main research problem in this thesis is to determine the crane design limits, e portal crane configurations in the pulp industry. In doing so, the needs and requirements of the discovered customers will be used to formulate the variables and constraints which will in turn be used to calculate the structure of the solution. Additional calculation will be made to optimize the woodyard size by using the metrics that were previously discovered as well as known capabilities. Finally, a simple tool that allows salespeople with less technical knowledge on the products they are selling will be created. The tool is intended to serve as a form or application that when customer requirements are put into the system it will automatically create an estimation/approximation of what is available and what is possible to do with further customization. This allows the sales force to quickly determine what can be offered to the customer while giving the customer a general idea of what can be expected conservatively. It can also serve as a starting point from which different aspects can be tailored to the customers' needs and implemented accordingly.

1.5 Research Questions

1. What are the key variables when approaching new markets?
2. How can the crane operated woodyard be optimized?
3. What are the principles of a tool used to offer better approximations to customers for crane operated woodyard layouts?

1.6 Thesis structure

This thesis will attempt to systematically solve the research questions by using a multidisciplinary approach. Each section will use a different theme to gather the information required to proceed with the following step starting with business related market analysis, followed by limit testing of the crane cross section and components, and fatigue calculation in the model calculation section, and finally, compounding those results with statistical

analysis and excel programming to produce a proof of concept. The main themes of this thesis are presented in Table 1.

Table 1. The main themes presented in this thesis.

Theme	Description
Market analysis	This section with identify priority regions and their unique characteristics, strengths, and weaknesses. The results will form the basis from which tool creation will begin.
Crane model calculation	Various representative portal crane configurations will be selected to represent typical dimensions and geometry. Those configurations will then be analyzed using finite element method and fatigue life calculation to determine the broad parameters on which tool creation will be facilitated.
Layout estimation tool creation	The results of the market analysis and model calculation section will be exploited to identify and formulate the principles and methods that should be used to create the framework of the layout estimation tool.
Analysis and discussion	Results of all three phases will be analyzed to determine the success of this thesis and discuss future research topics. This section will also discuss the possible applications of the thesis results as well as further considerations regarding the topic of this thesis.

1.7 Andritz Portal crane

A portal crane is made up of five main components: the legs, the girder, the trolley, the grapple, and the end trucks. An illustrative figure of the constructions is presented in Figure *1*, where all the main components are pictured. These parts make up the key elements that create a functional woodyard management tool. The grapple is suspended and carried by the trolley which moves along the girder. The girder in turn is supported by the legs of the crane which in turn rest upon the end trucks that traverse along the rails on which they lie.
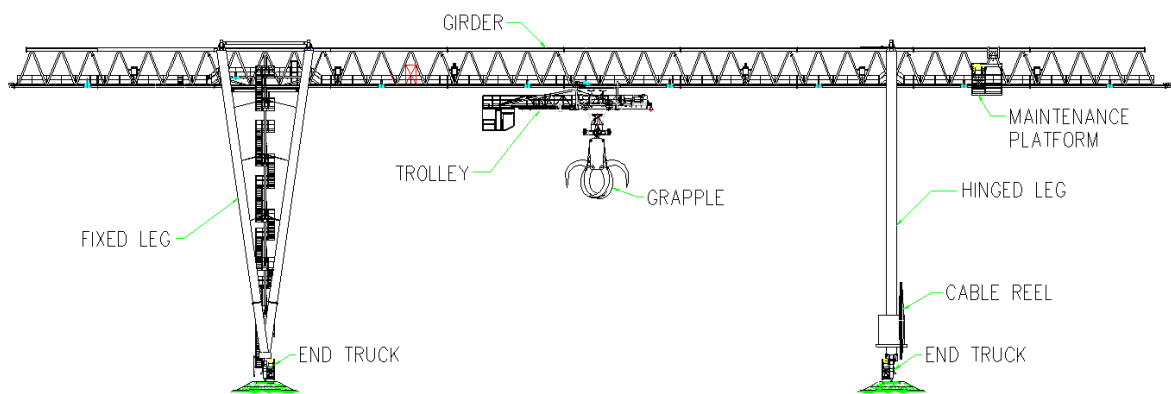
Figure 1. The main components of a portal crane presented on a two cantilevered configuration.

While cranes are well understood within the company, a new girder cross section has been developed for new markets. The new constructions cross section is so new that its limits aren't entirely known. Previous structures were designed mainly for single grapple configurations while the new cross section is designed to support two grapple configurations, and thus the institutional knowledge does not yet exist for the limits of the structure. The new markets also provide a different set of challenges with different customer needs and different environments in which the new structure will be used. This thesis will attempt to address those concerns to provide information that has not yet been gathered. The limits of the new design are constrained by plate thickness and diagonal cross section because neither can be increased indefinitely. In the case of plate thickness, one of the most restrictive limiting factors is that increasing the plate thickness quickly reaches a point after which the connecting bolts no longer fit, while increasing the cross section increases both weight and

wind area. The use of high strength steels could be considered on a case-by-case basis, however, the availability of both materials and skilled workers who can weld special steel grades to meet requirements may be restrictive in many parts of the world.

The crane cannot be entirely standardized due to widely different customer demands and environmental conditions that each require a different solution to some extent. The crane is however constructed from modular pieces with which crane configurations can be customized for each customer. This thesis aims to approach the problem by defining the unique conditions on the target markets and using those characteristics to test the limits of possible configurations using those modules while meeting the demands of the customers.

2 MATERIALS AND METHODS

As outlined in the introduction, the purpose of this thesis is threefold: to identify potential markets, create an initial layout for an intermediate portal crane operated yard, and finally create a tool that is based upon the previous sections that can be used by sales teams to provide guidelines for the product configurations that can be offered.

2.1 Literature review

This thesis will gather much of the theoretical background for the subject using literary resources, institutional knowledge within Andritz and expert interviews. This thesis is roughly divided into three sections: market analysis, layout optimization, and tool creation. Each section will build upon the preceding section, thus the foundations for the subject must be sound. The market analysis section will use research articles from the LUT library databases as a main source but will also rely on interviews with the experts within Andritz.

The research articles will be used to provide a general overview of the industry while the interviews will provide industry specific insights from the individuals who are the most experienced with specific applications of knowledge and within specific contexts. The layout optimization portion will introduce various strategies and optimization methods that are used with similar problems.

The calculation section will introduce the methods and applications used to calculate the fatigue life of each model that is selected for further analysis. This will include the fundamental analytical calculations that should be considered before FEM analysis as well as the steps within that analysis itself. Some of the main results that are desired from the calculation phase include: fatigue life, deflection, wheel loads, and the weight of the structure. The structures weight is particularly important because prices are calculated by relative weight. The weight also guides the mechanical designers to correctly size the motors and gears of the structure. Similarly, the tool creation section will describe the principal steps in tool creation from the idea generation phase to the iterative process that takes place using systematic design principles.

2.2 Market analysis

The market analysis will be conducted initially by studying various regions and determining their unique characteristics and trends. This will include a broad, but brief, consideration of market conditions, environmental factors, social factors, and economical factors. These variables will be determined using opensource information provided by companies themselves as well as historical data sourced from research articles on the paper industry in different regions. The initial scope of the locations was decided among my supervisors and myself based on the companies need and requirements. The target regions where to be narrowed to the most interesting areas using initial research.

Marketing and business analysis methods are exploited during regional research. First segmenting the market into broader regions according to geography will be conducted. The geographical grouping will serve three purposes: to create logistical grouping due to proximity, to cluster similar biomes together, and determine which companies act in which regions. Furthermore, regional segmentation allows for a more focused effort in identifying the key characteristics on aggregate in each region rather than narrow focus on dozens of individual countries. In this way, the regional characteristics will be used to determine the most promising countries that represent each region.

The regional characteristics that are studied should follow the needs of this thesis' end goal: tool creation. With that in mind, the market analysis phase should also focus on which factors are useful variables.

2.3 Layout optimization

Layout optimization is one of the most important parts of the design phase. Layout optimization has a large effect on the cost of the project. The material costs of the crane itself plays a part because, naturally, a smaller crane requires less material. Conversely, a smaller crane requires a longer rail length to meet the requires storage demands. The rail length in turn has implications on the gate-to-gate time of wood storage and process feeding. Perhaps the most important consideration, that drives the process is unloading logistics. Where and how unloading is undertaken effects all other aspects of crane operation and is often a determining factor when applying design constraints. The goal of layout optimization is to take all of this into consideration to provide a solution that satisfies service life requirements

while minimizing the amount of material requirements, movements in each process, and operation steps during the work cycle. An optimized woodyard should reduce both the crane size to limit total weight and reduce the woodyards footprint by minimizing used space to meet storage requirements. Optimization is a balancing between these two factors to reduce the total operation costs in the long run.

Grapple size should be selected according to wood size, log truck configuration and the cross section of the feed system. Depending on wood size (long wood or short wood) the initial grapple size can range anywhere from $2.8 - 6.0 \text{ m}^2$ for long wood and $6.0 - 8 - 4 \text{ m}^2$ for short wood. Besides the wood type, the available infeed system plays a prominent role in grapple sizing, where a table fed system allows for a larger grapple size when the conveyor system on the table allows for it. Conversely, a tableless feeding system where the wood is fed directly into the drum would require a smaller grapple corresponding to the production capability of the feeding drum with no buffer.

$$C = \rho \cdot A \cdot L \cdot \varphi \qquad (1)$$

Next the net lift capacity of the crane should be calculated using equation 1. where net lift capacity (C) is obtained by multiplying wood green density (ρ), grapple cross section (A), average log length (L), and grapple void factor (φ). Wood green density can be obtained from the appropriate documentation and grapple cross section is determined based on the previously mentioned factors. Average log length is based upon local practices and internal requirements while grapple void factor is set to either 0.45 for longwood or 0.65 for short wood. The smaller void factor for longwood is due to the taper that is caused by the lifting of long wood.

Additionally, the customer provides additional specifications affecting the net lift capacity, namely, expected wood curvature, branch density, and variations in log diameter [1]. Gross lift capacity is a simple summation of the calculated net lift capacity, grapple weight and lifting beam.

Next the girder dimensions and rail length should be determined by considering the requirements and restrictions that apply. While wood is always stored under the span of the

crane, the cantilever section is used for both storage, road access, and unloading operations. Span storage is preferable because retrieving and storing wood from under the cantilever section requires extra trolley movements because the gantry cannot be driven when the trolley is under the cantilever beam. Wood type should also consider due to its introduction of different restrictions depending on the wood type. Most prominently, the differences in maximum pile height creates a height disparity between the two wood types of about 5 m, where short wood can be stacked up to 12 m high while long wood can be stacked up to 23 m high. In practice, when short wood is stacked, it can be done so in piles of three so that they can mutually support one another from falling over, however this isn't always done. Conversely, long wood doesn't require mutual support, but can, due to its length, present its own challenges when managing storage optimization. Additionally, in all cases, an additional 2 m space should be added on either side of the stacked wood piles to provide appropriate clearance for the rails. [2]

$$W = \sum_{i=1}^{3} h_i \cdot b_i \cdot L_i \cdot \varphi \cdot \rho \qquad\qquad (2)$$

Depending on the local requirements on site, the storage tonnage should be considered and calculated using equation 2. In the equation, storage tonnage (W) is calculated by the long summation of the multiplication of average pile height (h_i), average pile width (b_i), average pile length (L_i), pile void factor (φ), and wood green density (ρ) where i is the index summation representing both cantilevers and span respectively with an upper bound limit of 3 and lower bound limit of 1 in this scenario.

Additional considerations must also be made regarding girder dimensions, lift height, and rail length. First, the cantilever length should not exceed or go below 0.20 – 0.45 times the span length to maintain an acceptable load distribution. When optimizing for unusually high storage tonnages, optimization should be started from maximizing pile height, then span length, and finally rail length. Increasing rail length typically increases average cycle times and should thus be the last option. In mixed storage long and short wood should be cycled to even out the average loading cycle. Furthermore, the process infeed point should be the center of operations and hot piling should be considered to maximize delivery flow and maximize operational efficiency. A hot pile is essentially a wood pile that is located near the

process infeed and unloading locations that is used to facilitate unloading efficiency by reducing the need to bring the wood to storage if it cannot be directly fed into processing.

$$S\% = 1 - \frac{a}{b} \qquad (3)$$

Storage circulation and turnover are both indicators of storage flow with the former showing a percentage of flow thru when compared to total storage flow while the latter give a value in days that gives a numerical value for how long raw material takes to reach processing from initial intake. These indicators are important for certain process and wood types. For example, eucalyptus tree must be processed within four weeks of logging, or the bark will harden too much for processing and debarking won't be possible until 6 months later. However, during those six months, tree rot will increase and there will be fiber loss, reducing the total yield [1]. Conversely in some cases it is desirable to allow wood to dry out before processing in which case a certain minimum should be reached before processing can take place. The average minimum flow thru of entire storage a percentage can be calculated using equation 3, where $S\%$ represents the average minimum flow as a percentage of entire storage flow, a represents truck receiving hours per week, and b represents mill infeed operating hours per week [2].

$$T = \frac{W}{IC \cdot S\%} \qquad (4)$$

Storage turnover time in days, T, can be calculated using equation 4, where W represents storage capacity as tons, IC represents mill infeed capacity show as tons/day, and the same $S\%$ value calculated in equation 3. [2]

2.4 Structural analysis

Structural analysis of the proposed crane configurations will be calculated using analytical methods, internal fatigue calculation tools, and possible FEM model calculations for a smaller selection of configurations. Analytical calculations should be used to get an initial approximation of the structure before heavier calculation is used for details.

Wheel load calculation will play an important role when determining the selected structure configurations that will be analyzed and calculated. Wheel loads is a quick preliminary calculation that can be used to determine whether a configuration satisfies the underlying boundary conditions. As previously mentioned, the individual wheel load on each wheel should be above 25 kip to guarantee necessary traction for the crane structure to move along the tracks without slipping. The wheel load must also be below 125 kip to safely remain within the bounds of fatigue life of both the rails and wheels alike. All crane configurations use the same standard wheel size and hardness; thus, it acts as a constant constraint and simplifies comparison of different configurations.

2.5 Crane design cycle

Traditionally, crane design follows a systematic cycle in an iterative way. A potential customer provides details regarding their pulp mill operations and available storage area. Requirements and constraints like production volume and physical available space give initial variables with which to start the design process. The first step is to calculate the storage requirements based on the customer specifications and create an initial SAP 2000 static model. Once the static model is given the green light for stability, a dynamic load model is created after which the results are exported to a fatigue calculation program called Log Crane. The dynamic model is iteratively designed until it can pass the requirements, after which the model is run through static analysis again to ensure that, even with the increased weight, the model is stable. Making changes to the model requires the whole process to start again, including static model creation. This same process must be repeated until a suitable approximation can be established, that can then be presented to the customer. This whole process is very time consuming, and many iterations are typically involved just to make an offer. This thesis aims to establish the groundwork with which this process can be streamlined, and initial approximations can be established more quickly. A graph comparing the traditional process and the process that is enabled by the tool is presented in Figure 2. Essentially the tool will replace the heavy calculations in the proposal phase and provide a good academic approximation which will give the customer an idea of the scale that is required to meet demands.
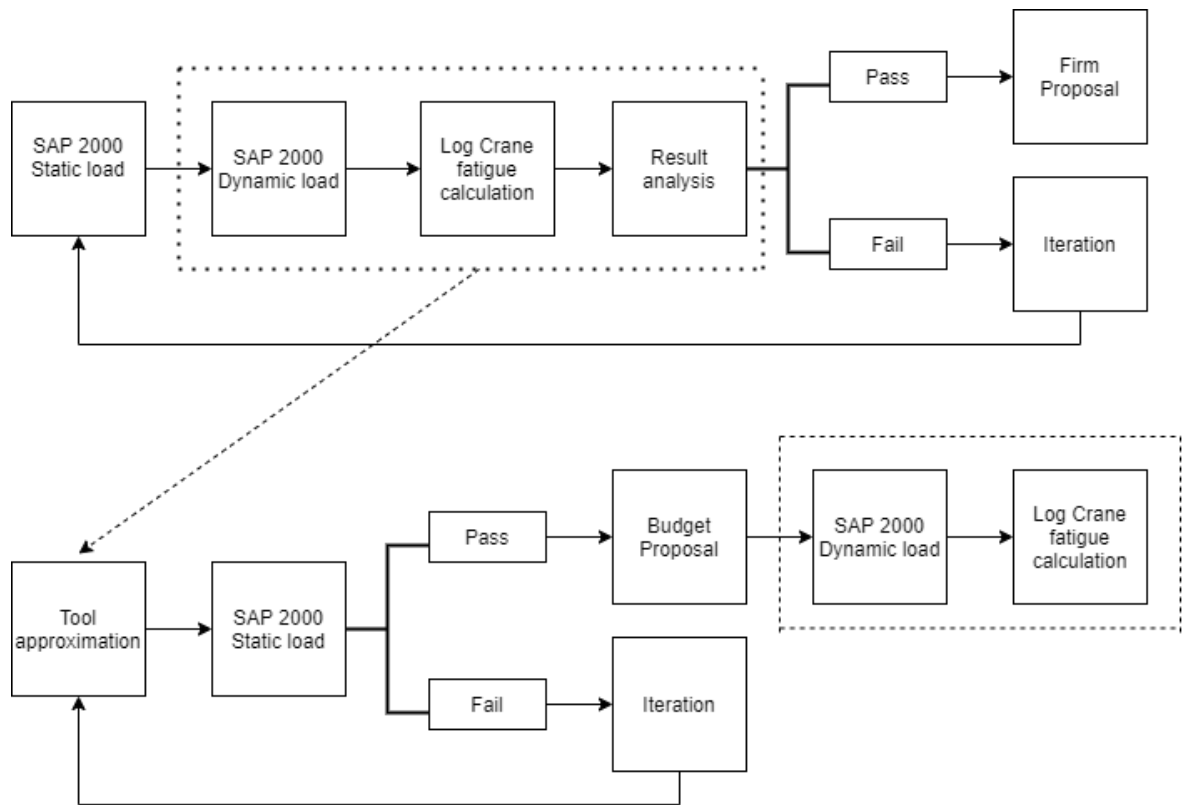
Figure 2. Flow chart of proposal process with portions of the topmost traditional cycle being replaced by the tool.

2.6 Crane model creation

To model several variations of the crane structure, a basic configuration must be created. The basic configuration should be representative of a typical crane structure and serve as a sort of blank from which all other models can be constructed. To that end, a modular design is desired to facilitate modifying the structure into other configurations. From the basic model, the different configurations are made by moving and/or replicating the cantilever portion of the model, removing a single modular section of the web, adding a pylon structure to the hinged leg portion of the structure, or a combination of two or more of the actions. In practice, all modifications will take place within the used FEM calculation program, SAP 2000. After the appropriate modification operations, the structure is loaded using an external excel spreadsheet that applies the fatigue loads along the length of the cantilevers and span. After these models are calculated and the results are exported into Microsoft database files used for further calculations. The basic idea of this process is to start to create a database for the new cross section without years of experience and historical data.

The database files, along with files containing stress concentration factors, are then used in the log crane program to calculate fatigue life. The process at this point is a straightforward and consists of initial importation of the database files and stress concentration coefficient files into the system. Next, a usage spectrum is defined by the user with which the program can create loading amplitudes to be used in the calculations. Next the stress concentration factors are checked and can be modified, however this is usually unnecessary if the coefficient files are working. After this, perhaps the most important interface is presented in which the used must define the operating parameters for the crane that is being calculated. This section has perhaps the largest variability depending on the use case and operational strategy of the specific plant in question. Briefly put, the operating values include key values such as operating and wood receiving hours per day, and similarly their corresponding values in terms of days per week.

The penultimate step requires that the user defines the leg positions of the hinged and fixed leg according to the model and places the plant infeed, truck unloading, and wood pile locations in their respective positions. It is important to place these values correctly to avoid calculation errors. An important thing to note, specifically when placing the wood piles, is that a suitable balance should be struck in the total number of piles because while increasing the number of piles gives more accurate results, each pile simultaneously increases the calculation time considerably. In practice, it is often a good idea to first to verify that the model works with a single pile before doing heavier calculations because even with a single pile the calculation can still take upwards of 20 minutes. Finally, before starting the calculation process, the name and location of the file to which the results should be written to is selected.

The output file containing the results of the fatigue calculation present the data for each load case in terms of fatigue life (cycles, days, and years) for each specified joint and location along the beam that is specified. Because each model is made from an identical blank, it is possible to directly compare the results of different calculations because they all have identically labeled joints and hot spots. The only exception to this is the case of the double cantilever structures where the copy of the original model requires that the joints are relabeled. Similarly, the reverse single cantilever structures will have identical names to their counterparts, however, it must be noted that the physical location of those points along the

cantilever section are on the opposite end of the span. It also follows the critical point where the cantilever is connected to the modular section integrated into their corresponding leg is named according to the leg it is attached too.

The main load case to be studied is one in which the process infeed and the truck unloading happens under the same cantilever beam. This serves a dual purpose by addressing the most time efficient configuration as it relates to plant operation, and this also happens to represent the most demanding load scenario for the structure. In some cases, namely the double cantilever configurations, a variation of this load case will be calculated in which the process infeed and truck unloading are conducted on opposite ends of the crane under their corresponding cantilever section. The result of these calculations will provide a very possible scenario for certain plant layouts but also give an opportunity to compare the effects of a pylon structure on the non-pylon reinforced leg due to increased stiffness in the span.

Once all the calculations are finished, the results will be compiled and grouped by configuration. Fatigue life analysis results will be used to determine which configurations have the longest fatigue life and how span length affects fatigue life in both single and double cantilever configurations. These results will be used to provide guidance in the tool creation phase where fatigue life will be one of the variables when the tool presents possible solutions for the given inputs. Finally, the results of cantilever analysis will be studied to determine what is the maximum standard cantilever length that does not break the boundary conditions and all results will be compared to customer requirements.

2.7 Tool creation

The tool creation process will consist broadly of idea generation, data collection, the exploration of methods and determining the variables and principles that it will consist of. The main function of the tool is to give product dimensions, from crane size to storage area based on customer inputs. The most important first step is to consider what the tool needs to achieve and what is needed to achieve those needs. Furthermore, those variables and needs should remain flexible throughout the process to accommodate for changing circumstances in the development process. To achieve the required flexibility for the undertaking, the basic principles of the tool should be well established and understood, so that their application can readily pivot towards a new direction if need be. This is not to imply, however, that the

development process, regardless of flexibility, should neglect the key guiding principles that are to be established.

Regardless of the implementation, the tool should serve as a platform that provides guidance to sales staff when offering products without requiring direct input from designers, provide a platform from which data pertaining to the dimensioning of the woodyard can be derived, and finally presenting that data in a visually appealing way that is easily digestible by potential customers. To that end, the development process can be approached from two paths: customer to user or user to customer. In the customer focused approach, the needs and wants of the customers should be addressed with the tool by working backwards from what should be presented to them to make a purchasing decision. Conversely, the problem can be approached from the user's perspective, i.e., what does the salesperson need to surmise the customers' needs and what can be done with the available data to fill in several unknowns?

It is, perhaps, unreasonable to base the entire project on assumptions of customer needs when, in this case, the market is an entirely new one. Conversely, creating a tool with a scattershot approach that attempts to fill in all potential holes and answer questions that have not, or may not, even been asked risks unnecessary complexity for a simple tool. So, this thesis will pursue a hybrid approach in which features of both methods are studied to determine a suitable compromise. This will allow for greater coverage while keeping the tool simple, yet flexible. In this way, the variables and datapoints determined in the previous sections of this thesis will be used to determine what can be calculated or predicted using historical data, but those calculations will be tempered by what customers will likely need or want to know. To that extent, this should allow for a tailored presentation to individual customers using the same data and calculations.

The tool creation process will start with brainstorming and determining which inputs should be used to achieve the desired outputs. With a vast amount of information needed to produce a specific output, it is important to select the correct constraints. Otherwise, there are too many variables that must be selected manually each time, defeating the purpose of the tool. Additionally, the brainstorming phase should search for different methods that can be used to achieve the set goals of the tool.

Once the general outline of what should be counted, with what, and how; prototyping of the tool will be conducted through trial-and-error testing of various methods. The end goal of this process being the development of a rudimentary proof of concept tool that provides a practical glimpse at what and how the tool should function when it is finalized. The entire tool creation process will be presented in its own section.

2.8 Modular design

A modular system is designed to make a whole out of different standardized components that can be assembled to achieve different tasks [3]–[6]. A modular design should allow for the core product to be customized to individual tasks by assembling individual components into a functional whole that suits the task [3]. In fact, flexibility and customizability are two of the key benefits of modular systems according to Tseng and Wang [7].

The flexibility gained from modular design is present in not only the different ways a product can be assembled, but also enabling the assignment of responsibility of different modules to different teams [6]. This can be especially useful in systems and products that require different fields of expertise. According to Salhieh and Kamrani, modular design attempts to reduce interdependence between different sub problems, so that changes in individual modules have a minimal effect on the whole [5].

The modular design process can be divided into four steps: needs analysis, requirements analysis, concept analysis, and concept integration [5]. Need analysis entails gathering information from the customer the needs and limitations for the product, by using different methods and available resources. In this thesis, for example, market analysis and interviews with Andritz employees will serve this purpose. Requirement analysis uses the data gathered in the needs analysis phase to produce functional objectives and their constraints that will guide the design process. Essentially, this phase consists of determining what is required to satisfy the customer specifications. The concept analysis phase further breaks down the functional objectives into individual elements. This includes defining the function of these individual components as well as their purpose. Finally, concept integration is assembling the components together to achieve the originally set tasks. [5]

3   PORTAL CRANE OPERATION IN PULP MILLS

Woodyards manage storage mainly using three different crane types: Portal cranes, circular cranes, and jib cranes. Different Andritz crane types are presented in Figure 3. In the past, the earliest and most prominent crane type was the jib crane, however, they have been largely replaced by both circular cranes and increasingly by portal cranes. Jib cranes provide a simple and convenient option but there are severe limitations in terms of lifting capacity and range that do not allow them to be scale with an operation without adding additional cranes. Even then it can quickly become cumbersome and unreasonable to operate.
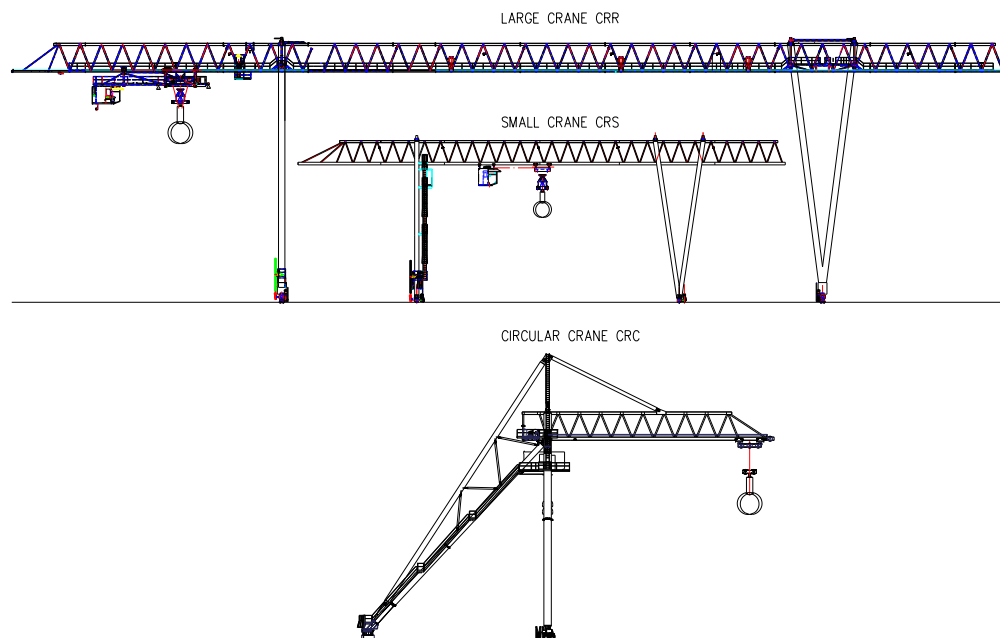
Figure 3. Andritz portal cranes in two different sizes and a circular crane.

Circular cranes on the other hand are suitable for medium sized storage space and several such cranes can be operated if the plant allows for the intake system to be built within the cranes reach. Circular cranes, however, are limited to long wood and are limited to a set storage capacity which cannot be increased. Portal crane on the other hand, are suitable for the largest storage requirements and are most easily modifiable to customers' needs with clear bins areas for different purposes available.

3.1 Structure of a portal crane

The main structure of a portal crane is made up of a fixed leg, a hinged leg, a span section, and a cantilever section. The crane gantry is made up of the aforementioned parts and is used to move the structure along the rails. The trolley is attached to the bridge of the crane and moves perpendicular to the gantry. Together, the gantry and trolley of the crane create the movement that is required in the woodyard to store materials and feed material into processing. The legs of the gantry rest on rails using large trucks that support the structure and facilitate movement.

Both the hinged and the fixed legs support the structure vertically, but the fixed leg also constrains lateral movement along the bridge axis. The hinged leg consists of two beams configured into a triangular shape, presented in Figure 4.
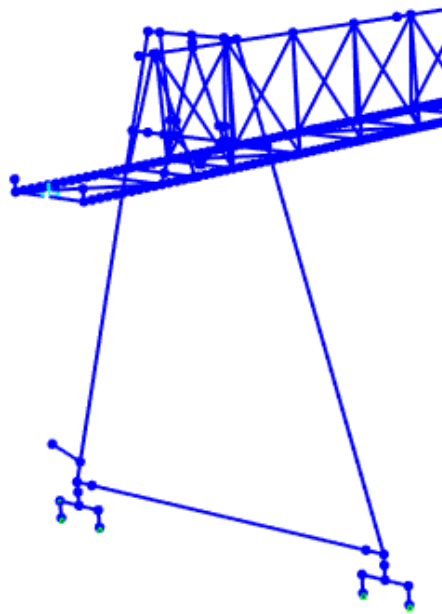
Figure 4. Hinged leg beam configuration with triangular shape resting on trucks.

The fixed leg consists of four beams that form a similar triangular shape along the same axis as the hinged leg, but the additional beams on either side also create a funnel shape on either side (Figure 5).
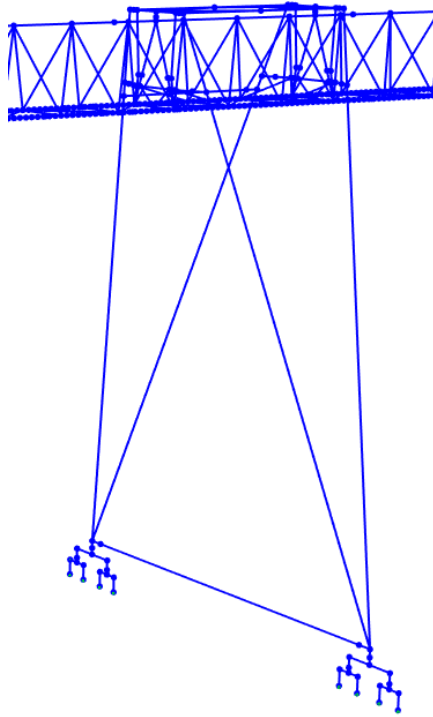
Figure 5. Fixed leg beam configuration with funnel shapes to constrain lateral movement.

The hinged leg effectively facilitates the gantries movement along the rails by providing additional degrees of freedom that accounts for possible skewing and rail eccentricities. Additionally, the hinged leg reduces the stress generated in the structure when loading and unloading the structure as well as global movement cause by heat by rotating with the hinge. The fixed leg, conversely, provides stability, enabling it to keep from tipping over during its work cycle and withstand wind loads from all directions.

The end trucks allow the gantry to move along the rails as well as carry the load of the entire structure. The trucks must be able to carry the rated load when it is carried on the extreme ends of the bridge, and have a wheelbase of at least 1/7 of the length of the cranes span [8]. Typically end truck arrangements are selected with either equalizing or compensating 8, 12 and 16 wheel configurations [8].

The trolley is installed onto the girder structure of the crane and facilitates the lateral and vertical movement of the logs. To do this, the trolley houses the grapple and its prerequisite hoist drum, with control of the whole system residing in the connected operator cabin attached to the trolley (Figure 6).

Figure 6. Portal crane operator cabin and grapple trolley docked at fixed leg. [9]

Wood is typically delivered by truck or train under the cantilever beam closest to the process infeed. However, this is not always the case due to logistic or layout constraints that may in some cases force the unloading to take place under the cantilever beam on the opposite end of the crane bridge. In theory, unloading can take place at any point along the bridge (except directly under the legs due to the track), but in practice, it is preferable to reduce the travel distance from unloading to infeed processing. This is simply due a desire to reduce trolley and gantry travel time, directly affecting the process time that is achievable. Furthermore, during delivery hours, logs are often fed directly into infeed processing or placed on a hot pile near the infeed to expedite delivery throughput.

3.2 Typical pulp mill layout design

At the most basic level, a crane operated woodyard only requires four basic elements: a material delivery method, a gantry crane, a material storage space, and a process infeed. Layout design starts from the material requirements to reach a specified production volume. Through that the storage requirements can be calculated based on how much raw material needs to be stored to ensure that production can continue when material deliveries cannot occur due to extenuation circumstances or region-specific seasonal characteristics. Next, based on the storage size, the crane specifications can be calculated, including the number of cranes that are required to meet demand. Finally, the logistical organization of wood delivery must be determined. The logistics of material delivery are constrained by geography and practicality, and the rest of the layout must be built around those conditions while satisfying production demands. Essentially, even approximations require solving the problem from both the start and end point simultaneously.

A typical woodyard layout will, ideally, have both the process infeed and wood unloading location at or near the center of the storage area. This setup provides the benefit of minimizing movement requirements when feeding the process directly from the trucks and reducing the maximum required gantry movement with its central location. Near the process infeed, a hot pile is typically maintained to quickly unload trucks. The hot piling effectively maximizes material delivery throughput while reducing the need for the crane to move the trolley into the storage area to put in or take out logs. Hot piling benefits the process by reducing the need to reorient log piles with the grapple for piling, effectively removing two rotations from the work cycle when compared to truck to storage to process. A typical basic layout is presented in **Figure 7**, where the unloading locations (**Figure 7**a), crane (**Figure 7**b), storage area (**Figure 7**c), and process infeed (**Figure 7**d) are highlighted.
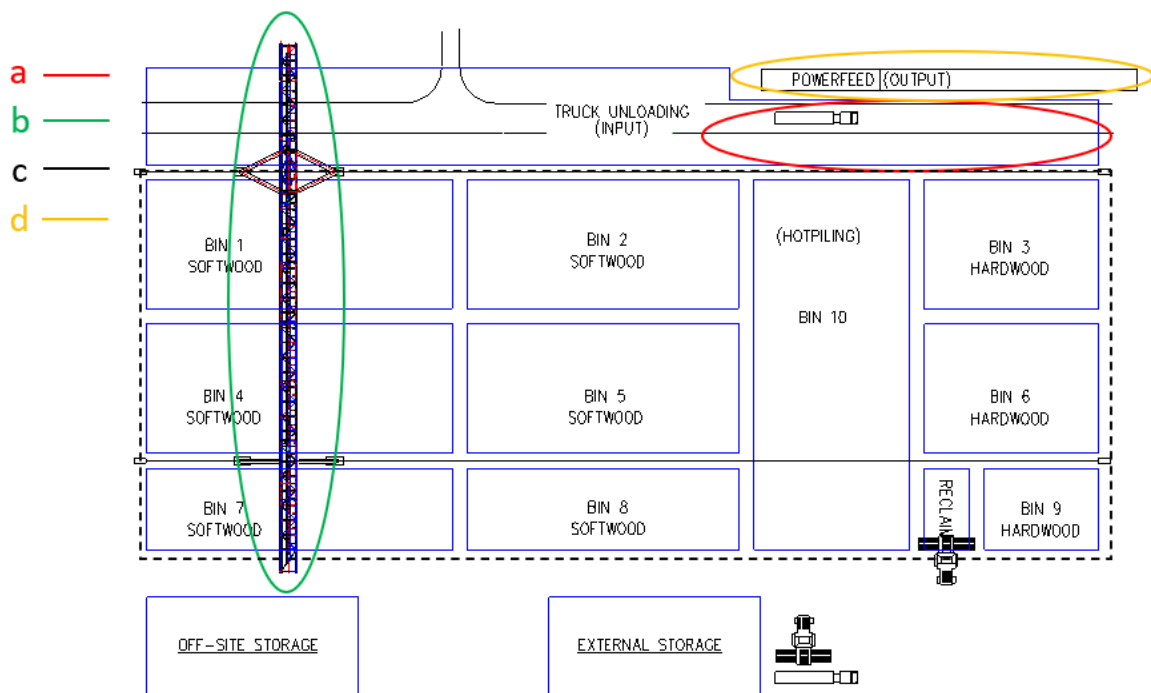
Figure 7. A typical woodyard layout with key portions highlighted: a) material unloading area. b) woodyard gantry crane. c) storage area bins with reserved area for hotpiling near the process infeed. d) process infeed location.

4   FEM AND FATIGUE CALCULATIONS

Finite element method calculations of selected models will be conducted using SAP 2000. Both static and dynamically loaded models are calculated withing SAP 2000. A "blank" model will be imported into SAP 2000 which will form the basis of all further calculations. This model will be modified within SAP 2000 to create all selected configurations for calculation. The different models will be modified by adding, removing, and mirroring different modules of the original model. The span section modification will be done by simply removing or replicating modules that each represent a 10 ft (3.048 m)
section of the span webbing. Using this method 145, 175, and 215 ft span lengths will be created. Similarly, each span length will be calculated with one and two cantilever configurations.

The base model is a 175 ft span section with an 80 ft cantilever (Figure 8) on the fixed leg side. Three versions of each span length will be created, one that corresponds to the original blank model with a cantilever on the fixed leg side, a cantilever on the hinged leg side, and finally a double cantilever model with an identical cantilever on both the fixed and hinged leg sides **Figure** *9*. With three versions of three span lengths, the total number of models will represent nine total configurations to be calculated.
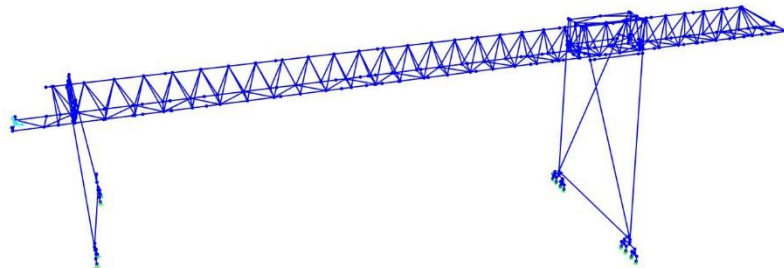
Figure 8. Basic blank configuration from which all models are modified.

Using this method, each model can retain the same joint and node groups, which in turn allows for direct comparisons between the models to be made during analysis. However, to allow for this, it is difficult to create models of arbitrary lengths. This is because the span must be gutted at certain points that do not contain any of the grouped joints. Furthermore, this also shifts the relative position of the grouped joints around so that creating entirely identical models is not possible in this case. In this case, however, it is sufficient due to the approximate nature of the calculations and their use.
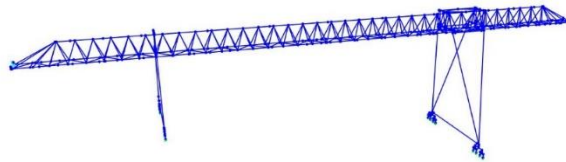
Figure 9. Double cantilever configuration of base model.

Mirrored hinged cantilevers on the hinged models are mirrored from their fixed counterpart, including the join groupings. Conversely, in two cantilever configurations the mirrored cantilever section is identical apart from the mirrored groupings are renamed. Great care in the modeling phase must be taken to ensure that the mirrored and replicated cantilever sections result in a length when summing the span and cantilever sections in both the fixed and hinged leg configurations.

4.1 Material and element model

An identical material mode was used for all configurations. The model was made using standard beam elements of varying geometry. The various components are mainly standard components made from S355 steel are selected to suit specific loading conditions in the structure. Rigid elements were used in the pylon connection so that the nodes on either end

of the connection of the pylon and legs follow one another. The exact selections are not discussed in this thesis.

4.2 Load placement

The models are loaded using an excel document which automatically calculated the load locations for fatigue loading. However, the loads for the static load are placed manually to get the correct trolley position for deflection and wheel load analysis. The document works by first inputting the total length of the span and cantilever sections in millimeters and allowing the document to calculate the placements. The document takes the total length of the structure and applies a fatigue load in 304.8 mm increments along the bottom chord of the bridge. The chords along which the loads are placed are presented in Figure 10, where the bottom chords are highlighted in red.
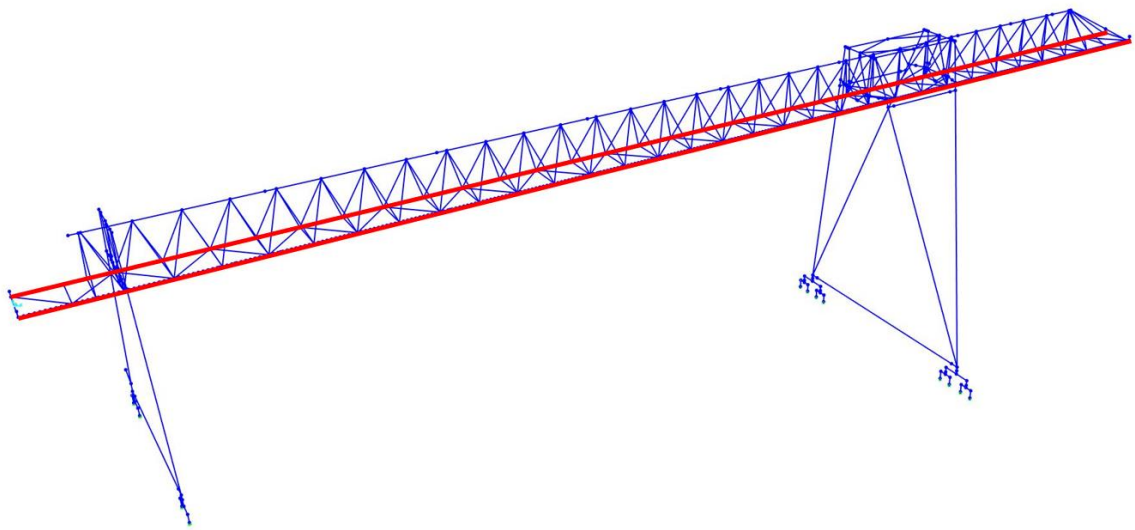
Figure 10. Bottom chords along which loads are placed highlighted in red.

The load placement at each increment is an identical load pairing on both bottom chords in increments of two. Meaning that two sets of parallel loads of -50 kN are placed along the chords followed by two pairs of -100 kN loads. This pattern is followed along the entirety of the bottom chords along their length and simulates a crane configured with two grapples attached [9]. This results in a loading pattern that represents the load carried by the gantry at each interval along the entire length of the structure so that a large range of loading cases can be explored later with fatigue calculations.

4.3 Analysis type

The analysis that is used in all the models is a simple linear elastic analysis considering only the applied fatigue loads. Modal loads and dead loads are not considered in the FEM analysis section of this thesis. After running the analysis, the results are checked at randomly selected load locations along the model to make sure that the structure behaves correctly. The results are not analyzed beyond checking for consistent behavior withing SAP 2000, but rather exported into a database file. The models' working units need to be changed from kN, mm, C to Kip, ft, F before exporting can take place due to the constraints of the fatigue calculation program. For further analysis, the data that needs to be exported form the analysis results are as follows: frame section properties, section designer properties, load pattern definitions, group data, load case definitions, connectivity data, frame assignments, and element output (excluding element stress results). The table settings used are presented in Figure 11.
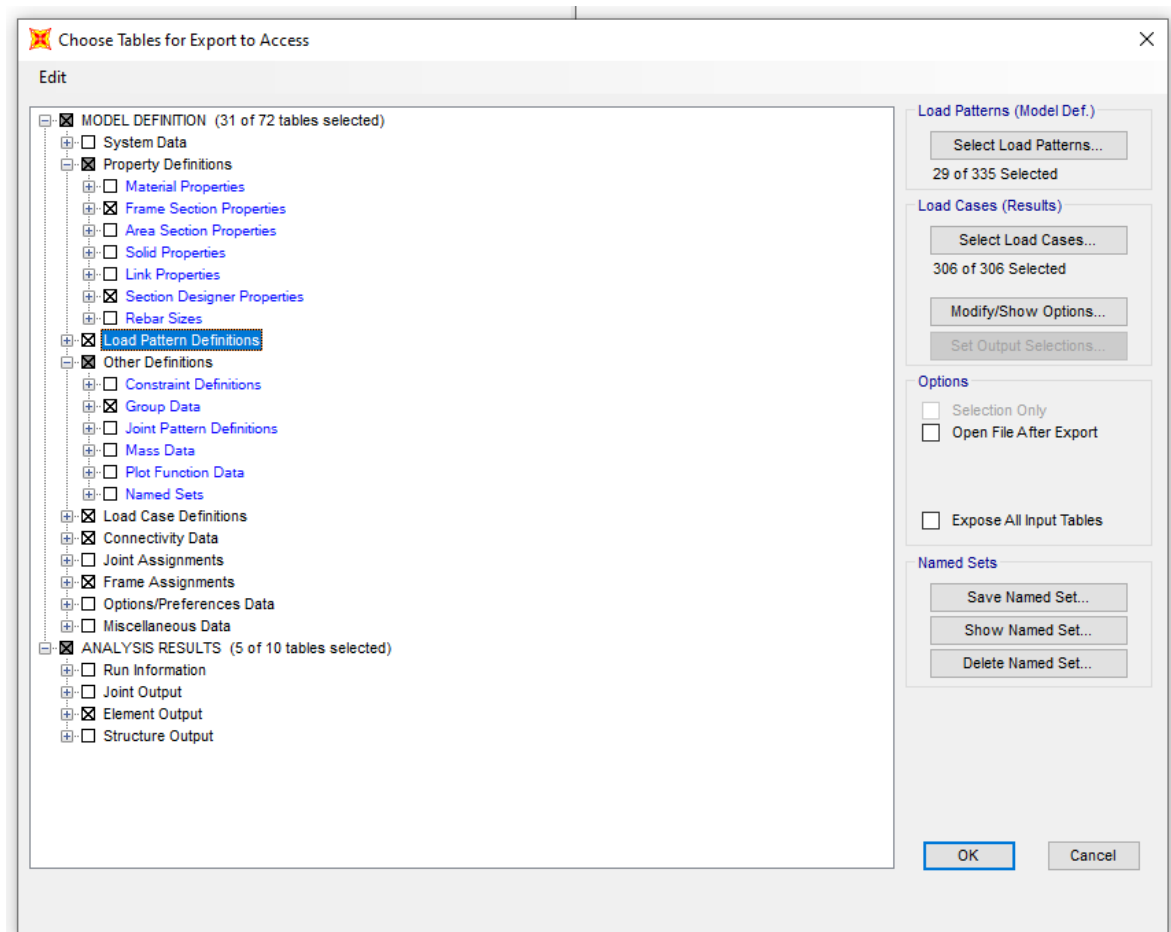
Figure 11. Table selections for database export.

4.4 Fatigue analysis

Fatigue analysis is conducted using internal software specifically developed for portal crane calculation. LogCrane was developed internally for the purpose of quickly calculating and analyzing different crane structures within the specific use cases of log yard management. The process begins with importing the SAP 2000 database created earlier along with a table containing the stress concentration factors (K_s values) used in the fatigue calculations. The program calculates the K_s values automatically based on plate thickness, material pairing and joint type from a database of hundreds of combinations.

Next the load amplitude is determined by defining the individual pile and truck pick values. Individual total percentage of picks and their corresponding pick rate percentages are defined. Picks percentage defines the percentage of total picks that their corresponding rating percentages represent, and the total must equal 100%. Conversely the rated percentage defines the coefficient by which the load will be multiplied by for its corresponding total percentage. Using these inputs, the program creates a rain flow analysis on the girder based on the layout, which is one of its most important features. The individual values for piles and trucks create a loading amplitude with which the program will calculate the fatigue life of the structure. After this step, it is possible for the user to modify individual KS coefficients if desired, but in this case, fine tuning was not carried out.

Next, crane operating values are entered into the software, corresponding to some of the equations presented in section 2.3 of this thesis. Crane rating in tons and wood usage in tons per day are entered in first. Next, wood receiving and mill operating hours per day are entered along with wood receiving and mill operating days per week. The program then uses those inputs to calculate storage cycling rate and the required truck values to achieve those figures.

In the final phase before calculation, a 2D model of the crane is presented and the user places individual piles, trucks, and decks along the length of the structure. The program will then use those placements to determine at which joints the loading process will take place. All configurations used a similar placement. Because there, are two cantilever and one cantilever configurations as well as differing span lengths, the placement needed to be made more compact to accommodate all the pile and truck placements.

In all models, the wood infeed deck was placed under the main cantilever beam along with a single pile to represent a so-called hot pile. Four piles were placed under the span in single cantilever configurations, while three were placed there in double cantilever configurations, with the fourth pile placed under the secondary cantilever beam, so that it does not go unused in the calculations. An illustrative figure showing the setup in a double cantilever configuration is presented in Figure 12, where D is the infeed deck, T represents truck unloading locations, and P represents individual log piles. Additionally, the dark vertical lines represent the legs of the crane, the horizontal line represents the girder, and the lighter gray lines represent where the cantilever beams end. Usually, trucks are placed under either cantilever beam near the process feed deck. In this thesis, however, two trucks were placed under the span between the hinged and fixed leg. The standard practice was deviated from as it is a special case that has been used as a real-world solution within the company. Furthermore, it is convenient when comparing different configurations to reduce the number of variables that deviate between each model.

Type	X	Usage %	Description
Deck	52	100	
Pile	51	22	
Pile	110	22	
Pile	152	22	
Pile	247	17	

Name			
Description			
Length	390	Span	215
HL	80	FL	295
HLCantilever	80	FLCantilever	95
TrolleyWheelSpan	24		
TrolleyWeight	85		
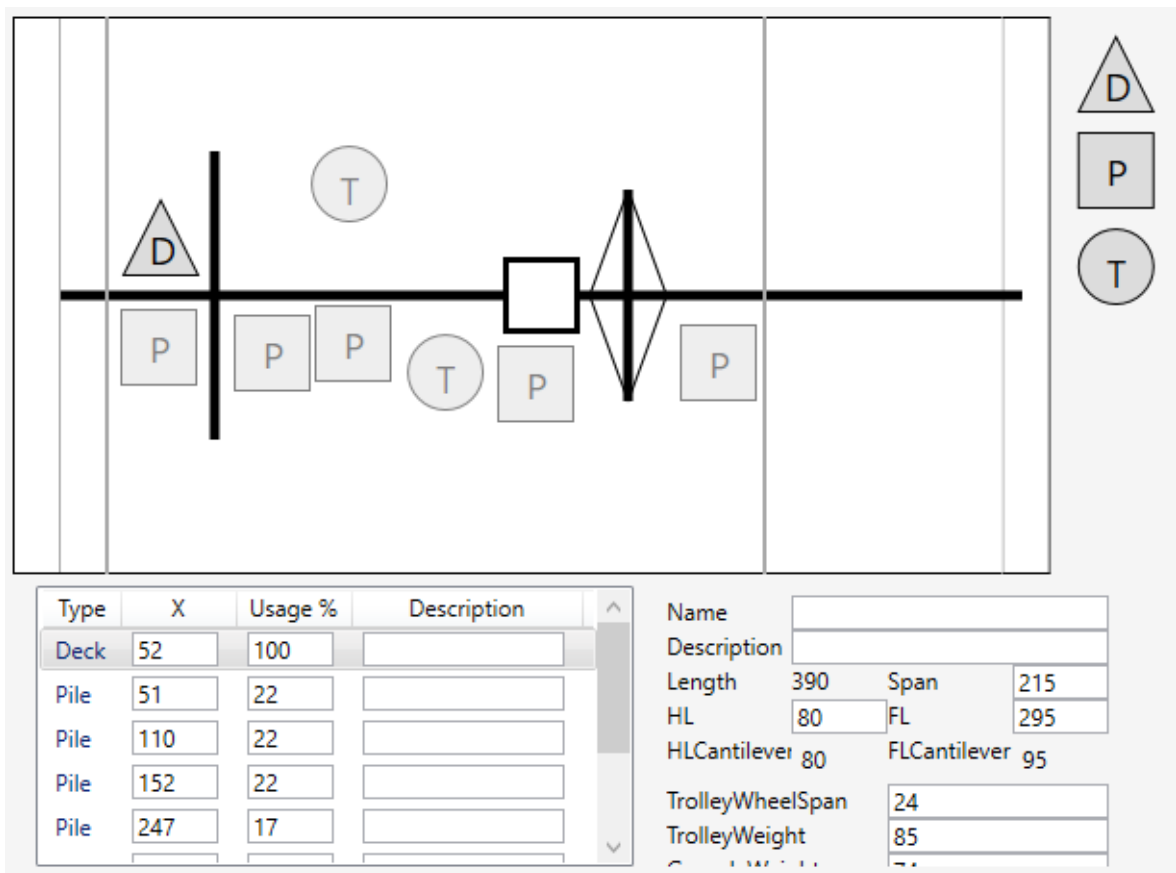
Figure 12. Deck, truck, and load placement used for fatigue calculation.

The program follows three main phases during calculation: data processing, tension calculation, and processing cycles. The first phase takes the imported SAP 2000 data and creates a table which includes all the required members and their forces. Next, the program calculates influence lines for all the selected joints. Finally, the program executes a rainflow analysis, classifies stress amplitudes, and calculates the fatigue at the selected critical joints using the hot spot method.

In earlier attempts a truck was placed under the cantilever beam with the deck and in the case of double cantilever configurations, under either cantilever beam. The previous solution was chosen because it required moving only the deck to either end of the cantilever to the opposite end where the primary cantilever is located.

4.5 Boundary conditions

In addition to the minimum and maximum wheel load limits of 25 kip and 125 kip respectively, additional constraints regarding maximum deflection are taken from CMAA 70 and standard practices. The maximum deflection of the girder span is equal to $L_S/888$, where L_S is the total length of the span section of the structure [8]. An additional maximum deflection is imposed on the cantilever section of the crane equal to $L_C/150$, where L_C is the total cantilever length of the individual cantilever section being calculated.

Additionally, the scope of finite element and fatigue analysis was limited to only a few different span and cantilever lengths. Span lengths of 44 m, 53 m, and 65 m as well as a cantilever beam length of 24,4 m were chosen for fatigue analysis. Additionally, a 27,4 m long cantilever beam was chosen to study the effect of a large standard cantilever beam without extra supports.

4.6 Wheel load

The wheel maximum and minimum wheel load was calculated by loading the model with a deadload representing the self-weight of the structure in addition to the trolley and hoist loads placed on the extreme ends of the structure, directly on top of the hinged and fixed legs, and directly in the middle of the structures span. The maximum wheel load from the applied loads was selected for both legs and were then summed with the wheel load cause by the structures self-weight to determine the maximum wheel load. Similarly, the minimum

wheel load was determined using the same methods, however in more constrained conditions due to practical considerations.

The minimum wheel load is set to ensure sufficient friction between the driven wheel and the rail to avoid slippage. Similarly, the structure must also be able to resist slipping during high winds. The gantry is only moved along the rails when the load is under no longer outside of the gantry's legs, therefore the minimum wheel load should be determined only from the minimum position from which movement is allowed, when the load is directly above either leg. In that position, the minimum wheel load during movement can be determined from the support reactions in the wheels on the opposite end of the loaded legs. All wheel loads were analyzed using imperial units, more specifically *kip*.

4.7 Deflection

The maximum deflection of the span section occurs when the full load, including the trolley, is directly in the middle of the span. The deflection caused by the structures' self-weight at the middle node is summed with the deflected caused by the rated load in the same position to determine the maximum deflection. Similarly, the maximum deflection in the cantilever sections is determined by placing the load at the extreme end of the cantilever.

4.8 Cantilever design

A persistent problem with crane design is choosing the correct cantilever length. The choice isn't as simple as a cursory inspection of the required dimensions. The size of the cantilever has a considerable effect on the structures weight balance and wind surface area and span section life. The structure must remain balanced to conform to the wheel load limits while remaining structurally capable of handling the rated workload. Similarly, the additional surface area can create issues for the structure outside of structural integrity. The increased wind surface area can cause skewing in high winds. All deflection analyses were conducted using metric units.

The weight problem can, of course, to some degree be accounted for by increasing the number of wheels and the wind surface area problem can be countered with additional motors on the wheels [9]. Increasing wheel size does not provide a substantial benefit when compared to increasing the number of wheels because the selection is made between only

two standard sizes, whereas the number of wheels can be increased. Increasing the number of wheels immediately reduces the proportional load carried by an individual wheel, but the number of wheels can only be increased to a certain point after which minimum wheel load restrictions begin to apply [9]. However, as is often the case in design engineering, those solutions bring their own difficulties with them. Changing the wheel size mean a deviation from standard part selection while adding motors to the wheels further increases the wheel load.

Perhaps the most reasonable solution within the scope of this thesis is to simply determine the maximum cantilever length that remains within the constraint parameters that are determined for the analysis. This is done by analyzing the initial results using the standard cantilever selection, selecting ones that are not too near the limit, and finally calculating the model using a larger standard cantilever section to ensure that it is applicable.

An additional pylon reinforced model (Figure 13) is created for comparison purposes. Pylon reinforcement should increase rigidity and allow for cantilever lengths even longer than the standard sizes that are typically used. However, the pylon reinforced model is likely to break the boundary conditions set for all other models, but will provide an interesting comparison, not only of the pylons effect on wheel and wind loads, but how it affects the structures fatigue life.
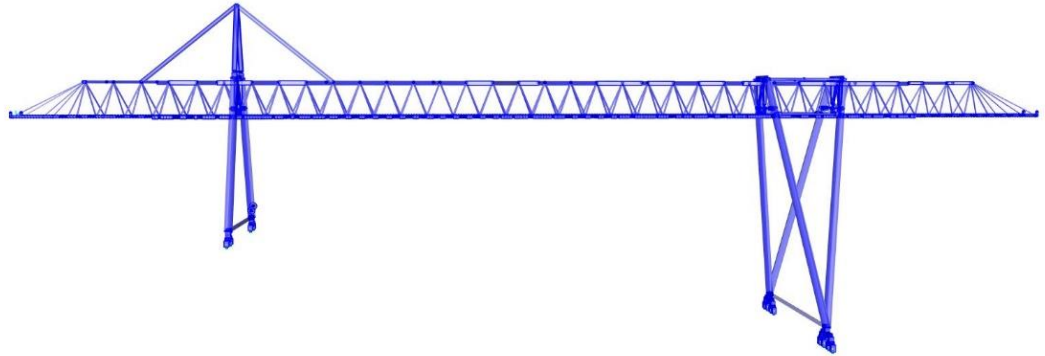
Figure 13. Pylon reinforced double cantilever configuration.

SAP 2000 allows the user to quickly select or change between units, between imperial and metric for example. This feature facilitated the calculation of wheel loads using imperial units and analyzing beam deflections using metric units within the same model without having to recalculate the entire structure. Without this feature, the analysis process would prove to be disproportionately cumbersome relative to the desired outcome of each analysis. This would have invariably led to a far smaller range of configurations that could be analyzed within the scope of this thesis.

5   MARKET ANALYSIS

Market analysis of pulp mills operating outside of the NA (North America) region is a large undertaking and requires diligent analysis of market trends and current operations around the globe. So much so that an entire thesis could be dedicated to such a broad scope. To better suit the purposes of this thesis, the scope of the market analysis must be carefully constrained in a way that the market research section both serves the purposes of the thesis, allowing for the following sections to be conducted as well as remain manageable in scale to avoid dedicating an unnecessary amount of time and resources for its completion. To that tend, the market analysis should focus only on the pulp mill operations that use short wood as their raw material. Furthermore, a specific region must be identified towards which all efforts should be focused.

The region that is to be selected should meet certain criteria to be considered. Of course, the main condition should be that it is a region in which investment into autonomous portal cranes either immediately or soon should be reasonable. The feasibility of such an investment is determined by several factors including labor costs, plant size, operating strategy, education level of workforce, codes, standards, and laws. In practice the investment decision can be boiled down to labor, operation scale, and laws. Each section should be considered individually but are also not mutually exclusive in that each consideration must be positively resolved for the region to be considered moving forward. So, for example, if the labor cost is high and the operation is on a very large scale where autonomous portal crane operation would make sense financially but there are laws in place prohibiting its use, that region is outside the purview of the research. Furthermore, future potential is also not to be considered within the scope of this work, at least beyond the typical lead time of a portal crane as of the completion of this thesis.

Labor related considerations are perhaps the most immediately tangible deciding factor. Because the investment is large, the profitability in the long term of the investment is highly dependent on savings of which a large amount consists of reduced man hours. If for example, you can reduce your work force operating on a single shift from 20 to 5, the benefit is directly proportional to the labor costs related to the reduction of manpower requirements. Indirect

costs associated to the reduction should also be considered in cases where in addition to a reduction in operating staff, the machinery being operated is also made redundant. Redundant machinery in turn reduces maintenance costs and fuel costs directly, providing a multiplicative effect in certain instances. With those considerations in mind, it becomes apparent that in extremely low wage environments where fuel prices are also lower, there may never be a break-even point when making such a large investment when compared to more traditional methods, at least in the short term. In some cases, there may even be the implicit expectation for "good company behavior", which would obligates the pulp mill to employ local villagers, which may further complicate the matter [1].

Another factor that should be considered relating to labor, is the general education level within the target region. When moving towards automated systems, the manpower requirements are reduced but conversely the remaining manpower must make up for it with a higher education level to monitor and operate the new machinery. This is not a problem in some regions like western Europe for example, but in other instances it may not be a practical expectation to find suitable candidates to operate the machinery in less developed regions that, in many cases, are far removed from the areas where the more educated populace resides. It is not reasonable to solve a problem that doesn't exist at the expense of creating a new problem that wasn't there before. Cultural differences should also be considered when making this assessment. High tech machinery not only requires a more educated workforce, but continuity and institutional knowledge to operate efficiently in the long term. If you can get qualified individuals to operate the machinery, can you also retain them long term? An autonomous portal crane woodyard requires a readily available and qualified local workforce to be a sustainable investment long term and to mitigate labor risk.

The European region can be split into three sub-regions: western Europe, eastern Europe, and Scandinavia. Of these three regions, Scandinavia accounts for the bulk of pulp production in the region producing over 45% of all pulp in the region followed by Eastern Europe and Western Europe accounting for 35% and just under 19% respectively. Scandinavia has a notably newer plant population when averaging operation start dates in 1994 average start rate compared to considerably older averages of eastern and western Europe in 1985 and 1984 respectively.

Total pulp production is still greater in Europe, where the Nordics are the largest producer, followed by Eastern Europe. The total yearly pulp production by region is presented in Figure 14, where LA represents South America and EU represents the entire European region. WE, EE, and SC represent individual components of the EU total representing Western Europe, Eastern Europe, and the Nordics respectively.
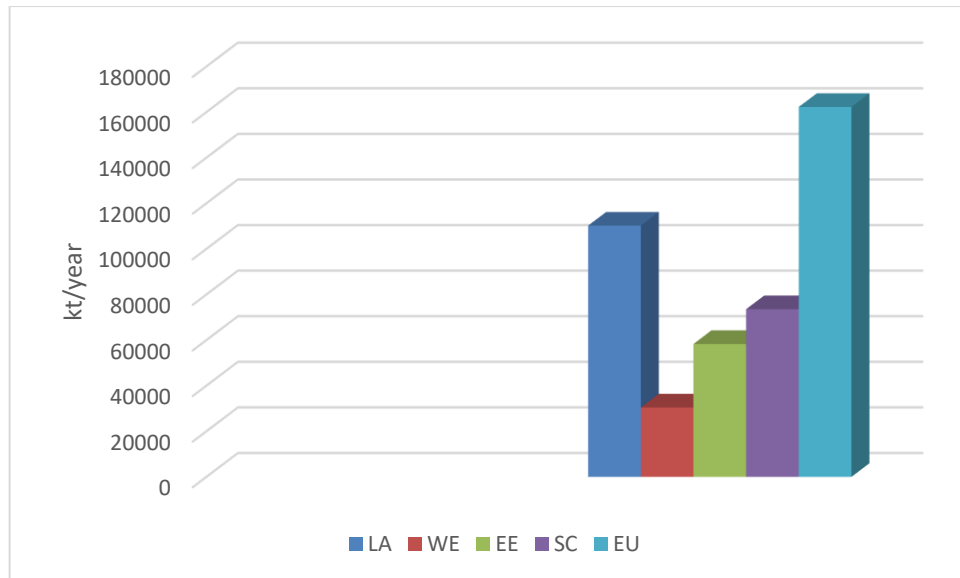
Figure 14. Total pulp production in South America and Europe.

Interestingly, average pulp production favors South America, where the data suggests that large scale production is greater than either Eastern Europe or the Nordics. Western Europe seems to be the opposite, where both production and average production volume are both low. The average yearly pulp production is presented in Figure 15.
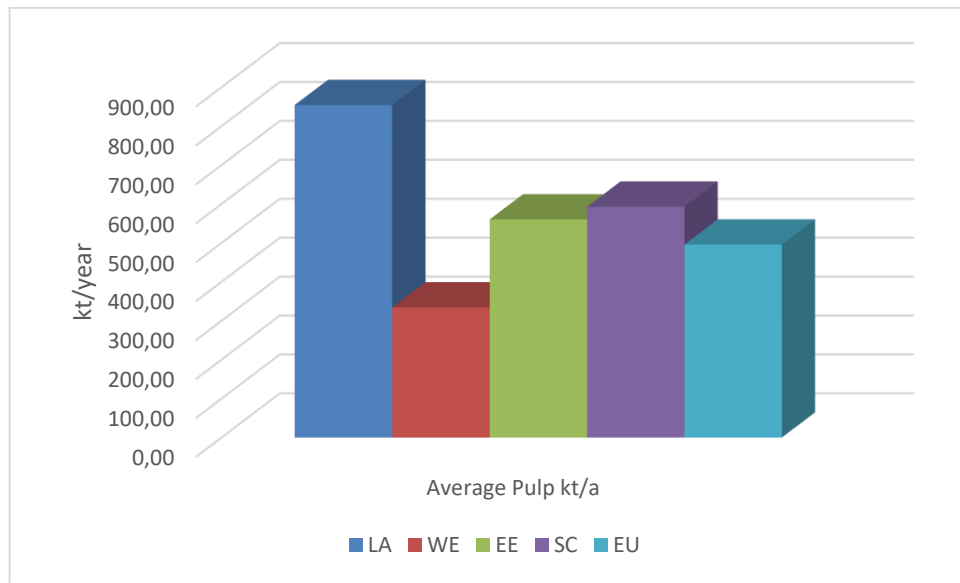
Figure 15. Average pulp production of pulp mills in South America and Europe.

It is noteworthy that the two largest regions by production volume also represent the regions with the latest average start up time, suggesting that newer technology continues to play a significant role withing the industry. The average startup year of plants within each region is presented in Figure 16.
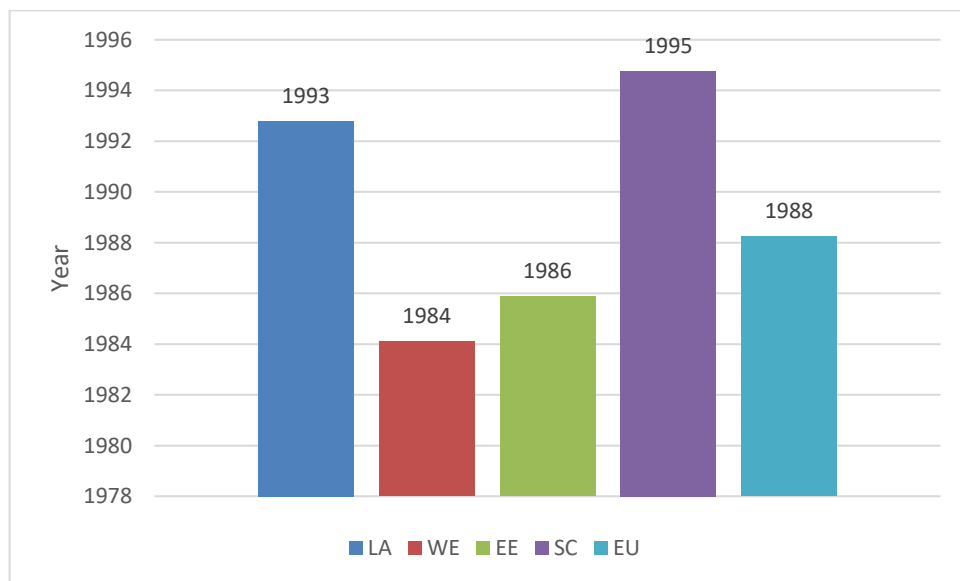
Figure 16. Average startup date of pulp mills operating in each region.

Evolutionary research by Lewinn et al. and Murmann suggests that how dynamic interrelationships contribute to the rise and fall of industry in different regions [10], [11]. This model consists of four categories: external factors, national socioeconomic environment, global competitive dynamics, and extra-institutional environment driven change. While local socioeconomic policies determine resource availability, market potential, and available investment; industry infrastructure and technology affecting production are guided by outside forces [12]. Global competitive dynamics represents international trade and technology transfer between regions, including the productivity of those technologies in their respective regions. Extra-institutional environment can be felt on a macro-level, where things like environmentalism, political movements and where competitive focus is targeted (e.g. technology and innovation). [12]

5.1 Historical operations

The Nordic countries are traditionally known for their paper industries, especially Finland and Sweden. Today Finland and Sweden are known as large players within the pulp and paper industry, however, it was not always so. Despite their similarities, due to market conditions, social pressure, and geographical advantages, the Nordics each have their own unique attributes that led them to where they are today. In this section, the history of the paper industry of the Nordics will be briefly studied to get a better understanding of the prevailing market conditions of today.

5.1.1 The Nordics

While the first paper mill is thought to have been built in Finland in 1667, a whole 200 years later, only five mills were in operation. Low domestic paper demand resulted from low living standards and a small population size [13]. Innovations in the mid-1800s, including the possibility of utilizing wood in the paper making process and the introduction of the sulfite pulp process the 1870s initiated the process of rapid growth [13]. By 1890, the total number of paper mills in Finland had grown to as much as 30, a process that was facilitated by founding paper mills alongside groundwood pulp mills, creating what may in modern times be known as rudimentary integrated paper mills [14].

Starting in 1890 and ending in 1913, a period marked by rapid growth in the Finnish paper industry, the total annual production of pulp and paper grew from $27000\ t$ to $300000\ t$ and

13000 t to 170000 t respectively. This growth represents an 11- and 13-fold increase over a period of 23 years. This period coincides with a global economic boom, which lead to increased demand. More importantly for Finland, however, was its position as an autonomous Grand Duchy of Russia. At the time, many new groundwood mills were established and some later integrated pulp and paper production, leading to many small firms. Simultaneously, however, some of the country's largest firms were in the paper industry [13].

Following the collapse of imperial Russia, a newly independent Finland had to turn to new trading partners because the supply far outpaced domestic demand [13]. Finland turned to Western Europe and North America, where despite the highly competitive market, Finland's paper industry was able to compete with a lower resource cost, sales cartels that are characteristic in the Nordics, and currency devaluations [13]. During the interwar period, Finland's paper industry continued to grow, total annual production grew from 180000 t to 760000 t by 1938, despite the great depression. It grew to be such an important industry to the Finnish economy that by 1927, 14 of the 20 largest firms in Finland were in the forest industry [13].

Following the down years during the second world war, Finland directed a large portion of its production towards the Soviet Union as war reparations payments. Despite this, paper was still sold to a rebounding Western Europe. Finnish competitiveness was assured by further devaluation of the Finnish currency and common sales organizations, to which almost every Finnish firm belonged to [13]. The economic growth and the sharp rise of paper prices during the Korean war presented an immense growth opportunity. While the growth in standard of living drove increased demand in paper products, market liberalization through trade agreements like the EFTA in 1961 and the EEC in 1973 reduced trade tariffs.

While the Finnish paper industries importance to the country's economy is evident from their heavy involvement in trade agreement negotiations, it was also heavily involved in a characteristically Nordic tradition, sustainable development. Due in part to concern over wood availability and the following increase in prices, the industry stated to invest in environmentally-friendly technologies as early as the 1960s and government regulation increased silviculture so that new growth is not exceeded by forest felling. [13]

Finally, from the 1970s onward, smaller, and medium size firms start to merge into larger entities, as the industry starts to concentrate into larger concerns. It was justified to achieve sufficient economies of scale. Large companies reduced the need for common sales organizations to maintain competitiveness in the global market, and following Enso-Gutzeit opting out of Finnpap their relevance continued to decline until in 1996, such organizations were made illegal when Finland joined the European Union. [13]

Sweden's first paper mill was started as early as 1612, but like Finland, it took some time for rapid growth to take place. Conversely, that growth started much earlier and by 1830, there were over 80 paper mills in operation. This contrasts with the total number of paper mills in Nordic countries including Denmark, Finland, Norway, and Sweden being just 98 in total in 1825. Similarly, to Finland, the introduction of wood as a raw material further accelerated industry growth. Sweden was in fact one of the technological leaders in the industry at the time, even inventing the groundwood pulp process. [13]

The time between 1890 and the first world war was similarly a time of immense industry growth, with total annual pulp production growing from $100000\ t$ to $1200000\ t$ by 1914, making Sweden the world's largest exporter of pulp [13]. Paper production reached $300000\ t$ during that same time, 50% of which was exported mainly to Western Europe. Sweden was hit hard by the great depression and the industry focused on closer cooperation through associations, while devaluation was also used to keep the industry competitive. During the interwar period, total annual pulp production continued to grow from $1300000\ t$ to $3500000\ t$. [13]

Sweden's paper industry was highly dependent on exports and growth relied upon demand increasing those markets rather than domestic needs. When customs policies changed in their most important export markets, the Swedish paper industry reacted by focusing on products with low duties and further increased intrafirm cooperation. This cooperation finally led to the creation of an export cartel called Nordic Scan, whose members were made up of pulp and paper industry firms within Nordic countries.[13]

The onset of the second world war negatively affected the Swedish paper industry, despite not being participating, because of a decline in demand in Western Europe. Despite government regulation of export prices in 1946 and an additional tax applied to paper products from 1948-1950, rapid recovery within the industry was achieved following the second world war.

From the 1950s to the 1970s, the industry saw structural change that presented new challenges to the global export leader. North American pulp production companies began to integrate vertically and were purchasing paper producers in Western Europe, reducing the Swedish industries pulp customers. At the same time, North American paper mills replaced Swedish pulp with Canadian pulp leading to Canada's rise to global pulp export leader. This led to Sweden changing the industries focus from pulp production to paper production while simultaneously concentrating their firms with vertical integration, like what happened in Finland.

The vertical integration and concentration were further rationalized by increased competitiveness of North American firms compared to Nordic firms, pulp production vulnerability to currency fluctuations, and material scarcity concerns. Scarcity concerns were alleviated in the mid-1980s with the increasing prevalence of recycled paper. [13]

5.1.2 South America

The pulp and paper industry in South America is relatively new when compared to the Nordics; having only started as late as the mid-1900s. Despite the comparatively late start, South America has become one of the largest producers in the pulp and paper industry. Brazil for example, is the second largest producer of wood pulp for paper and paperboard, with a total capacity of over 25 million metric tons in 2020 according to the Food and Agricultural Organization of the United Nations (FAO) [15]. Brazil has also become one of the largest producers of paper and paperboard, with a total capacity of over 14 million metric tons, led only by France, Japan, and the United States [15]. In this section, the background and reasons for that rapid development will be discussed.

South America has had a different path to their current position in the pulp and paper industry than the Nordics. South American firms were able to take advantage of their own geographical advantages while implementing similar economy of scale principles as were

becoming the norm in Europe and North America. One key factor is South Americas favorable location in the southern hemisphere in addition to their main raw material, Eucalyptus. According to Lima-Toivanen, South America has a natural comparative advantage in plantation growth [16]. The climate along with the characteristics of eucalyptus tree allow for South American firms to grow raw material in an industrial setting on plantations.

Eucalyptus grows at a far faster rate than Nordic pine. Tropical hardwood takes around seven years to grow before it can be cut while Nordic pine takes up to 45 years [1]. Plantation growth and faster growth times also allows for more predictable forecasting. Eucalyptus grown on plantations grow at similar rates and deviations are less common, when compared to pine that can see significant variation in size and shape simply due to variance in growth conditions. Similarly, a plantation growth allows the producer to know exactly what the wood will be used for and when it can be used, clearing entire plantations in one go. Conversely, partly due to variance and location, a whole area cannot be cleared at once. Only suitable trees will be cut, while others are left to grow or are used for different purposes. Even ownership structure varies between the two regions; in South America the firms themselves may own the plantations from which the eucalyptus is taken, while in the Nordics, ownership is far more fragmented. [1]

In Finland there are regulations and quotas regarding forest management that also effect wood acquisition. This leads to large areas from which wood must be gathered sporadically, in some sense limiting supply increases. Conversely, in Brazil supply can be increased by acquiring more land for plantation operations. Of course, making space for plantation operations often requires clearing rainforests. [1] While eucalyptus and geographic location offer many advantages, they do not alone account for the rapid development in the region.

A late start in the industry is not always a disadvantage, and in the case of South America, it played a key factor in their rapid development. A certain kind of leapfrogging effect can be seen in South America, where intermediary steps of consolidating many smaller companies into larger entities that is seen in the Nordics was, for the most part, skipped [16], [17]. South American firms have focused their efforts on large economies of scale and investing in technologies including selecting the most favorable eucalyptus varieties [16]. The

government in South American has played a large part in boosting the industry, as it did in the Nordics, by implementing policies that helped forestation and attracted foreign investment.

5.2 Market trends

The growth of the pulp and paper industry has grown incrementally over the past two centuries, taking larger leaps each when new technology allows for better processes. During this time, the global leaders have changed for various reasons and market conditions. The first countries to embrace industrialization, like Britain, France, and Germany, were originally the biggest players before the Nordics developed their industry and was able to take advantage of their low costs of material and labor alongside heavy investment by their respective governments through policy. [13], [16], [18] Since the mid-1900s a new paradigm has begun to form, where the South American region began to play a more and more prominent role by using economies of scale, government policy, and natural comparative advantage through climate and genetic selection in plantation farming [18]. Today, Asia may be seen as the future powerhouse, Chine alone has become one of the largest producers in the pulp and paper industry.

According to Ojala et. al., the industry has gone through phases of growth, maturation, and decline through many facets of the industry, like all industries. They further suggest that because the industry has been global since the beginning of the 19th century, its development correlates heavily with industrial and commercial development of the same period of time [18]. A strong correlation between paper consumption and GDP (gross domestic product) growth can be observed over that time, according to Järvinen et. al. [13], [18]. In a general sense, the demand for paper rises alongside GDP growth up to a certain point, after which further growth requires new markets. In that sense, the shift to dominance from Europe to South America and Asia is more intuitive in that context.

South America and Asia represent regions where there is great potential for both increasing production and more importantly increasing demand for paper products as GDP continues to grow. China, for example, has had a real average GDP growth of 9,1 % between 1992 and 2021, while being by far the largest consumer of paper and paperboard products in the world at 110 million metric tons in 2018 [19], [20]. The population growth in less developed

countries is predicted to grow at a faster rate the more developed countries [18]. While population and GDP continue to grow, so will demand. However, as with Europe and North America, only to a certain point. However, these factors suggest that South America and Asia present enormous opportunities both offering excellent production capabilities and growing demand. [18]

Pulp and paper market size projected to grow from $348.83 billion in 2019 to $368.10 billion by 2027, producing a CAGR of 0.8% over the period. Total of 4.38% growth over the projection period [21]. COVID-19 provided a boost in paper product demand through an increased demand and tissue paper, for example. This despite an industry facing numerous challenges in an ever-increasing digitalization effort across the globe, especially with consumer grade products [21]. This trend, however, is unlikely to provide a sustainable long term revenue stream, although as the population at large has become more accustomed to the use of masks and sanitizers it is possible that the production will remain higher than pre-pandemic levels regarding sanitation and hygiene products.

Rapid increase in internet and smart phone users in emerging markets is expected to increase demand for convenient packaging solutions for online products as well as food and cosmetics. Online shoppers are projected to reach 220 million by 2025 according to Brand Equity Foundation [21]. Up to 15% sales of pulp and paper are expected to occur online in 2021. Furthermore, technological change and size advantage have had an increasing affect in R&D activities, and has left to a shift from product focus to process R&D. This is increasingly advantageous to large firms that can spread R&D costs over larger production volume. [12]

The cost of a new mill is expected to rise to as much as EUR 2-3 billion in the coming years. Export credit agencies are used to finance total cost of which Finnvera typically guarantees under 20%. New and modernizing mill construction projects are building up where the wood is most readily available and plentiful: South America, Southeast Asia, and the Nordic countries. [22]

5.3 Outside NA

The most significant region to which sales have been shipped has been and remains the Latin American region. Most prominently Brazil and Chile, but large mills have recently also been established in Uruguay. In recent years the sales have been more diverse, albeit still heavily represented by the Latin American region, with several sales in the Scandinavian and Eastern Europe region.

Heavy investment has been concentrated on large scale operation in the Latin American region, particularly Uruguay, where large mills have been built in the last half decade using best available technology. Similarly, large mills have been trending in the Scandinavian region where a seemingly concerted effort has been made by various companies to minimize environmental impact while maximizing profit. Conveniently, these two goals synergize exceptionally well in the pulp and paper industry where maximizing process efficiency and material usage almost always leads to a direct and/or indirect reduction in greenhouse gas emissions. The trend towards more efficient production machinery also lends itself to reduce the number of required operators which in turn reduces operation costs considerably, especially when moving from a loader operated wood yard and older machinery to a portal crane system and highly digitized machinery that can be remotely monitored and operated by only a few individuals per shift. In that regard, Andritz is positioned well to take advantage of this opportunity and utilize its position as a technological and market leader in conjunction with its unique position of delivering turnkey solutions.

Moving forward, by increasing the efficiency and reducing the number of operators required, a highly automated system can be easily justified to mills of all sizes. Despite the higher initial capital investment cost, the payback time is considerably shortened the more automation is implemented along with the best available monitoring technology. With an automated system, implementing further upgrades through optimization and simulation capabilities could produce a highly adaptable ecosystem that could be developed further with emerging technologies.

5.4 Environmental factors

Plastic consumption level reached 359 million tons worldwide in 2018 of which Europe consumed 61.8 million tons. However, while plastic consumption has continued to grow

rapidly around the world, consumption has stabilized in Europe. 70% of the plastic used in Europe comes through packaging, building and construction, and the automotive industry of which packaging represents a total of 40%. Pulp and paper manufacturing processes have relatively low direct emissions (MtCO2) compared to, for example, iron and steel, chemicals, or cement. [23]

Many industries are turning towards recyclable and environmentally friendly packaging. Both public awareness and government legislation have played a large role in this shift to a sustainable packaging model [24]. Large efforts have been made in recent years to reduce plastic waste through different measures. China, for example, took the step of banning the importation of most plastic waste in 2017, before which it imported over 55,7 % of the worlds plastic waste [25]. California was the first state to ban the use of single-use plastic bags in 2014, followed by eight more states, including New York [26]. Similar measures have been taken by the European Union, where a directive banning certain single-use plastic bags took effect on July 2, 2021 [27]. The targeted ban on, formerly ubiquitous, plastic bags present an opportunity for pulp and paper industry which is an obvious place to look for a solution to fill the gap.

The trend towards environmentally friendly business practices and an effort to reduce the carbon footprint of products is a potential source of an increase in demand for the pulp and paper industry. Many industries are turning towards the most environmentally friendly and recyclable packaging medium, paper, and cardboard, for their packaging needs. In that regard, focusing heavily on the environmental factors that can probably be used to reduce the carbon footprint can have an enormous appeal for manufacturers whose clients include companies with meaningful sustainability goals. An additional benefit of using the best available technology, in addition to the ancillary benefit of GHG reduction is that they, for the most part, provide the most cost-efficient methods of production and in some cases can be carbon neutral. A motivation for some European companies may be that if a plant can achieve carbon negative production, an additional revenue stream can be generated through the sale of unused carbon credits.

Corporations have been under pressure to commit to sustainable development goals and make good on promises. Through this process a paradigm shift has occurred, and we are seeing accelerating investment into green technology aimed at reducing GHG emissions and

limiting the carbon footprint of end products. Some methods and processes themselves are being replaced and phased out, as is the case with fossil fuel produced energy such as coal or slowly moving from traditional gasoline to electric vehicles. Simultaneously, many industries are focusing on increased efficiency as the catalyst for the endeavor through a reduction in energy requirements for processes. In applicable industries carbon capture and energy capture methods have been developed to produce a tangible resource out of biproducts that may have gone unused before.

5.5 Market segment

Consultancy firms are an important factor in selling the portal crane concept in places like South America [1]. In the region consultancy firms play an integral part in developing and designing paper and pulp operations and make suggestions to the customers based on what they believe to be the most profitable solution for the customer. So, it is especially important to not only sell the idea to the customer but to the consultant firms that the customers in the region rely on. Furthermore, by gaining traction and acceptance of the technology within the firms, this will be an efficient way to further propel the idea to a larger customer base through a sort of intermediary, rather than going to each customer separately. The potential reference of not only the end customer but also the consultant firm could also prove to be invaluable when proposing portal crane operations for other customers within the region as well.

Overall, larger companies with upcoming plans of building large mills or upgrading their current mills with a higher capacity and best available technology should be prioritized. The pulp mill industry is specifically targeted because of its typically large-scale production and profitability when compared to sawmill type facilities, for whom the large capital investment may not make sense at this time. Furthermore, customers who value improving efficiency, lowering operating cost, scalability, environmental considerations, and sustainability that are willing to invest in emerging technologies form a prominent base of potential customers.

6 LAYOUT OPTIMIZATION

A recurring problem in woodyard optimization and crane optimization is the layout of the storage space. The issue boils down to how to optimize the crane configuration in a way that satisfies both the structural requirements as well as efficient storage activities. Oftentimes a deciding factor tends to be whether to store all the wood under the span and thus maximizing span length while minimizing the need for cantilever sections. Conversely some configurations may warrant the opposite solution by increasing the cantilever length while span length is minimized.

6.1 Crane standards

Crane standards vary from region to region and each regions standard should at the minimum be used to verify calculations to assure compliance with local requirements. For example, in the United States CMAA 70-2015 Specifications for top running bridge and gantry type multiple girder electric overhead traveling cranes published by Crane Manufacturers Association of America should be used to guide design work. Conversely in Finland calculations and methods should be verified by using the appropriate SFS and ISO standards like the EN 15011 bridge and gantry crane standard. Much of the cranes are designed based on north American standards because that has been the product home for gantry cranes, but when designing cranes for operation in different jurisdictions, cranes must be in compliance with local requirements presented in the region's own standards. For example, depending on crane height, a stair platform must be installed. Many standards relate to safety factors like electrical cabinet placement and minimum distance to evacuation locations if the operator must exit the crane in emergency.

Before ideation and sketching is started, a base level of reference data was gathered by looking at portal cranes that have been previously sold and delivered to customers. Using the dimensional data from North American sales, several graphs were created to visually depict average, maximum, and minimum dimensions of the selected data. The data graphs are categorized into lifting capacity, process and hinged leg side cantilever length, span length, and light height. Furthermore, the differences of each individual statistic between one and two crane systems are also graphed to provide a look at how the number of cranes

affects different aspects of the cranes themselves on average. The lift capacity graph is presented in Figure 17. Cranes are typically designed to have a lifting capacity of 30-32 tons because in some states in north America like Georgia, the maximum load of a log truck is 28 tons. Larger cranes have been made where the lift capacity is up to 47 tons have been made in places where the humid climate can cause the wood loads to be considerably heavier than they would normally be.
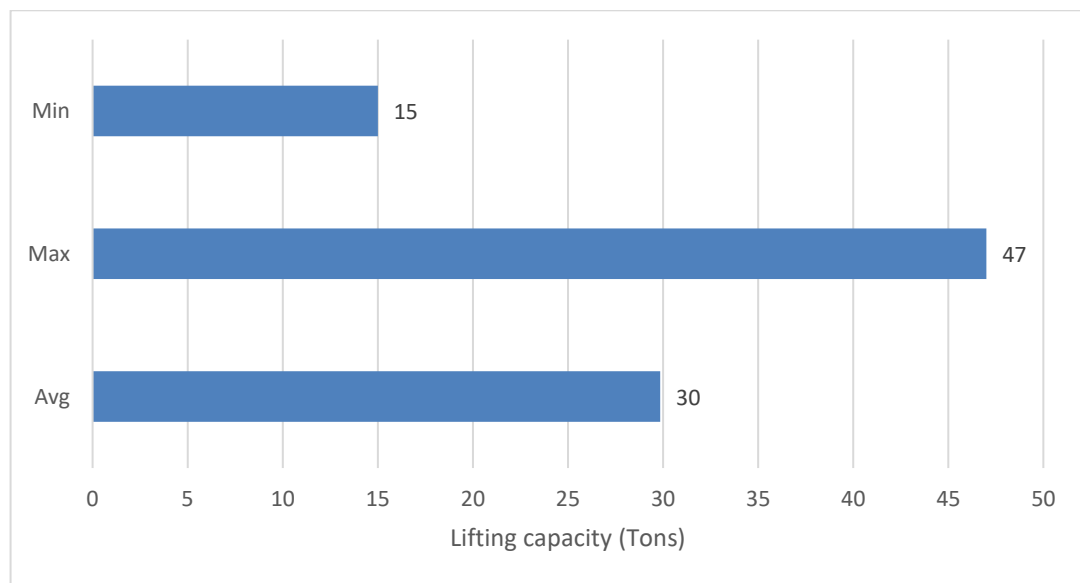
Figure 17. Minimum, maximum, and average lift capacity of portal cranes sold in North America.

The graph showing both the process side and hinged leg side cantilever length statistics is presented in Figure 18.
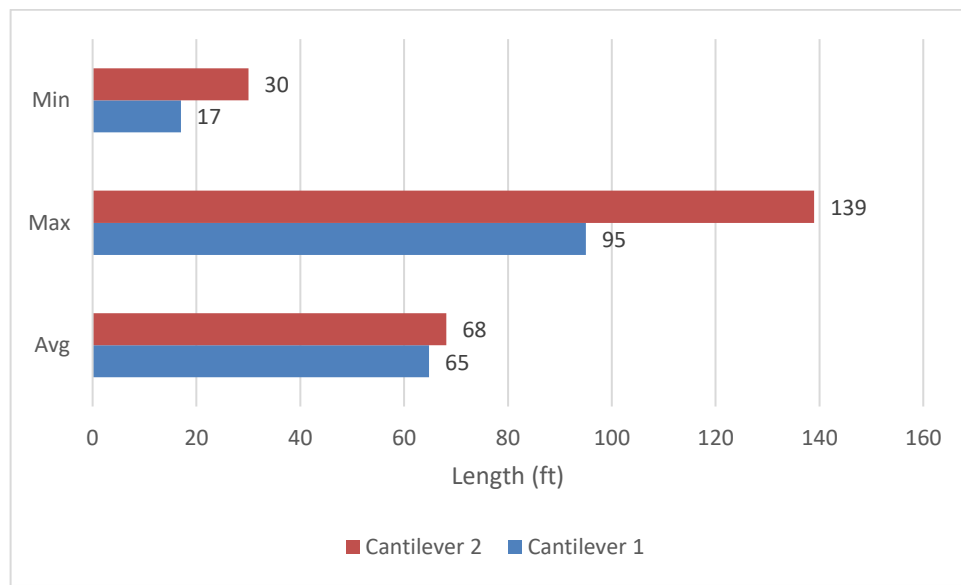
Figure 18. Minimum, maximum, and average process and hinged leg side cantilever length.

The spang length graph is presented in

Figure **19**.
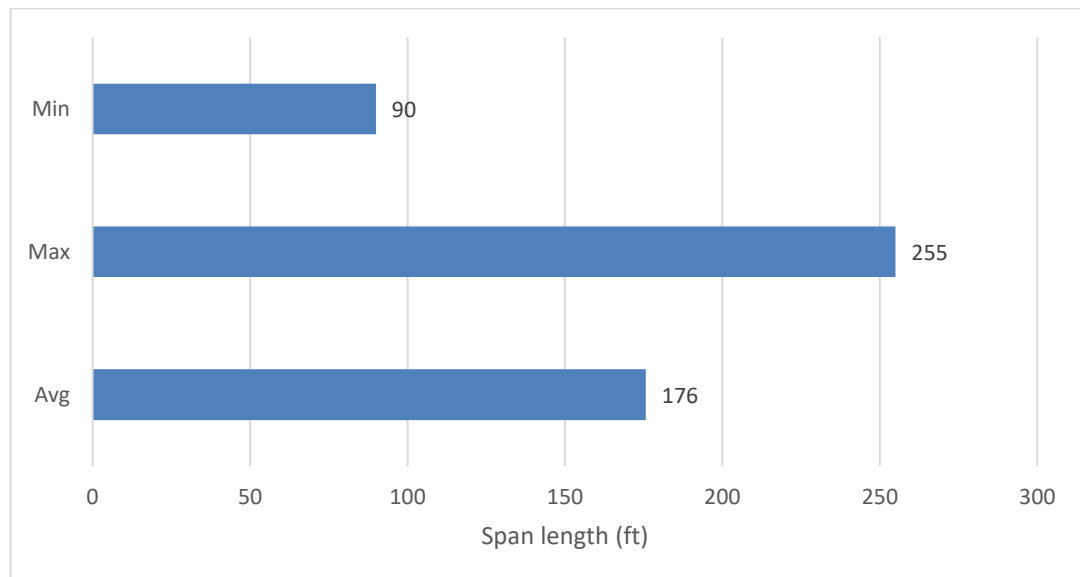
Figure 19. Minimum, maximum, and average span length of sold portal cranes in North America.

The lift height statistics for portal cranes sold in North America are presented in Figure 20. Lift height can vary anywhere from 9 – 25 m, but in the case of short wood, since the pile

height is limited to 12 m the lift height of the applications studied in this thesis are lower than in those cranes sold in north America.
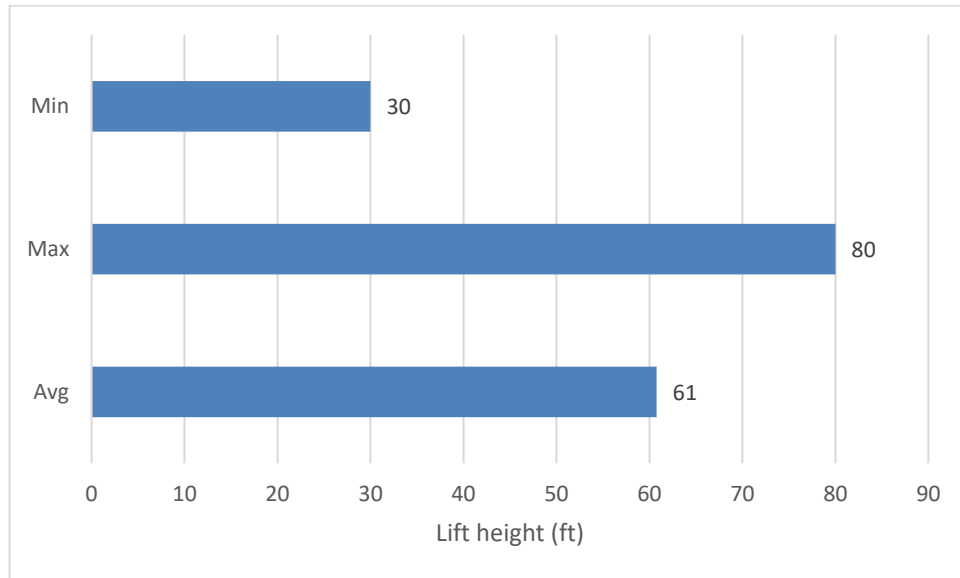
Figure 20. Minimum, maximum, and average lift height of portal cranes sold in North America.

The differences in key attributes between single and double crane systems is presented in Figure 21. When comparing single and double crane operations, on average, cranes in single use are noticeably smaller dimensionally, but have a slightly larger average lifting capacity.
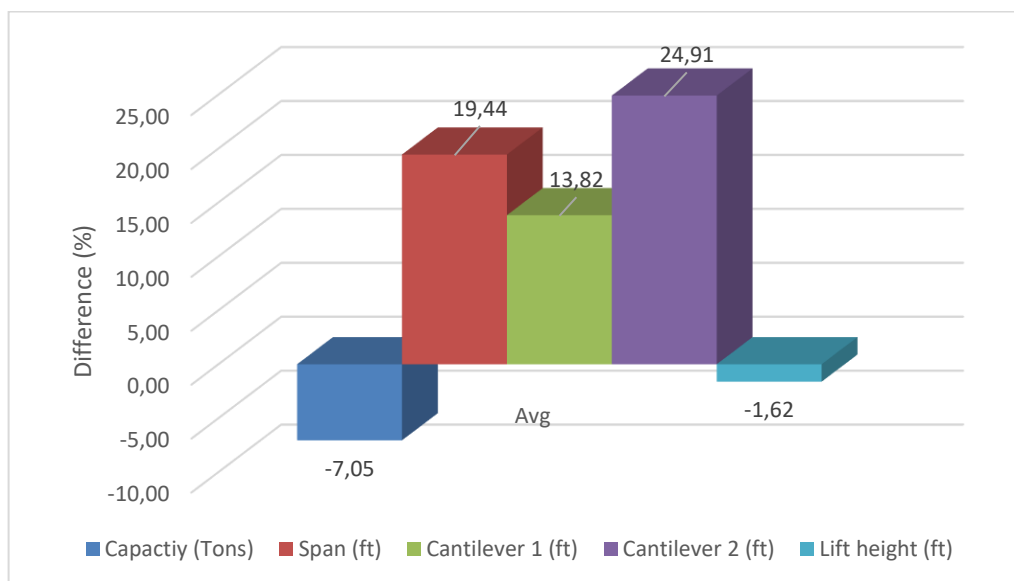
Figure 21. Difference in key statistics between single and double crane systems.

For the purposes of idea generation, a statistical analysis was conducted to categorize the prevalence of certain parameters that appear on portal cranes. The table for all cranes is presented in Table 2, while the tables representing one and two crane operations are presented in Table 3 and Table 4 respectively.

Table 2. Table showing the percentile statistics of sold portal cranes in North America for all Andritz cranes.

Percentile all [k]	Lift capacity (tons)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total length (ft)	Lift height (ft)
0.9	40	215	86	85	165	75
0.75	37	200	75	77	147	65
0.5	30	175	65	65	130	60
0.25	22	146	60	58	110	55
0.1	15	132	35	42	55	49

Table 3. Table for single crane operations.

Percentile single crane [k]	Lift capacity (tons)	Lift capacity (tons)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total length (ft)
0.9	40	205	85	85	165	74
0.75	35	201	75	85	160	65
0.5	30	162	65	65	130	65
0.25	22	145	55	55	110	55
0.1	15	126	35	31	66	55

Table 4. Table for double crane operations.

Percentile double crane [k]	Lift capacity (tons)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total length (ft)	Lift height (ft)
0.9	39	232	79	86	166	68
0.75	33	217	67	77	145	65
0.5	30	195	65	75	140	55
0.25	18	187	65	75	140	55
0.1	15	159	65	72	137	55

6.2 Initial sketching

In the initial stages of the optimization process, using the data collected in the previous section, initial variations of different crane structure types will be created to build a list of references. These models will be created in AutoCAD using standard components from the Andritz catalogue. The main variations in the models will be leg configuration, cantilever configuration and length, span length, and models that include support beam structures. In the case of leg configuration, a crane typically has two supporting legs that connect the bridge structure and contact the rails used to movement. The first leg type is the hinged leg that, presented in Figure 22, that is made up of two beams set up in a triangle shape in which the bottom ends are connected to the end trucks and the top ends are connected to the support beam to which the bridge is attached. Between the end trucks is an additional support beam that serves to stabilize the structure and maintain an appropriate distance between the end trucks. It additionally serves as a buffer that can absorb the energy of a falling log from directly hitting the track.
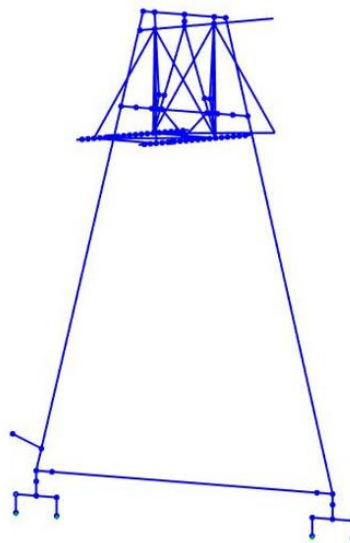
Figure 22. Isometric profile of the hinged leg.

Conversely the triangular leg is set up identically when the profile is viewed from the side, however, it is made up of 4 legs instead of two where each side has a set of legs in an inverted triangular shape. The frontal profile, perpendicular to the bridge, is presented in Figure 23. This leg provides lateral stability to the structure and usually serves as the platform to which stairs leading up to the control room is placed.

When determining optimal leg configuration, configuration refers mainly to which side of the storage pile the legs are to be placed. The 4-legged structure is typically placed onto the plant side while the hinged leg is placed onto the far side of the storage. This standard configuration achieves two things, it allows for the operators to walk directly out of the plant and to the stairs to change shifts and reduces the need for operators to circumnavigate the entire storage area, often crossing train tracks or other roadways in the process. This is because stairs are typically installed onto this 4-legged structure to begin with, however it is not always the case. There are, however, advantages to both configurations and should thus be explored.
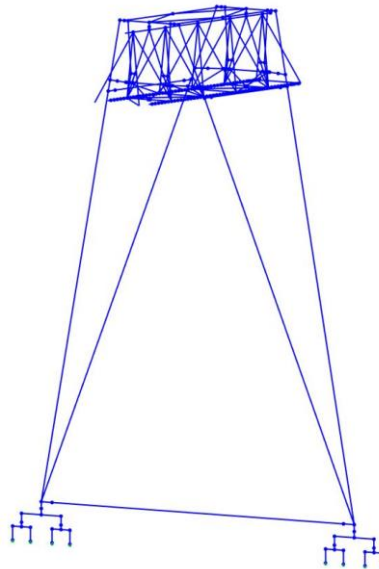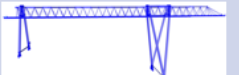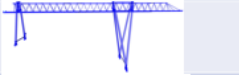
Figure 23. Isometric profile of the fixed leg with four legs supporting the structure laterally, vertically, and horizontally.

Conventional wisdom dictates that the configuration should reflect a desire to increase efficiency and production volume. Furthermore, in many pulp-mills it is often preferable to unload arriving logs directly into processing. Thus, traditionally the unloading should take place as close to the processing input as possible. In other words, to reduce process time, the crane's gantry and trolley should move as little as possible. The initial sketching reflects this by focusing all loading and unloading operations under a main cantilever beam, even in the case of double cantilever configurations. Of course, in the case of double cantilever

configurations the use of the additional cantilever is addresses by placing an additional wood pile under it from which the crane will transport material to the process.

With the configuration selection, it was desired to capture broad coverage of use cases and applications. This meant including double cantilever models as well as single cantilever models. Additionally, a pylon supported model was created for the sake of comparison. The selected configurations are presented in Figure 24.

Variation	Span Modules	Cantilevers	Infeed	Reinforcement truss	
A	5	2	Fixed	No	
B	5	2	Hinged	No	
C	5	2	Hinged	Yes	
D	5	1	Fixed	No	
E	5	1	Hinged	No	
HI	4	2	Fixed and hinged	No	
H	4	2	Hinged	No	
I	4	1	Fixed	No	
QR	3	2	Fixed and hinged	No	
Q	3	1	Fixed	No	
R	3	1	Hinged	No	

Figure 24. Variation matrix of initial choices to be calculated.

6.3 Design Criteria

When designing the structure of the crane, the variable loading caused by the loading and unloading of the logs from trucks/trains to the plant in local areas should be given special attention. While global loading and strain is important on a large scale, local fatigue is likely

a bigger concern should the duty cycle cause the structure to carry the load in a smaller are. Historically this is often the case, especially in pulp mills where the raw material is often fed directly into the process. Local stress peaks should be identified in the heavily loaded areas to ensure that the local primary and secondary stresses remain within acceptable margins. Generally, the global concerns are the bending of the cantilever beam, and the most prominent local concern is the wheel load applied to the box rail that can cause lateral torsional buckling in the bottom chord of the girder beam [9].

6.3.1 Wheel load

Wheel load is an important constraint in the design of portal cranes. The vertical force applied to the wheels should be high enough to reduce the chance of slipping from wind loading but also remain small enough as not to fatigue and wear the railing or wheels too much. If it is not possible to ensure sufficient wheel load, more motors will need to be installed to compensate [9]. Of course, additional motors increase complexity and just adds more parts that need to be maintained, including the additional cost. Not to mention, additional motors increase energy consumption, even if it a small increase.

Furthermore, wheel loads play a large part in civil engineering costs in the form of foundations laying costs for the rails, where the specifications should not go over the required spec. Additionally, the wheels themselves are expensive, both to make and change. The wheels must have a maximum of 0,15 % difference in diameter, meaning that all the wheels must be changed when the difference grows larger. [9]

6.3.2 Safety

Safety must be considered from not only a structural analysis point of view but also an operational point of view. Especially when the desired result is an overall decrease in adverse safety events stemming from both equipment failure and human error. A woodyard crane is a very large piece of machinery that moves while carrying heavy loads. This presents many unique safety concerns that must be addressed during the layout optimization phase.

The layout must allow the crane operator a good view of the woodyard in which they are working and the wood load that is being lifted. The drivers that deliver wood to the mill must

have a safe shelter that they can go to during the unloading process so that if, for example, a log falls out of the grapple, they are not injured. The shelter should typically be placed near the unloading location for convenience and to help the crane operator maintain situational awareness during the lift. Related to unloading operations, areas where it is safe to travel, and unsafe areas should be carefully considered and designated to maintain a high level of safety without disrupting the operation of the woodyard or mill in the process. Of course, the design of the crane itself must guarantee the stability of the crane during operation.

Safety should be considered from a statistical point of view. The number of accidents and errors should be calculated within a degree of certainty like automated dock operations. Of course, since no actual data is available at this time, it must be specified that the safety figures are predictive and based on retrodictive assumption from comparable figures gathered from dock operations. The role of predictive analysis is to give a point of comparison relative to more traditional loader-based operations.

Layout optimization is difficult if not outright impossible to tackle ahead of time. It requires detailed knowledge of the site, operation, needs, requirements, local laws and regulations, preferences, and much more. Even armed with all the required information, your initial designs and plans can be rendered useless when you step onto to site only to realize several limitations and constraints that prevent its implementation. The pre-emptive layout optimization process should focus on general rules and guidelines without committing to anything concrete until a final plant design is laid out and all issues and variables that can reasonably be anticipated are well known.

Emphasis should be placed on determining and calculating the optimal layout schemes for generalized scenarios. Statistical modeling and simulation can provide invaluable tools when determining optimized strategies and contingencies for a broad layout spectrum. The problem with this approach, however, is that finding an exact solution is impossible and even an approximate solution requires more constraints than can be obtained without input from customers.

7   TOOL CREATION

Initial tool creation could consist of a spreadsheet or Mathcad tool which calculates the key parameters according to requirements. The initial idea is to create a worksheet in which it is easy to modify certain parameters given by customers and based on those a calculation will take place and give you a range of options. Perhaps the most reasonably approach initially is to create conditions with their own ranges using standard components. Some sort of Boolean logic could be applied to the program so that certain preconditions trigger a different branch of the calculation to take place. For example, one initial condition could be the requires storage size. Using the storage size input the worksheet could then trigger a certain range of options and then depending on the storage size, another input would be required. The next input could be something along the lines of production volume or required input output. The program could then narrow the scope of possibilities by determining that, based on the storage size and production requirements, withing these constraints the optimal outcome is to produce a smaller storage area but with two cranes or vice versa.

To produce a program with the required accuracy, various cases should be studied and calculated to give the program the information that is needed. Naturally, the more cases that are implemented into the system the more accurate the results. This however is outside of the scope of this thesis but should be considered for further study. While the program will serve as a proof of concept, it should still be functional to a degree that its efficacy can be validated in real world usage. Should it prove to be a useful tool, investment into higher functionality and increased complexity by introducing databases, dynamic models and simulations could provide enormous benefit and competitive advantage.

7.1 Modular design

One important focus of the tool creation process was the development of a modular framework in which different functions can be organized into individual components. This should be done for many reasons including adding flexibility and reducing redundancy. A modular design structure in which each module can be selected and executed individually or as a chain allows for the user to choose which functions, they wish to use. This is especially important when considering the different motivations that customers have when investing in

new technology. Furthermore, by allowing the user to select ahead of time which modules they wish to use, the tool does not waste resources on unnecessary calculations while also removing redundant data that would otherwise be included in the results.

In theory separating and categorizing different functions is simple enough, but in practice great care and consideration must be taken to ensure that each module is both functional and useful and dependencies are thoroughly mapped. In the case of crane size estimation, the different modules can be broadly separated into three categories: primary, secondary, and tertiary modules. Primary modules consist of modules that are essential in all configurations and provide the key results of the tool, crane dimensions. Secondary modules include functions that serve a supporting role to the primary data. This may include, for example, savings estimations, environmental impact estimations, and safety impact factors. Tertiary modules include functions that may include functions that are specifically created for individual customers. Additionally, tertiary modules may also include QoL (quality of life) tools that can be used in conjunction with other modules to organize results.

Another way to look at this type of categorization is that primary functions represent modules that provide us with a way to calculate the things that a customer needs to know, secondary functions represent modules that can be used to present the customer with an answer to why the results are justified, and finally, tertiary functions represent modules that provide the user additional tools with which to present the data. An illustrative flowchart of module classes is presented in Figure 25.
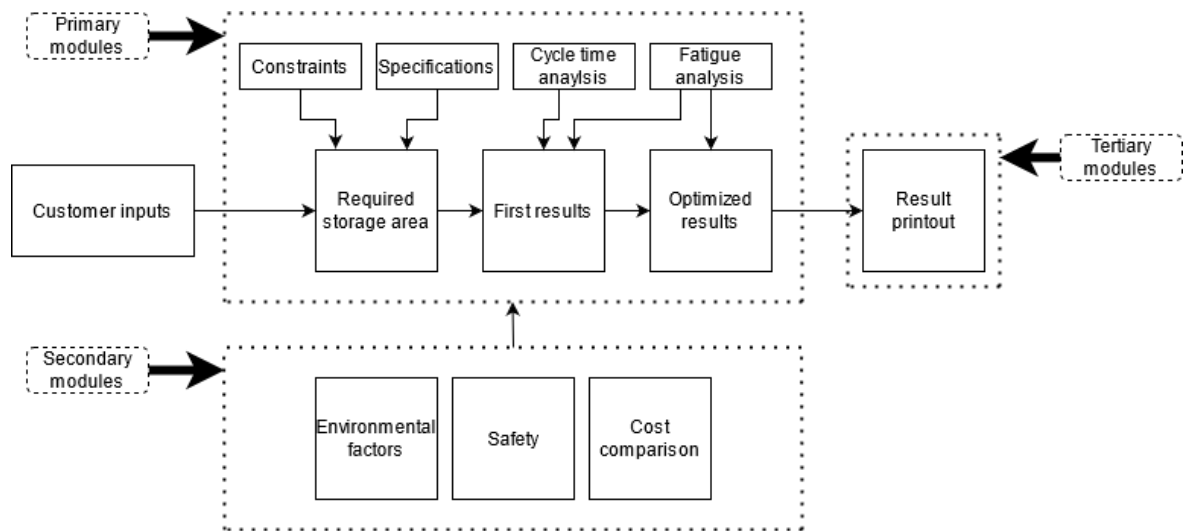
Figure 25. Module diagram of the main tool functions.

7.2 Production volume

Production volume will be used as an input for the primary calculations. The customer should provide an estimate of their required production volume and storage requirements can be calculated based on those figures. Additionally, the customer provides general restrictions for the storage space by determining the dimensional constraints of the available space that can be used for the layout. In this case the area will be restricted by maximum rail length as far as the tool is concerned. Based on the rail restriction value, the tool will provide various span and cantilever length options, however, it is possible to add additional total length constraints beyond which the span and cantilever length cannot go.

7.3 Program structure

To test some of the discussed methods, a proof-of-concept prototype of the potential tool was created using Microsoft Excel. While the tool was not meant to be created to be an entirely functional fully fleshed out product, the goal was to make it functional. In this section, the design process, used methods, and results for the tool creation process will be presented. The design process consisted of three main phases: researching methods that could be used, brainstorming, and selecting the most reasonable methods, and finally implementing them by using an iterative approach. An iterative approach was selected because no established frameworks for modular software design was discovered for this application, at least publicly.

Based on the market analysis section of this thesis, a general idea of what should be calculated, with what, and how. Equations for calculating storage space and turnaround time were gathered from internal documents which provided guidance when assessing their application in the tool. These equations were laid out and examined to determine their dependencies and required inputs. A workflow was developed based on these calculations which would form the basis of the primary module of the tool. This is not enough however, because the tool needs to be able to suggest various solutions that fit the pre-determined criteria based on customer requirements (storage size and production output). This is where an initial database of example cases is required.

7.3.1 Baseline approximations

Before calculation steps can take place, a baseline database must be compiled with which to generate initial solutions. For this purpose, a document containing the dimensions of all portal cranes sold in North America, including number of cranes, lift capacity, span length, the length of one or both cantilevers depending on configuration, and lift. The data was imported into an excel spreadsheet, that would be the basis for the proof-of-concept tool, and the data was sorted. Initially, all the cranes were studied as a group, but later they were separated into one and two crane systems to analyze the differences. These groups where analyzed and the averages, minimums and maximums for each variable and tables were created. The results are presented in for all configurations, single crane configurations, and two crane configurations are presented in Table 5, Table 6, and Table 7.

Table 5. Average, maximum, and minimum dimensions of all sold portal crane configurations.

All configurations	Lift capacity (ton)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total (ft)	Lift (ft)
Avg	29	175	64	68	129	60
Max	47	255	95	139	234	80
Min	15	90	17	30	17	30

Table 6. Average, maximum, and minimum dimensions of all sold single portal crane configurations.

Single crane	Lift capacity (ton)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total (ft)	Lift (ft)
Avg	30	159	59	57	117	60
Max	45	255	95	139	234	80

Min	15	90	17	30	17	30

Table 7. Average, maximum, and minimum dimensions of all sold double portal crane configurations.

Double crane	Lift capacity (ton)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total (ft)	Lift (ft)
Avg	28	198	69	76	146	60
Max	47	250	90	90	180	75
Min	15	145	65	65	130	55

These tables show that while on average single crane configurations skew towards the smaller side, they also contain some of the largest cranes produced. Conversely, the minimum crane size in two crane systems is much larger than in one crane systems. The percentual differences between two and one crane systems are presented in Table 8.

Table 8. Relative difference between one and two crane systems.

Difference % 2-1	Lift capacity (%)	Span (%)	Cantilever 1 (%)	Cantilever 2 (%)	Total (%)	Lift (%)
Avg	-7.05	19.44	13.82	24.91	19.65	-1.62
Max	4.26	-2.00	-5.56	-54.44	-30.00	-6.67
Min	0	37.93	73.85	53.85	86.92	45.45

For the purposes of this thesis, the overall difference was small enough that further study would consider all configurations as a single group. The table data consisted of 20 unique span lengths and 16 unique cantilever lengths. This presents a massive range of possible combinations, far more than is reasonable to consider within the scope of this thesis. This list had to be reduced significantly. Further statistical analysis was conducted, and the various variables were organized into top and bottom quartile and decile as well as a 50th percentile. The results are presented in Table 9.

Table 9. Sold portal crane data organize by percentile.

Percentile all [k]	Lift capacity (ton)	Span (ft)	Cantilever 1 (ft)	Cantilever 2 (ft)	Total (ft)	Lift (ft)
0.9	40	215	86	85	166	75
0.75	37	200	75	77	152	65
0.5	30	175	65	65	135	60
0.25	22	146	60	58	110	55

0.1	15	132	35	42	65	49

Based on this table, the search for parameters could be narrowed further. However, the percentiles don't tell the whole story by themselves. Using individual percentile values, six ranges where created: $>= 215$ ft, $200 - 215$ ft, $175 - 200$ ft, $145 - 175$ ft, $130 - 145$ ft, and < 130 ft. The total number of occurrences of each span length in each range was calculated to determine the most common span lengths. The results are presented in Table 10.

Table 10. Table showing the occurrence span lengths within the selected ranges.

Range	Percentage [%]	Cumulative [%]
>=215	15	100
200-215	13	85
175-200	26	72
145-175	33	46
130-145	5	13
<130	8	8

The table shows clearly that most spans are 145 ft and above in length with just under 60% being in the $145 - 200$ ft range. Using this table, the final span length selection was made. 145 ft, 175 ft, 195 ft, 200 ft, and 215 ft were selected. The first two were selected simply because of their prevalence in all configurations. The smallest selection represents the low end of the most common span lengths, while the second shortest span represents a sort of middle ground being almost exactly equal to the 50th percentile. Similarly, 200 ft is a convenient selection as the 75th percentile counterpart to the 145 ft spans 25th. A 195 ft span was selected to intentionally be very close to 200 ft in length to serve as a comparison point about program behavior with two close values. The top end was selected partly due the industry trending towards larger plants and partly because the large span length was convenient comparison during calculations and finding the limits of standard sized components.

A similar, but more rudimentary, analysis was conducted on cantilever beam lengths. There was far less variation in generally used lengths, with just over 65 % of cantilever beams being either 55, 65, 75, or 85 ft in length. This list was further narrowed by analyzing the

most common combinations of the four, the result of which yielded 65 and 75 ft cantilever beams to be used in the tool.

7.3.2 Variables and constants

Before the program can be built, various variables and constants must be determined. In this case variables represent values that should be obtained from the potential customer and input manually into the tool. To start off, the desired storage volume in metric tons should be calculated or provided, followed by rail length constraints. Next, cantilever configuration and length should be decided based on available storage space and best estimates. Next, the wood expected wood specifications including wood length and the proportional amount of that average length compared to total storage capacity. These values allow the tool to apply the correct void factors depending on wood length and to calculate how many piles can be placed in each column and how many columns are required to house the specific amount of wood for any given span and cantilever combination. Finally, if possible, the customer can provide an estimate of what proportion of incoming wood is fed directly into the process, stored into near storage, and long storage. This variable serves as a function with which the tool can later further optimize crane dimensions.

The constants used in the program, are the void factors for short and long wood which in this case is automatically selected based on wood inputs and a roughly 20 ft space reservation between the rails and the nearest pile. Additionally, the maximum speed and acceleration as well as an operator personal time allowance of 15 s are used in cycle time calculation.

7.3.3 Workflow

In this chapter, the basic workflow and methods of the tool are presented to describe how an actual tool should be created. The principles of the calculation process of the primary module functions will be presented using the example of the proof-of-concept tool that was made.

The calculation process begins with the user entering the required storage volume, maximum rail length, approximate cantilever dimensions that can be used, wood specifications, and the ratio of direct to process vs storing of incoming materials. The program then calculates an

initial required rail length when using each of the span lengths in no cantilever, one cantilever, and two cantilever configurations. This considers the raw volume while considering the void factor and reserved rail space between the rail and the pile. The results of each iteration are compared to the maximum rail length that was entered earlier and selected the smallest possible span length for each solution. At this stage, an initial result is obtained, meaning that for the given inputs we now have three different solutions considering only the raw storage volume under the span and cantilever beams. Of course, this result assumes that there is no wasted space, and thus no unused gaps between the theoretical maximum space usage. This does, however, give a general picture of the scale being considered.

The next iteration begins by taking the customer wood specifications and calculating the length of each row of wood. This accounts for the reserved rail spacing on both sides of the pile, meaning that, for example, one row of 3,5 m long wood would mathematically be seen as over 15 m long. The tool calculates the number of rows per column up until the length of the wood in addition to two times the reserved rail space is less than or equal to the maximum span length that is studied. In other words, the total length cannot go over 215 ft (65,53 m). The process is done with each assigned wood length and duplicated with the cantilever beams, albeit this time with only one reserved space between the rail and pile rather than two.

The maximum row count is then indexed for each span and cantilever length that is being studied. These values are dependent only on wood length and the maximum span and cantilever length that is being studied and can be considered an independent module. This is so that the wood specifications can be easily modified at any point in the process independent of the other variables. Next, the initial span length estimations for the three configurations are used to index through the previously calculated row counts for their corresponding span length and that value is then multiplied by the corresponding wood length for each index. This gives us the raw wood length for the maximum row count allowed for each span and cantilever length. Those values are then used to calculate the required rail length to store the required percentage of total storage volume of each individual wood length, accounting for void factor, rail reservations, and relative storage space consumption. The individual rail requirements for each wood length are summed up and then that rail length is used as a more

realistic representation. Calculating it this way in phases allows us to simplify the final calculation by removing the span length from the calculation entirely, so that the calculation can be done independently because the span length only serves an indexing function.

The final iteration is then conducted using the previous results as initial guesses. The last phase considers cycle time as the main variable. In this phase the dimensions of the second iteration solution and its corresponding rail length are used to calculate truck to near storage and far storage to feed. The truck to process is assumed to be equal in all configurations as it depends only on the relative location of the truck and infeed regardless of crane size. The truck to near storage is dependent only on span and cantilever length, meaning shorter span and cantilever lengths equal faster process times because the travel distance used in the calculations is half the total length of the portal crane. Conversely, the far storage to process is dependent on rail length, and to a far lesser degree cantilever and span length, meaning that larger span lengths benefit from faster process times since the required rail length is shorter the longer the span. The long storage travel distance is estimated at $\frac{2}{3}$ the length of the rail from the process in feed, assuming the process infeed is located at the center of the rail.

The same process is then repeated for each span length and their calculated rail lengths from the initial results corresponding to the required storage volume. The far storage and near storage are then summed and averaged for a general comparison time. However, using the initial ratio, this is further optimized to account for what kind of process is being done most of the time. The program then uses Boolean logic to compare the cycle times of the 2nd iteration results to all other possible results. If there is a faster process time, the span length corresponding to the fastest time is selected. Once the new optimized span length is established, an initial rail length is again indexed from the initial calculations for all cases after which the same process is repeated as was used to obtain the 2nd iteration results resulting in a new optimized rail length. The result is a 3rd iteration time optimized solution for the initial inputs.

7.3.1 Secondary module functions

The main secondary module that was studied was fatigue analysis. The key principle of the fatigue module is to, again, provide a comparison between different solutions. As mentioned earlier in this thesis the results are sorted according to minimum fatigue life and their corresponding critical joint. In the tool, after having calculated the six results we may end up with six different configurations. Sometimes the differences in process time may be marginal or the results are too close to call without deeper investigation. Most importantly, the user wants to be confident that the solutions that are presented can handle the required production volume and be structurally sound. Fatigue analysis provides a broader picture of the differences in capabilities of each configuration, even if it is only an approximation.

Essentially, when the results are calculated, the tool takes the combination presented in the solution and indexes through fatigue calculation results, that are near if not exact matches. The minimum fatigue life and critical joint location are then presented alongside the solution dimensions as an additional data point. With the critical fatigue life values visible next to each solution, an easy comparison can be made between different configuration, the difference can be substantial in some cases.

7.3.2 Tertiary module functions

The main tertiary module function studied in this thesis was a function to help making comparisons. A very rudimentary addition was made that automatically compared the results by calculating the increase or decrease of all the calculated results with one another. Similar functions that help visualize the collected data should also be considered, although none were implemented in this thesis.

7.4 Coordinate system

The entire model should be put into an individual coordinate system. Within the coordinate system, the origin should be placed at the process infeed, while the position of the crane system, the gantry, the log piles, and truck unloading locations should all be presented as their relative position to the process infeed. In this way, everything can be calculated and compared to the same end position of all the wood without tracking individual bins. The main application of a coordinate system is to be able to track and compare alternative loading

locations and storage strategies with one another using simple analytical geometry. The global coordinate system is only required to be on a 2D-plane as vertical lifts and differentials produce a marginal difference in processing times relative to the ones produced by gantry and trolley travel times. However, local coordinate systems for individual system components should take advantage of a 3D coordinate system to provide data points where necessary.

7.5 Future considerations

The modular design of this quotation tool allows for the inclusion of modules in the future. There were many proposals during the brainstorming process that were not included in the final proof of concept model, but merit discussion. The three main functions that merit further study are cost benefit analysis, environmental impact, and safety factors. These three modules would serve tertiary functions and help to provide additional detail to the results rather than function as individual optimization parameters. However, a coordinate system calculation method for cycle times should be implemented as a primary optimization parameter with which to calculate cycle time differences more accurately between crane sizes.

7.5.1 Coordinate system

The entire model should be put into an individual coordinate system. Within the coordinate system, the origin should be placed at the process infeed, while the position of the crane system, the gantry, the log piles, and truck unloading locations should all be presented as their relative position to the process infeed. In this way, everything can be calculated and compared to the same end position of all the wood without tracking individual bins. The main application of a coordinate system is to be able to track and compare alternative loading locations and storage strategies with one another using simple analytical geometry. The global coordinate system is only required to be on a 2D-plane as vertical lifts and differentials produce a marginal difference in processing times relative to the ones produced by gantry and trolley travel times. However, local coordinate systems for individual system components should take advantage of a 3D coordinate system to provide data points where necessary.

7.5.2 Cost benefit analysis

A cost benefit analysis tool should be created as a supporting secondary module. The goal of this module should be geared toward justifying the investment with numbers. The focus should not be on a direct cost estimation at this stage, but the module should rather be used to create a simple comparative analysis, comparing the proposed crane system to a traditional loader run wood yard. The module should be able to estimate average yearly cost savings and payback time. Lower labor costs can be justified through a reduction in labor requirements. Fuels cost reduction can be justified by calculating the smaller number of loaders needed. Beyond fuel costs, reducing the number of vehicles that require maintenance should be considered. Beyond direct costs associated with loader maintenance and fuel, the reduction of potential oil and fuel leakage into the group may be beneficial in certain locations where environmental damage may be particularly costly.

7.5.3 Environmental impact

The environmental impact of a crane operated wood yard compared to traditional layouts can be compared to one another by calculating CO2e (carbon dioxide equivalent) values for each method. This is, however, difficult to accurately estimate and should for that reason be a simple analysis. For the purposes of the proposed too, CO2 equivalents should be calculated mainly from the associated fuel and energy consumptions of each layout. At the most basic level, comparing the CO2 equivalent of the electricity used by the crane system with the fuel consumption of the required loader fleet. The source of the energy should be considered in this calculation by applying coefficients according to the environmental impact of the generation method, where, for example, wind energy would be valued higher than fossil fuels. Similarly, relative environmental hazards from, for example, oil spillage could be compared.

7.5.4 Safety factors

A safety comparison module would ideally include an approximation of the reduction in injuries when comparing the proposed crane setup with a comparable sized loader-based plant. A risk assessment is required to identify common safety concerns and adverse events in both cranes run operations and loader run operations. Using the gathered data, a probabilistic model should be created that gives a very broad view of the most critical parts

of the system. Next, the data should be used to identify the key areas that need to be addressed in both operations. The focus, of course, being on how the crane operation eliminates or greatly reduces the occurrence of those events when compared to loader type operations. [28] Furthermore, the risk profile of the suggested plant must include possible increased risk in the categories in which an increase is observed.

The metrics used should underline the unique needs of the pulp and paper industry, concerning wood yard operation. To promote coalescence with the other modules suggested in this thesis, the metrics should reflect the production volume. Thus, each solution characteristic production will serve as a variable in the safety approximation. This variable will remain constant between operational strategy comparisons and the characteristic probability model will provide coefficients for each process.

8 RESULTS

In this section the fatigue life calculation results for each configuration selected for analysis will be presented. Due to the large number of results from the models, due to high number of loads and elements, only the most critical sections will be presented. The most critical sections were selected based on areas where the calculations produce the shortest fatigue life value. Furthermore, the sections are selected with a consideration for comparability between different models. Most importantly the results should provide a basis to make determinations over which configuration is most suitable for a particular operation strategy. Additionally, the added benefit of a pylon structure compared to an identical structure without one will be studied in the analysis section.

8.1 Wheel loads

The wheel loads were taken from both fixed and hinged legs. The data was imported into an excel spreadsheet and the summed total wheel loads were calculated. The data is presented in kip units as dead load hinged (DLH), dead load fixed (DLF), fatigue load hinged (FATH), fatigue load fixed (FATF), wheel load hinged (WLH), and wheel load fixed (WLF). The results of wheel load analysis for the 65 m span section with 80 ft cantilever is presented in Table 11.

Table 11. Wheel load calculations from 80 ft cantilever configurations based on a 65 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]
A_2	75	50	44	16	119	66
B_2	68	50	44	16	112	66
D_1	60	51	33	23	94	74
E_1	82	42	43	18	126	61

The results of wheel load analysis for the 53 m long span section with 80 ft cantilever is presented in Table 12.

Table 12. Wheel load calculations from 80 ft cantilever configurations based on a 53 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]
HI_2_F	62	42	46	24	108	67
HI_2_H	62	42	46	24	108	67
H_1_F	53	48	34	24	88	73
I_1_H	78	42	46	19	124	61

The results of wheel load analysis for the 44 m long span section with 80 ft cantilever is presented in Table 13.

Table 13. Wheel load calculations from 80 ft cantilever configurations based on a 44 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]
QR_2_F	65	45	47	25	113	71
QR_2_H	65	45	47	25	113	71
Q_1_F	56	47	34	25	91	72
I_1_H	62	40	47	19	110	60

The wheel loads and maximum deflections of each model was additionally calculated using a larger 90 ft cantilever to approximate at which cantilever length the initial boundary conditions are broken. The calculations were done using the same worksheet and thus the variables remain the same. The wheel load results are for the 65 m, 53 m, and 44 m span configurations are presented in Table 14, Table 15, and Table 16 respectively.

Table 14. Wheel load calculations from 90 ft cantilever configurations based on a 65 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]	Pass
A_2_F	78	51	-14	24	64	75	OK
B_2_H	78	51	45	-5	123	45	OK
D_1_F	65	53	34	24	100	77	OK
E_1_H	85	45	43	18	129	64	Fail

Table 15. Wheel load calculations from 90 ft cantilever configurations based on a 53 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]	Pass
HI_2_F	65	49	17	25	83	74	OK
HI_2_H	65	49	48	7	113	56	OK

H_1_F	58	50	34	25	93	76	OK
I_1_H	81	38	48	19	129	57	Fail

Table 16. Wheel load calculations from 90 ft cantilever configurations based on a 44 m span.

Configuration	DLH [kip]	DLF [kip]	FATH [kip]	FATF [kip]	WLH [kip]	WLF [kip]	Pass
QR_2_F	68	47	20	26	88	74	OK
QR_2_H	68	47	50	-8	118	39	OK
Q_1_F	55	49	34	26	89	76	OK
I_1_H	73	40	50	19	123	59	OK

8.2 Deflection analysis

The maximum deflection results were taken directly from SAP 2000 and manually entered an excel spreadsheet, where the results were compared to the boundary conditions presented earlier to determine whether they pass. The results are presented in millimeters, where in the cantilever results L_C is the length of the cantilever being analyzed, $DefCant$ is the maximum deflection of the studied cantilever beam and $L/150$ is the maximum allowable deflection. The results of cantilever deflection analysis for the 65 m, 53 m, and 44 m span configurations are presented in Table 17, Table 18, and Table 19 respectively.

Table 17. Cantilever deflection results for the 65 m long span and 80 ft cantilever configuration.

Configuration	L_C [mm]	DefCant [mm]	L/150 [mm]	Pass
A_2_F	24384	154	162	OK
B_2_H	24384	105	162	OK
D_1_F	24384	154,5	162	OK
E_1_H	24384	116	162	OK

Table 18. Cantilever deflection results for the 53 m long span and 80 ft cantilever configuration.

Configuration	L_C [mm]	DefCant [mm]	L/150 [mm]	Pass
HI_2_F	24384	139	162	OK
HI_2_H	24384	95	162	OK
H_1_F	24384	139	162	OK
I_1_H	24384	99	162	OK

Table 19. Cantilever deflection results for the 44 m long span and 80 ft cantilever configuration.

Configuration	L_C [mm]	DefCant [mm]	L/150 [mm]	Pass
QR_2_F	24384	132	162	OK
QR_2_H	24384	90	162	OK
Q_1_F	24384	132	162	OK
I_1_H	24384	90	162	OK

In the deflection results of the span, L_S is the length of the studied span section, $DefD$ is the deflection caused by the dead load, $DefFat$ is the deflection caused by the rated load, $DefTot$ is the sum of $DefD$ and $DefFat$, and $L/888$ is the maximum allowable deflection in the span section. The span deflection results for the 65 m, 53 m, and 44 m span configurations are presented in tables Table 20, Table 21, and Table 22 respectively.

Table 20. Span deflection results for the 65 m long span and 80 ft cantilever configuration.

Configuration	L [mm]	DefD [mm]	DefFat [mm]	DefTot [mm]	L/888 [mm]	Pass
A_2_F	65532	32	39	71	73	OK
B_2_H	65532	32	39	71	73	OK
D_1_F	65532	36	40	77	73	Fail
E_1_H	65532	40	40	80	73	Fail

Table 21. Span deflection results for the 53 m long span and 80 ft cantilever configuration.

Configuration	L [mm]	DefD [mm]	DefFat [mm]	DefTot [mm]	L/888 [mm]	Pass
HI_2_F	56398	13	23	36	63	OK
HI_2_H	56398	13	23	36	63	OK
H_1_F	56398	16	23	39	63	OK
I_1_H	56398	18	24	42	63	OK

Table 22. Span deflection results for the 44 m long span and 80 ft cantilever configuration.

Configuration	L [mm]	DefD [mm]	DefFat [mm]	DefTot [mm]	L/888 [mm]	Pass
QR_2_F	44196	12	17	29	49	OK
QR_2_H	44196	12	17	29	49	OK
Q_1_F	44196	10	18	27	49	OK
I_1_H	44196	11	17	27	49	OK

The results of cantilever deflection analysis for the 65 m, 53 m, and 44 m span configurations with 90 ft cantilevers are presented in Table 23, Table 24, and Table 25 respectively.

Table 23. Cantilever deflection results for the 65 m long span and 90 ft cantilever configuration.

Configuration	L [mm]	DefCant [mm]	L/150 [mm]	Pass
A_2_F	27432	192	182	Fail
B_2_H	27432	135	182	OK
D_1_F	27432	192	182	Fail
E_1_H	27432	156	182	OK

Table 24. Cantilever deflection results for the 53 m long span and 90 ft cantilever configuration.

Configuration	L [mm]	DefCant [mm]	L/150 [mm]	Pass
HI_2_F	27432	174	182	OK
HI_2_H	27432	120	182	OK
H_1_F	27432	174	182	OK
I_1_H	27432	139	182	OK

Table 25. Cantilever deflection results for the 44 m long span and 90 ft cantilever configuration.

Configuration	L [mm]	DefCant [mm]	L/150 [mm]	Pass
QR_2_F	27432	165	182	OK
QR_2_H	27432	114	182	OK
Q_1_F	27432	132	182	OK
I_1_H	27432	114	182	OK

The results span deflection analysis for the 65 m, 53 m, and 44 m span configurations with 90 ft cantilevers are presented in Table 26, Table 27, and Table 28 respectively.

Table 26. Span deflection results for the 65 m long span and 90 ft cantilever configuration.

Configuration	L [mm]	DefD [mm]	DefFat [mm]	DefTot [mm]	L/888 [mm]	Pass
A_2_F	65532	26	39	65	73	OK
B_2_H	65532	26	39	65	73	OK
D_1_F	65532	33	40	74	73	Fail
E_1_H	65532	37	39	76	73	Fail

Table 27. Span deflection results for the 53 m long span and 90 ft cantilever configuration.

Configuration	L [mm]	DefD [mm]	DefFat [mm]	DefTot [mm]	L/888 [mm]	Pass
HI_2_F	56398	19	23	42	63	OK
HI_2_H	56398	19	23	42	63	OK
H_1_F	56398	14	24	38	63	OK
I_1_H	56398	16	24	41	63	OK

Table 28. Span deflection results for the 44 m long span and 90 ft cantilever configuration.

Configuration	L	DefD	DefFat	DefTot	L/888	Pass
QR_2_F	44196	25	5	30	49	OK
QR_2_H	44196	25	5	30	49	OK
Q_1_F	44196	10	17	27	49	OK
I_1_H	44196	11	17	28	49	OK

8.3 Fatigue analysis

Fatigue analysis was only conducted using one cantilever length: 80 ft. Since the intention of this thesis was not to calculate theoretical maximums, it is sufficient to get a relative fatigue life between various configuration using only one cantilever length. In total, 12 configurations where calculated, 14 if the pylon structures are considered.

The calculations produced three sigma sums on both the left and right side of each critical joint. This resulted in an enormous amount of data to sift through. The excel formulas were created to sift through the results and produce the results that represent the ten lowest fatigue life values each calculation produced. For the purposes of this thesis, only the top three will be presented as additional data proved redundant in a comparative analysis. The data is presented in terms of which *N* value the results represent, its corresponding fatigue life value in years, which sigma sum the lowest value was gathered from, and finally the name of the joint so that it can be found in the model.

The fatigue life results representing the three lowest values for all 65 m configurations are presented in Table 29, where fatigue life is presented in years.

Table 29. Fatigue life results for all 65m configurations in years.

Configuration	B_2_F [years]	A_2_H [years]	D_1_F [years]	E_1_H [years]

1	18	78	10	97
2	22	85	15	410
3	29	137	16	451

The fatigue life results representing the three lowest values for all 53 m configurations are presented in Table 30.

Table 30. Fatigue life results for all 53m configurations in years.

Configuration	HI_2_F [years]	HI_2_H [years]	H_1_F [years]	I_1_H [years]
1	22	132	22	141
2	38	169	39	459
3	40	412	72	576

The fatigue life results representing the three lowest values for all 44 m configurations are presented in Table 31.

Table 31. Fatigue life results for all 44m configurations in years.

Configuration	QR_2_F [years]	QR_2_H [years]	Q_1_F [years]	R_1_H [years]
1	20	310	17	263
2	37	388	33	339
3	52	854	52	772

8.4 Pylon calculations

The fatigue life characteristics of the unstiffened double cantilever configuration were already so good that the results of fatigue life calculations for the pylon model are unnecessary. The most interesting comparison is however the deflection results. The results of beam deflection analysis compared to the identical unreinforced model are presented in Table 32.

Table 32. Cantilever beam deflection results from pylon reinforced and unreinforced models.

Configuration	L [mm]	DefCant [mm]	L/150 [mm]	Pass
B_2_H	24384	105	162	OK
C_2_H	24384	80	162	OK

9   ANALYSIS

The calculation results will be analyzed in this section in the same order as the results are presented. Starting with the wheel load result analysis, followed by deflection analysis, and finally the fatigue calculation results will be discussed. The results will be analyzed mainly based on whether they meet design standards and boundary conditions as well as comparing different configurations with one another. For this thesis, the main point of interest is the comparison of different configurations and their strengths and weaknesses.

9.1 Wheel load analysis

Wheel load analysis of the models using 80 ft long cantilever sections all passed apart from E_1_H representing the 65 m long span section with one cantilever on the hinged leg side. Additionally, I_1_H representing the 53 m long span configuration with hinged leg side cantilever beam placement was just over 0,5 kip under the 125 kip limit. The results are to be expected considering that the hinged leg side can freely bend and works as a lever for the hinged leg. The single cantilever configuration does not have a corresponding cantilever that provides balance in the structures weight distribution or the stiffness of the fixed leg side that resists bending from the span side.

The 90 ft configurations caused the I_1_H configuration to similarly go over the 125 kip limit, while the R_1_H configuration representing the 45 m span section with hinged leg side cantilever placement came within just under 2 kip of the limit. Comparing the two results it is noteworthy that relative increase in wheel load on single cantilever hinged models is higher, the shorter the span of the configuration. The wheel load increased by just over 2,2%, 4,1%, and 11,8% for the 65 m, 53 m, and 45 m configurations respectively. The relative wheel load first doubling when comparing the 65 m and 53 m spans and again almost tripling when comparing the 53 m and 45 m spans. This is perhaps due to a direct affect the span length has in supporting the increased load in relation to increasing the cantilever length. While the length ratio increases for all configurations, the relative increase is larger in smaller span configurations. A similar mechanism could be at play in the 45 m span configuration, where the 80 ft cantilever configuration is the only layout in which the single cantilever hinged model has a lower wheel load than its two-cantilever counterpart.

From the wheel load data some general conclusions can be made regarding cantilever beams and wheel load. Lower wheel loads can be achieved using shorter crane spans and double cantilever or fixed leg cantilever configurations. However, longer spans are less effected by cantilever length increases, meaning that in some cases it may be easier to modify larger span sized because the relative increase in wheel loading is moderate compared to shorter span configurations. This is however only part of the equation and other factors must be considered when making the decision.

Fixed leg cantilever fatigue life is considerably lower than hinged leg or two cantilever configurations despite providing the lowest wheel load values. Similarly, it may be favorable to select a shorter span precisely because increasing cantilever length can be used to balance out wheel loads in the fixed leg due to various equipment installations. This same principle can be exploited in double-cantilever configurations with the use of cantilevers of different lengths.

9.2 Deflection analysis

Based on cantilever deflection analysis, all the configurations satisfy the boundary conditions placed on maximum deflection. In fact, the closest any model came to passing the limit was D_1_F representing the single cantilever fixed leg configuration with a 65 m span length, which was about 5% under the limit.

However, when the cantilever length is increased both D_1_F and A_2_F, representing the double cantilever fixed leg loaded 65 m span length configuration, go over the maximum deflection limit. As expected, although no other configurations with shorter spans went over the limit, all models had their largest deflection in fixed leg configurations where the cantilever beam has fewer degrees of freedom. Because the fixed leg cantilever is fixed, there is effectively no difference in total deflection between double cantilever and single cantilever counterparts. Conversely, in hinged leg configurations the double cantilever configurations appear to offer some support and produce a smaller maximum deflection.

The maximum deflection in hinged leg configurations were the largest in the models with the longest spans. The relative difference in maximum deflection between two cantilever

and one cantilever configurations at each span length interval halved between the 65 m and 53 m configurations from a difference of 11,7 mm in the former to just 4,1 mm in the latter. This perhaps shows that the shorter span length offers more resistance to bending over the hinged support due to greater stiffness. Interestingly, when analyzing their corresponding 90 ft cantilever configurations, the relative difference almost evens out to 21,5 mm and 19,6 mm respectively.

Both single cantilever, hinged leg configuration's deflection increases by an identical increment of 40,2 mm and suggests linear deflection growth regardless of span length. However, the longer span configuration increases by 34,4% while the shorter span increases by 40,4% The two cantilever configurations, however, increase at different rates, *the* 65 m span configuration increasing by 30,4 mm and the 53 m configuration increasing by 24,7 mm corresponding to a 28,9 % and 25,9 % increase respectively. Despite the initial figures suggesting otherwise, upon further inspection the single cantilever configurations have a greater relative increase in deflection compared to double cantilever configurations.

The calculations for the configurations using the shortest span provide interesting, if not dubious, results. Results from calculations using both cantilever lengths suggest that while the fixed leg results are identical to the ones obtained for the longer span length configurations, the hinged leg results paint an entirely different picture. The hinged leg results for both single and double cantilever configurations produce an identical deflection result with no perceivable difference. Assuming that the model is indeed valid, this suggests that somewhere between a span length of 53 m and 45 m the resistance offered by the span is identical regardless of configuration. This suggests that there is a span length at which, using the studied cantilever beam lengths, a threshold is reached after which behavior between double and single cantilever configurations begin to diverge. Finally, the results show that, regarding cantilever deflection, a 90 ft cantilever beam can be safely applied to all but the fixed leg side of the 65 m span configurations.

9.3 Span deflection

The span deflection results were somewhat more straight forward compared to the cantilever deflection results, showing that 65 m span length single cantilever configurations using either a 80 ft or 90 ft cantilever beam fail to meet the boundary conditions. Conversely, the

corresponding double cantilever configurations can withstand even the larger cantilever beam quite comfortably. Every examined configuration using shorter span lengths remain under the maximum deflection limit with both cantilever beam lengths.

Perhaps the most interesting discovery when examining the results is that all configurations using a 65 m span length produce a smaller maximum deflection when the longer 90 ft cantilever beam is applied while the reverse is true for all other span lengths. This suggests that there is a span length between 53 m and 65 m where additional cantilever length decreases rather than increases maximum span deflection when using the studied cantilever beam lengths. Furthermore, the configurations using the shortest span length shows an almost identical result for both double cantilever and single cantilever configurations.

9.4 Fatigue analysis

The fatigue analysis results present a clear and unambiguous picture about which configurations should be seriously considered for further analysis. Each span length shows conclusively that the fatigue life of configurations with the main operational cantilever on the fixed leg side offer far shorter fatigue life capabilities than their hinged leg counterparts. Hinged leg configurations, at worst, have a fatigue life that is over 4,2 times longer than their fixed leg counterparts, as is the case when comparing A_2_F and B_2_H. The most dramatic difference is observed between Q_1_F and R_1_H, both representing single cantilever configurations with a 45 m span, where the fatigue life of the hinged R_1_H configuration offers a fatigue life that is over 15 times longer than its fixed counterpart.

These results indicate that whenever possible hinged side cantilevers should be selected and in two cantilever configurations fixed side cantilever usage should be limited only to necessary lifts. Considering the considerable limitations of fixed leg configurations compared to hinged leg configurations, it is reasonable to rule them out entirely as viable choices in standard setups. Although, with further modification and design work, perhaps a design could be developed which would produce a more desirable result.

The results show that regardless of hinged configuration the shorter the span the longer the fatigue life calculation, as expected. The relative fatigue life when compared to span length is much higher in shorter span lengths.

When comparing the fatigue lives of both hinged configurations of each span length, the highest fatigue life observed changes according to span length. In the largest 65 m configurations the higher fatigue life is achieved in the single cantilever configuration. The same can be said for the 53 m configuration, although the difference is smaller. However, in the 44 m configuration, the opposite is the case. The two-cantilever hinged configuration has a much higher fatigue life than their single cantilever counterpart: both in raw numbers and relative difference. As has been the case in both deflection analyses, there is a span length between 53 m and 44 m at which, using a 80 ft cantilever beam, two cantilever configurations should be favored when maximizing fatigue life is desired for the application. Of course, by the time that breakpoint is reached, the fatigue life values are high enough in this specific case that it may not matter. However, the differences can be considerable given different starting variables and loading cases so it must be determined on a case-by-case basis.

9.5 Pylon analysis

Even a simply modeled pylon stiffener provides considerable fatigue life benefits, providing anywhere from 2 to 5 times the fatigue life depending on the load case. However, in a practical sense, the increase is irrelevant. The more interesting subject is the over 20 % reduction in total cantilever deflection. This suggests that a longer cantilever beam is a possibility that should be studied further. Of course, the structure must still be balanced accordingly to accommodate the weight increase from the pylon structure and longer cantilever beam.

When comparing results for the double cantilever models both with and without pylons on either end it is apparent that it is almost always preferable to place the infeed on the hinged leg side to greatly reduce the additional stresses caused by continuous use of the fixed leg. Similarly, even a simple pylon structure provides a very large increase in fatigue life in the most critical areas while the reduced fatigue life in joint connection areas is negligible for the most part. A pylon model was created for the fixed leg consisting of 4 support beams coming from each leg.

These results show that while hinged configurations are preferable, in usage cases where the fixed leg infeed is preferable, a pylon supported structure is a feasible solution, provided that by doing so, the wheel loads are not exceeded. Further study and calculations must be conducted to determine whether the added weight of this type of structure would produce negative effects that outweigh the potential benefits, including cost relating to capital investment, maintenance costs and overall life in other areas. Given, however, the very large increase in fatigue life at the most critical joints, it is likely that there are cases in which this would be a realistic option.

9.6 Tool analysis

The tool creation process can successful and was able to achieve the goals of this thesis. The resulting tool can be used to reduce the time between receiving customer specifications to providing the customer with an initial proposal. The tool can be used to effectively cut out the dynamic load and fatigue calculation processes during the initial phases of iteration, by approximating initial crane specifications that satisfy the customers requirement. The tool provides viable solutions by presenting pre calculated configurations with which the customers' requirements can be satisfied. Using the tool, the need to calculate several different iterations in each case is unnecessary in the proposal phase as the precalculated results provide a reasonable approximation that can serve as a indicator of what can be offered. Of course, the tool does not circumvent the process entirely, nor does it aim to, because once an agreement is reached on the general specifications, the real calculation work can commence, but this time with an initial approximation which provides a strong starting point.

The pre calculated models were selected based on their statistical prevalence in previously sold crane configurations and represent the most common combinations and sized. They were thus selected to be both representative of past projects but also serve a predictive function for the most likely configurations that should be considered in the future. While the program itself does not implement a database, it serves as one in a figurative sense; a database model would ideally be created as the backbone for a fully developed tool.

The tool was successfully tested and used in a real-world proposal for a project within the Andritz. The tool was able to provide a set of approximate solutions from which the

experienced engineers were able to extrapolate realistic specifications that could provide an initial approach for the proposal. Based on feedback, a quality-of-life module was created which creates a printout of the most critical approximation information needed for quotation purposes, an example of which is presented in Figure 26.

ANDRiTZ

```
Production Volume:        2900000 m3/a        2508491 tons/a
Storage for 1 months:     241666.7 m3/mo      209040.9 tons/mo

Pile height:     10.0584 m
Cantilever 1:     25.908 m
Cantilever 2:     19.812 m

Single Cantilever configurations
First result
Span:            56.388 m
Rail:            528.852 m

Second result
Span:            65.532 m
Rail:            465.314 m

Double cantilever configurations
First result
Span:            44.196 m
Rail:            509.444 m

Second result
Span:            65.532 m
Rail:            393.144 m
```

Figure 26. Example printout of the QoL module created for the tool based on feedback.

10 DISCUSSION

This thesis set out to find different methods and solutions for a problem that was presented by Andritz. The development of a tool that can be used to quickly approximate possible products that can be offered to customers, given specific constraints. The problem seems rather simple on the surface, but underneath the surface a complex network of cause and effect must be considered. It is simple enough to create a tool that mechanically calculates values and variables based on its inputs, but it is quite another thing to make it simple and easy to understand.

The tool should not only provide a list of raw data that has no meaning without context, but it should provide data that can be used to paint a picture. To contextualize simple figures and complex equations, one must understand what those figures and equation mean and why they are important to telling the story. It is one thing to show a customer what you can offer or how you can offer it. It is something else entirely to also show potential customers why you are offering a certain product and the reasoning behind it.

Throughout this thesis, an attempt was made to keep the customer at the heart of each process. To put it more bluntly, if it didn't make sense for the customer, it didn't make sense. To that end, the market analysis section of this thesis was dedicated to finding out characteristics of the target regions, their trends, and what is important to local companies operating pulp mills. This led to the identification of key points of emphasis that play a large role in decision making, especially regarding investing in new technology.

Some regions were shelved early due to social factors and labor market considerations like extremely cheap labor which all but precludes investing into automated systems because they would, in fact, increase their overhead. Other regions were, conversely, selected for similar reasons: high labor and fuel costs. The two selected regions hosted a multitude of factors that overlapped in key areas, while still providing their own opportunities.

10.1   Limitations

The calculations in this thesis are only general representations that are mainly used for comparison purposes. They are not exhaustive calculations that should be used to draw conclusions of real-world capabilities. They are, however, representative of the relative advantages and disadvantages between different crane configurations. It was noticed late in the thesis writing process that two of the models used, E_1_H and I_1_H, a slightly shorter cantilever beam section that all the other models. Fortunately, it was determined that the resulting difference in fatigue life values would not change the results of the comparative analysis, so they were not recalculated. The cantilever beam sections were, however, changed for both the wheel load and deflection analyses.

Another limitation of this thesis is due in part to the broad topic. Each section of this thesis could themselves be written about extensively within their own academic fields. Due to both the time and scope restrictions, it was simply not possible to give each section the attention that they deserve, and many compromises had to be made to keep the thesis within a reasonable scope. On the other hand, this forced the writer to give serious thought towards what are the key themes of the thesis and what is necessary to present. As a result, a better understanding of the big picture was developed, which produced a more cohesive presentation of the subject.

Near the end of this thesis, it was easy to overlook the groundwork done in the market research section and the statistical analysis that accompanied individual portions of this thesis. However, in retrospect, the information gathered during those processes is an excellent result and serves the goals of this thesis well. At the end of the day, the tool is just a way to manage and manipulate the information gathered, while the compiled data itself is what is valuable in the long run. The resulting compilation of the basics of woodyard operation and Andritz cranes alongside a historical perspective and statistical as well as computational data gives the user a starting point and tools from which to tackle potential challenges in Andritz portal crane woodyard operations.

This topic presents many opportunities for further research. It is a very broad subject and requires a multi-disciplinary approach; a much broader scope that one person can tackle alone. The real-world implications, however, make it a worthy subject to study from any

number of angles to produce systemic improvements in how pulp and paper mills are operated, designed, and maintained. In the era of IoT 4.0 and an ever-increasing reliance on connectivity, analytics, and automation, the pulp and paper industry is an especially ideal candidate to take advantage of emerging technologies, due to its vertical integration and competitive environment. Automation is already starting to take place and as it gains acceptance, the desire to increase automation and process integration will lead to new challenges, but even greater rewards. As was the case in the Nordics in the 1800s and South America in the mid-1900s, a new advancement in technology is again ready to shift the market, where the winner will be they who seizes the opportunity and implements new technology to suit their capabilities and restrictions. While concepts like digital twin and fully automated smart factories may not be mature enough for pulp and paper industry applications, the next best thing may be just around the corner.

11 CONCLUSION

During the process of completing this thesis, many different areas relating to portal crane implementation were studied. This topic has endless topics to take a deep dive into and unfortunately, within the scope of this thesis not all of them could be explored. However, the scope of this thesis was sufficiently constrained to produce a suitable niche with which the initial questions could be answered.

Market analysis was conducted from a historical perspective to both give context to the current market climate as well as provide potential factors with which to better predict future development. It was discovered that while the methods and location of the industries leaders changed, the underlying principles remain the same: technology is king. Each paradigm shift was preceded by a technological advancement that provided others with a competitive advantage over others, while in some cases everyone benefitted from the same advancements in different ways. The underlying theme of the industry has been and continues to be a focus on centralizing firms into larger entities and vertical integration to take advantage of both economies of scale and a higher capability of adopting the newest technology through R&D investment, compared to the more modest investment potential of smaller firms.

Layout optimization was determined to be an almost impossible task ahead of time, beyond broader general principles that guide all cases. No matter how much one prepares and analyzes past cases, the fact remains that the layout of a woodyard is driven by the site itself. This led to the conclusion that the best way to develop wood yards is to start from what is possible to do with the customers' requirements and then hammer out the details once a better grasp of the site is obtained by site visits.

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