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Design and optimization of a light-weight aluminium gantry system

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DESIGN AND OPTIMIZATION OF A LIGHT-WEIGHT ALUMINIUM GANTRY SYSTEM
Design og optimalisering av lettvektsløsning for skiltbrosystem i aluminium

Since 1995, Lattix has developed, manufactured and delivered light-weight gantry system solutions for road traffic and other applications. In addition to low weight, the competitiveness of their products is closely related to capabilities such as total system delivery, design agility, delivery time, customization, visual appearance and maintenance cost. The main challenge, however, is cost—which is driven by material cost (aluminum extrusions), high degree of customization, lack of standardization of solutions, components and subsystems, less than optimal base designs, amount and cost of purchased components, manufacturing (manual in/house processes), field assembly, etc. To be able to sustain competitiveness in existing markets and possibly expand into new markets with large gantry systems, it is therefore desirable to, rather than handling the projects as single opportunities more on an ad-hoc basis, establish a common design platform suitable for mass-customization. This essentially means a stronger focus on standardization of design solutions and processes while maintaining the capability to tailor-make gantry systems for individual customer needs.

The overall objective of this MSc thesis is to establish a design strategy along with robust design solutions for future gantry systems with primary focus on value outcome as represented by maximizing the perceived customer benefits-to-cost ratio. In order to achieve this, the student shall perform, but not limited to, the following tasks:

- Literature review to establish an overview of suitable design strategies based on principles from mass-customization,
- Establish an overview (literature, www, etc.) of innovative node configurations for truss type structures in aluminum and steel,
- Conduct need finding by customers, suppliers, manufacturers and other stakeholders to establish an overview of needs and wants associated with gantry systems,
- Perform a business case comparison of one selected existing gantry system from Lattix with one selected gantry system from a competitor, with primary focus of establishing a model breakdown into manufacturing logistics, material and work (man-hours) cost elements. The goal is to use this approach as basis for design decisions related to a new, more cost-effective gantry system.

- To establish conceptual solutions for key elements of a gantry system, using an existing system and requirements as reference. These elements include overall solution for the vertical columns, the corner connection/joint between the column and the boom, the connection between boom members and the connection and cross section of the truss diagonals, including joining configuration.
- Systematically evaluate different alternatives using a Pugh type matrix to indentify the most promising design alternatives for the above concepts. The evaluation matrix has to reflect underlying characteristics associated with the challenges described above.
- Work with suppliers and project members to assess and resolve manufacturability and assembly issues associated with the design solutions, with the goal of identifying a mainstream design,
- Use rapid prototyping techniques (3D printing, wood, plastic, paper, etc) to make tangible rough parts for physical visualization.
- Conduct verification of structural performance using FEA or analytical calculations. Evaluate potential for weight/material cost optimization based on findings,
- To make breakdown structure including bill of materials, process route, layouts and cost, and compare with existing reference model,
- To establish the design strategy including classification of consumables, purchased parts, core parts and subsystems (preferred and acceptable), and strategic parts and assemblies (preferred and acceptable)
- Report, document and summarize the results obtained in this study

The thesis should include the signed problem text, and be written as a research report with summary both in English, Portuguese and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the Master's thesis is submitted.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's thesis.

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Abstract

Lattix has developed, manufactured and delivered light-weight Gantry systems for road traffic support since 1995. Besides the low weight, their products are competitive due to capabilities such as the total system delivery, high design agility, on-time delivery, possibility of customization, appealing visual appearance, low maintenance cost, and more. Nevertheless, the main challenge is to reduce the total cost. It embraces the material cost, purchased components, assembly and installation cost, and, the most important driver, the customization cost. A lack of standardization solutions, components and subsystems that enable to have a product matrix that covers a wider range of customers' needs requires engineers to redevelop existing solutions to make them fit to specific customer needs. In order to be able to sustain competiveness in the existing markets and allow the possibility of expanding into new growing markets, a common design platform across the variants that provides possibilities for mass-customization is desired. The challenge can be summarized as the focus of creating standard design solutions, which maintain the capability of tailor-make Gantry systems accordingly with individual customers' needs. Therefore, a new gantry will be developed in this work, having a holistic product perspective with the final goal of minimizing the total cost and maximizing perceived customer value. In order to achieve that goal, cost evaluations will be performed to different Gantry concepts.

Keywords: *Lattix*, Gantry, cost, design

Resumo

A empresa *Lattix* desenvolve, produz e distribui portais de baixo peso para suporte ao tráfico rodoviário desde 1995. Apesar do baixo peso, os seus produtos são competitivos devido a capacidades tais como distribuição total do produto, agilidade no projecto, tempo de entrega, possibilidade de personalização, boa aparência visual e baixos custos de manutenção. Contudo, o maior desafio é a redução do custo. Este engloba o custo do material, componentes comprados, custos de montagem e instalação e, o factor mais importante, custos de personalização. A falta de soluções *standard* (componentes e subsistemas que permitam ter uma matriz de produtos que cubra um leque maior de necessidades dos clientes) requer que os engenheiros re-desenvolvam soluções existentes de modo adaptá-las a necessidades de clientes específicas. De modo a garantir competitividade nos mercados existentes e permitir a expansão para mercados emergentes, é desejável estabelecer uma plataforma comum de projecto que permita uma filosofia de personalização em massa. O desafio pode ser resumido no objectivo de criar soluções de projecto standard, que mantenham a capacidade de produzir portais específicos de acordo com necessidades individuais de cada cliente. Portanto, um novo portal será desenvolvido neste trabalho, tendo uma perspectiva holística com o objectivo final de minimizar o custo e maximizar a percepção de valor por parte do consumidor. De modo a cumprir este objectivo, análises de custo serão efectuadas a vários protótipos de portais.

Palavras-chave: *Lattix*, portal, custo, projecto

Sammendrag

Lattix har utviklet, produsert og levert lettvekts portalsystemer brukt som supplement for veitrafikk siden 1995. I tillegg til den lave vekten, er produktene deres konkuransedyktige grunnet egenskaper som totaleveranse, enkelt design, punktlig levering, mulighet for tilpassning, tiltrekkende utseende, lave vedlikeholdskostnader, med mer. Likevel så er hovedutfordringen å ha en lavest mulig totalkostnad. Den omfavner materialkostnad, innkjøpte komponenter, montering- og installasjonskostnad, og tilpassningskostnad (hovedtyngden ligger her). At det ikke finnes standardløsninger, komponenter og undersystemer som vi kunne ha kombinert i en produktmatrise som hadde dekket mer av kundenes behov, gjør at ingeniørene må redesigne eksisterende løsninger slik at de passer kundendes spesifikke behov. For å kunne opprettholde konkurransedyktigheten i eksisterende marked og åpne for nye, voksende marked, anbefales det å lage en felles designplatform som gir mulighet for masse-tilpassing. Utfordringen kan bli oppsummert som å lage standard designløsninger, som har mulighet for skreddersydde portalsystemer etter kundenes behov. Derfor vil et nytt portalsystem bli utviklet i denne oppgaven, med et helhetlig produktperspektiv med et mål om å minimere totalkostnaden og maksimere tilsynelatende kundeverdi. For å nå dette målet, vil kostevalueringer bli gjennomført mot forskjellige portalkonsepter.

Nøkkelord: *Lattix*, portal, kost, design

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List of Acronyms

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

CNC – Computer Numerical Control

Cu – Copper

FEA – Finite Element Analysis

HSFG – High Strength Friction Grip Bolt

Mg – Magnesium

Mn – Manganese

QFD – Quality Function Deployment

REF – Reference

Si – Silica

VMS – Variable Message Sign

Zn – Zinc

Symbols

A – Projected exposed area

B – Profile’s width

c_d – Drag coefficient

E – Young’s Modulus

EI – Stiffness

F_d – Drag force

F_{wind_VMS} - horizontal load from the wind on the *VMS*

H – Profile's height

h – *VMS*'s height

H_y – Gantry's height

I – Second moment of inertia

K – Length factor

L – Beam's length

l – *VMS*'s width

M – Moment

P – Concentrated load

P_{cr} – Critical axial load

q – Uniformly distributed load

S – Gantry's span

t_B – thickness of the profile's horizontal walls

t_H – thickness of the profile's vertical walls

v – Wind's velocity

W - Weight

x – Distance from the beam's supports

δ – Deflection

δ_{max} – Maximum deflection

θ – Angle of the deflection

ρ - Wind's density

1. Introduction

1.1 Background

Over the last years, across many different industries, words like *safety* or *efficiency* are playing a more and more important role. A product or a business model that enhances the customer’s safety will have added value. Analogous, the constant attempt to increase efficiency with the goal to reduce cost and waste, and increase manufacturing productivity, results in a high-quality product and thus enhances the perceived added value for the customer.

Regarding traffic, a global challenge is the increasing of road safety by managing the traffic flow, avoiding congestions and potential danger situations for the drivers. Therefore, it becomes important to signs or visual traffic systems to enable communication with the drivers. For support of these systems, adequate safe and cost-efficient support structures are required.

In an industrial and economical point of view, a traffic support product must be cost effective and have an efficient use of material. It needs to fulfil the mechanical requirements in order to provide a safe structure for the road users and perform its role in traffic management. For the producer avail, to be competitive, the design should have an aim of minimizing development and manufacturing costs.

1.2 Objectives

This work will focus on long span Gantry systems. The goal is to design a light-weight aluminium Gantry from a holistic benefit-cost perspective. This means, to design a functional system regarding the entire life-cycle of the product, considering development, manufacturing, assembly, installation, and recycling.

The objective of this work is to establish a design strategy along with robust design solutions to be used in future Gantries, which allows a reduction of the total cost in comparison with the current solutions and maximizes the customers’ perceived value.

The work will focus on developing a strategy that allows the use of standardization principles enabling the creation of a product matrix that can fulfil a wide range of the customer's needs. It is believed that following this approach re-engineering for new deliveries can be avoided since products, in future, can be configured out of a set of pre-developed elements.

Here, a balance between standardization and modularity and the possibility of configurability needs to be found to provide the customers a high value while at the same time reducing internal cost.

Mass-customization principles, which ally standardization with customization, leading to maximizing the product value and minimizing the costs, will be considered. The proposed design will be evaluated and developed applying various methodologies. A set of different structural Gantry configurations will be assessed. Then, a new concept will be developed in detail, where its solutions will be analysed and evaluated critically following a logic pattern.

1.3 Scope of Work

To describe the necessity and understand the purpose of using Gantries, this work will start by presenting the basics of traffic management in Chapter 2. Also, the products used for traffic support, including Gantries, will be addressed, as well as their main production process, materials and connection methods.

After a brief presentation regarding the methods to be used in this work (Chapter 3), the requirements associated with a generic Gantry system will be presented. Then, different Gantry concepts will be described (Chapter 4) and subjected to the evaluation methodology (Chapter 5).

With the results of the referred assessment, a Gantry model will be further developed (Chapter 6), with the focus on the design of the connections between the different parts. The major topics related to the proposed design will be addressed, as well as the remaining uncertainties and weaknesses of the design (Chapter 7).

Lastly, after summarizing the results and solutions proposed (Chapter 8), some suggestions for further works related with the contents addressed in this document will be presented (Chapter 9).

2. Basics of Aluminium Gantries

This chapter will cover the necessities of using Gantries for traffic managing purposes. Further it will embrace the different types of traffic support structures and their structural configurations. It introduces the relevant manufacturing processes for the subject and the importance of the mass-customization principles. Lastly it discusses the use of aluminium as the chosen material for the Gantry system as well as the different options for connecting structural parts.

2.1 Traffic Management

Introduction

In present times, it is possible to observe a continuous increasing in the number of automobiles that travel globally. It's noticeable that automotive brands are making an effort to reach more economical markets by extending their models' range to an entry level segment, which gives access to more people capable to own an automobile. Besides that fact, there are several big countries with fast developing rate. This results in increasing economic power for the masses and consequently a proliferation on the transportation segment.

In the following chart, the global tendency to continuous increasing of vehicle production is visible.

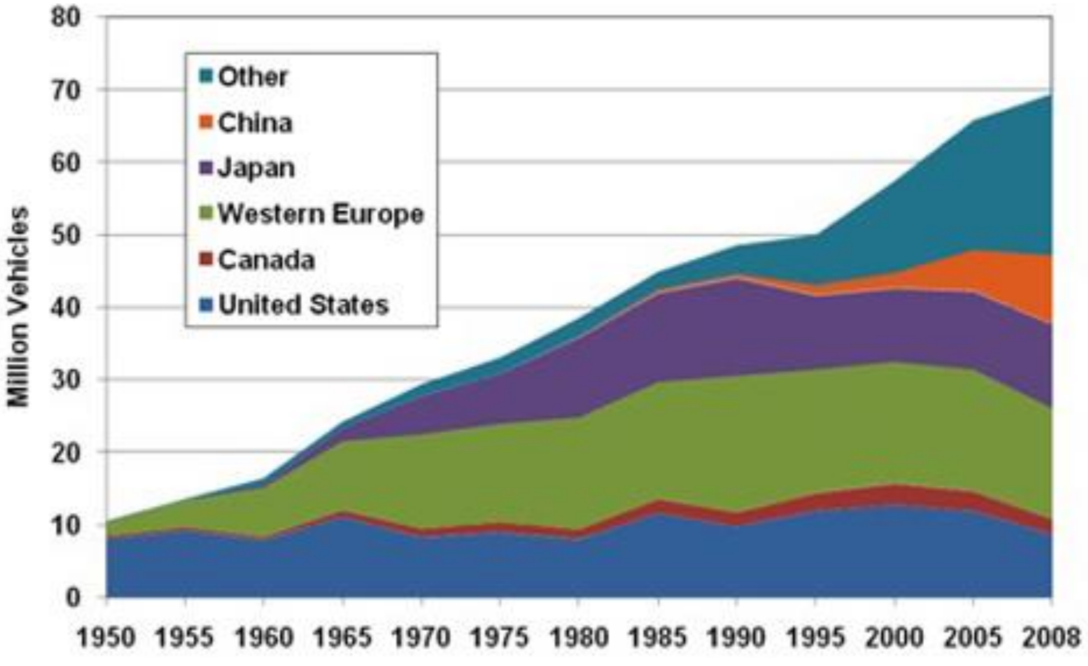


Figure 2-1: **World Motor Vehicle Production from 1950 to 2008 - In *Vehicle Technologies Office***

As a result of a larger number of vehicles, there is a propensity for roads to be overloaded with traffic. In order to balance this global overload, a natural trend is to build more roads, which is the current situation in fast growing countries, creating a big demand for traffic support structures. But, in the more developed countries, mainly in Europe and North America, there is a smaller potential for road expansion due to the high level of space saturation, or, in other words, the space available for road construction tends to be more limited.

After this short introduction the importance of traffic management arises. With smart traffic management the usage of roads can be optimized, which reduces the need for expanding the road network.

Traffic Management

The goals of traffic management are to provide a safe, predictable, and orderly flow of traffic (Lay, 2009). Besides making the road usage safer and more efficient, the traffic control enables the road users to comply with the legal regulations (Slinn, Guest & Matthews, 2005). There are several different types of traffic managing devices with the purpose of instructing, guiding and informing road users or identifying warning situations, but for the purpose of this work it will be focused the Signs, the Signals and the Variable Message Signs.

In a very short explanation and according to the *Highways Agency* (an Executive Agency of the Department for Transport from UK), the main difference between Signs, Signals and Variable Message Signs is the following: a Sign carries a directional or other informational static and unchanging messages, whereas a signal is a device that uses lights to give advisory or compulsory instructions, and finally a Variable Message Sign can display different types of changeable messages in the form of text or symbols.

Gantries' Role

On multilane roads it is imperative that all users can access simultaneously all the messages displayed. Therefore, in many applications, it is convenient that the messages lie on top of the road instead of on one of the sides, in order to improve the visibility for the users of all the lanes. In multilane roads sometimes it's needed to give different messages to each lane, which must result in top displayed messages. The structures that support signs or signals over the road are named Gantries and they play an important role on traffic management, mainly on highways where there are at least two lanes in each direction.

The next topic will, in more detail, focus on the different types of structures that support the relevant information to the road users, but, since this work consists in the design of a Gantry, it is relevant to discuss the role of such structures as well as the need for using more of them.

One of the difficulties of informing drivers, especially on the highways, is that with speed the amount of information perceived is decreased. Because of this fact, there is a requirement dictated by the *Highways Agency* that has the goal of avoiding the overload of information. It requires that signs and signals must not be mixed in the same Gantry.

> *"The functions of displaying signs and signals on Gantries shall be separated"*
>
> (Highways Agency, 1998)

To be able to abide by this norm, the necessity of Gantries is increased in order to clarify and divide the amount of information from a longer distance over any type of road.

2.2 Products for Traffic Support

In this section the different types of products used for carrying traffic information or lighting purposes as well as their main structural configurations will be addressed.

2.2.1 Gantries, Cantilevers and Masts

Gantries are portal shaped structures, normally with two vertical masts and a horizontal transom (also called boom) connecting them, which can cover significant large spans. An example of a Gantry configuration can be visualized in the figure below.

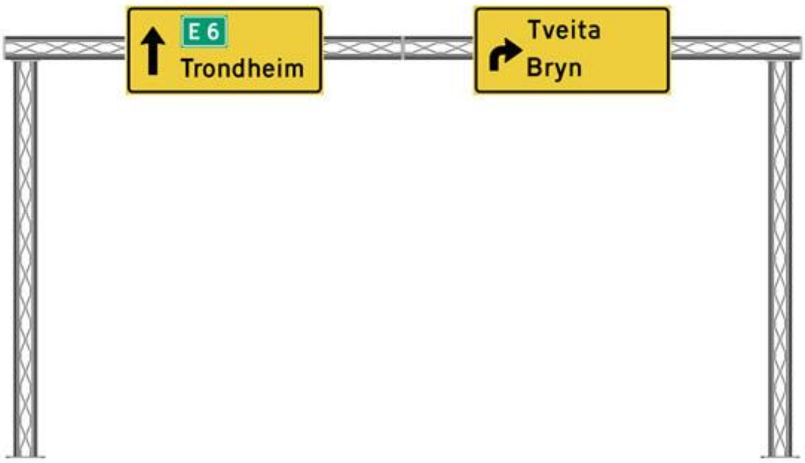


Figure 2-2: Example of a Gantry - In *Lattix*

Another type of structures named Cantilevers can also be used, with similar characteristics as the gantries but only for shorter spans. Often, Cantilevers are used on urban roads due to their relatively short spans. These structures can have a “T” shape or a simple 90 degree shape. Two examples are shown below.

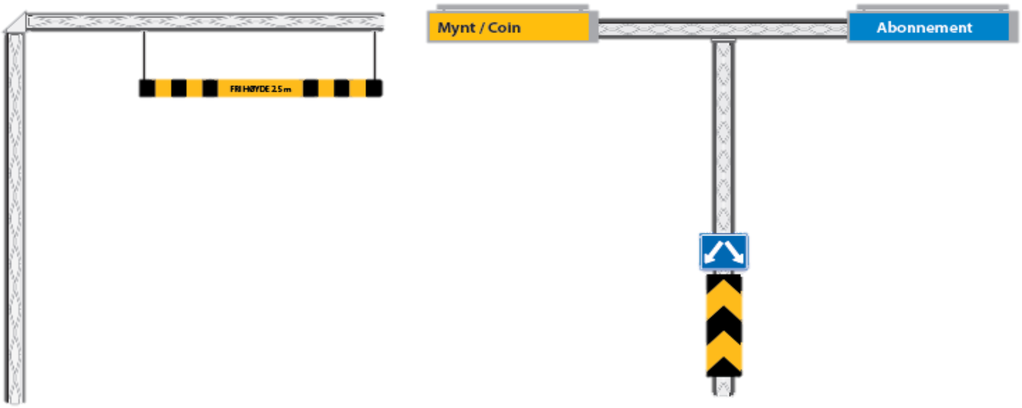


Figure 2-3: Example of Cantilevers - In *Lattix*

Lastly, the Masts are responsible for all the vertical signalling or lighting. These are the most common and more versatile structures and besides being used in rural and highway roads they are massively used in urban environments. Below it is presented an example of a Mast holding a sign.

Figure 2-4: Example of a Mast - In *Signway*

2.2.2 Type of Structures

This section addresses the structural configurations of a Gantry system.

As the Gantry systems need to cover a considerable span, especially the ones over highways (may reach about 30m), they should be as light as possible and able to transfer properly the loads to the masts (or legs). Considering this, several possible and viable solutions are either to resort to a frame, a truss configuration, or even a hybrid solution.

Frames

In this section, the concept of rigid frames will be introduced. In literature, occasionally these structures can be also referred as portals.

A rigid frame is a structure that typically has two vertical columns, which in a Gantry system correspond to the masts. These are connected to a horizontal beam, the boom in a Gantry. Regarding rigid frames it is important to highlight the nature of the joints between the columns and the beam. The joints are rigid, which implies that no relative rotation occurs between the two members. Therefore, the angle of the joint remains constant when loads are being applied to the structure.

Before going into further details as to the nature of the rigid joints and their consequences to the structure, it is pertinent to introduce two simple concepts: A beam fully fixed on both ends and a beam with both ends pinned. The difference between these two configurations results in a big difference regarding the type of forces induced to the supports, which, in the case of a frame, are the joints with the columns.

Both supports, in a fully fixed beam in its extremities, restrain either the vertical and horizontal movement but also the rotational degrees of freedom. This means that in the case of a single vertical central load applied, besides the vertical component of the supports' reaction, there will appear a bending moment reaction as well, since the rotational movement is also constricted. In the drawing below it is possible to visualize the described behaviour.

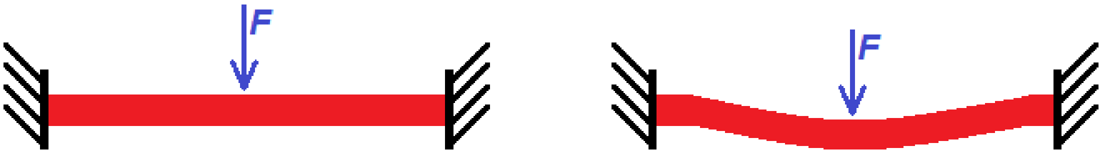


Figure 2-5: Behaviour of a beam fully fixed in both ends subjected to a vertical load

Contrasting with the previous case, a doubly pinned beam allows the rotational movement at the extremities. This means that the reactions at each support will consist only of the vertical component, considering the same single vertical load applied. As before, in the drawing below is represented the described behaviour.

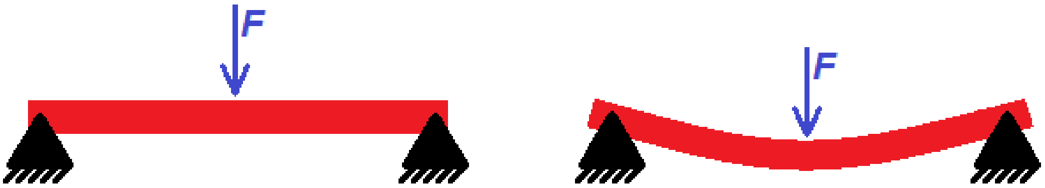


Figure 2-6: Behaviour of a beam fully fixed in both ends subjected to a vertical load

Comparing the structural performance between the two presented concepts and regarding the supports' reactions the fully fixed beam demands more robust supports than the pinned beam. Regarding to the rigidity, the fully fixed beam will perform with smaller deflection and smaller internal bending moments hence a higher stiffness (Schodek & Bechthold, 2008).

With these two concepts briefly introduced, the subject regarding rigid frames shall be resumed.

The joints in a rigid frame are, as the name implies, rigid, constraining all degrees of freedom. Thus, the horizontal beam should perform like the first case introduced: a fully fixed beam on both ends. The core of the topic lies on the fact that instead of a single support at each extremity the horizontal beam is supported by a vertical column. The column is fixed to the foundation and, by the rigid joint, the column and the beam work as one. This means that when vertical loads are applied, the whole joint tends to rotate together, where the angle between the two elements remains approximately constant.

The implication of what has been just stated is that the behaviour of a rigid frame lies somewhere between a fully fixed beam and a pinned one, since the rotation of the extremities is constrained to a certain degree. This means that the columns are either subjected to an axial load but also to bending moments, which requires high stiffness for both the horizontal beam and the vertical columns.

It is also necessary to analyse the rigid frames' capacity to resist to lateral loads. If pinned joints were used, the ability of a frame to resist to horizontal loads would be minimal or even null. Being the joints rigid, the rigid frame is capable of resisting lateral loads with the joints enabling the transfer of loads from one column to the other. In case of an exposure to greater magnitude lateral loads, it may be necessary the reinforcement of the joints using bracings or even resort to a trussed horizontal section. The goal of such reinforcement would be to reduce internal forces and moments. This issue reveals the lower efficiency of the frames when subjected to horizontal loads.

Many Gantry systems use the configuration of rigid frames. They are usually made of steel. The joints are normally welded to the columns and consist in a flange that connects to the beam. There are a lot of different ways to connect the beam to the columns using mainly welding technologies. Below some Gantries with a rigid frame configuration are shown.

Figure 2-7: Example of a framed Gantry 1 - In *Skyscrapercity*

Figure 2-8: Example of a framed Gantry 2 - In *Público*

Trusses

A truss is theoretically defined as a structural system, where all the single parts are applied to compression or tension. Thereby, its members only carry axial loads to the respective nodes, or in other words, to the intersection between them (Nageim, Durka, Morgan & Williams, 2010). This way the members are treated like bars, without bending, torsion or shear being applied. The nodes are considered pinned and frictionless. Therefore, they don't restrain rotation. All the external forces and reactions are applied only on the nodes.

A truss system is arranged in a triangular framework, which provides a stable modular configuration (Schodek & Bechthold, 2008). They can be considered plane trusses, if the truss and the applied forces are in the same plane (as the name suggests) or space trusses if the forces and the truss elements are laid on the three dimensions. Below some applications of these structural systems are shown.

Figure 2-9: Example of a trussed bridge (London) – In *Bristol*

Figure 2-10: Example of a space truss (King's Cross Station, London) – *In* Now-here-this.timeout.

Despite the definition of truss, in the real world, these structures have connections that behave like fixed joints, instead of frictionless pinned joints, where the loads are applied. Thus their elements are also subjected to bending, torsion and shear, and they perform like beams instead of bars. Nevertheless, the predominant forces are still the axial ones.

Below some examples of trussed Gantries are shown, where both the boom and the masts have a truss configuration.

Figure 2-11: Example of a Trussed Gantry 1 – In *Sapagroup*

Figure 2-12: Example of a Trussed Gantry 2 – In *State-Ends*

Trussed Frames

This type of structural configuration will not be discussed in detail in this work, since it is a hybrid of the ones described previously.

Trussed frames are rigid frames where the horizontal beam is a truss structure. This configuration improves the lateral load capacity of the simple rigid frames significantly. This enables to cover bigger spans, due to the higher stiffness of the horizontal trussed section.

There are numerous examples of Gantries with this configuration, where the boom is truss type and the masts are simple columns.

Figure 2-13: Example of a trussed frame Gantry 1 - In *Interstate275florida*

2.3 Production of Traffic Management Structures

In this section, the manufacturability aspects of the previously presented traffic management structures, namely Gantries, Cantilevers and Masts, will be addressed. Before, is pertinent to introduce briefly the concept of mass-customization and its relevance to the present work.

2.3.1 Mass-Customization

The goal of this work is to design a Gantry system (the product) and naturally it will have to fulfil all the needs of the entities that buy these structures (the clients or customers). With a smart and efficient design it is possible to expand the range of customers. A factor that enables that expansion is the capacity of having a product that can be personalized to the individual needs of each client. At the same time it is important to keep the production costs low. Hence, it is important to have some kind of platform that enables the product to be modular.

In short, in order to achieve what was presented before, namely the increase of value of the product, it is relevant to address the mass-customization principles. Thus, without going too deeply on the subject, the next paragraphs will introduce the concept of mass-customization and approach some of its main challenges and benefits.

The first exposed idea is that, in mass-customization principles, the main driver is the customer (Blecker & Friedrich, 2006) and the realization of his needs. Through this concept, manufactured goods are delivered as if they have been customized and the purpose is “build-to-order” or, in order words, make the customers design the final product.

In order to keep costs low it is not sustainable to produce full customized products from scratch. Some percentage of the end product should be standard. By compromising the individualization with the concepts of mass production, firms can offer differentiating products on a large scale at nearly the same price as the mass produced ones (Toffler, 1970). This concept was firstly introduced by Toffler (1970) as a consequence of the increasing technological development and sophistication. Hence, it has been reached the main goal of mass-customization: to deliver products and services that best meet individual customers’ needs with near mass production efficiency (Tseng and Jiao, 1996). This balance is met by the use of a modular product. Modularity enables a large batch production as in mass produced products and consists of a limitation of the customers' individualization options (da Silveira et al, 2011). Mass-customization is thus the integration of modularity and standardization with individualization.

This methodology makes customers' demands predictable and the production or assembly is started after the ordering process ("build or assembly-to-order") instead of manufacturing to create inventory ("build-to-stock") as in pure mass production. This allows keeping the costs low by reducing stock and reducing the risk of producing unwanted products or ones becoming obsolete. By using standard components and modular products a new product doesn't need to be reengineered from the zero level, which results in higher competitiveness, reduced lead times, and reduced product development costs.

One major focus to this approach is the relation with the customer, which is vital to the success mass-customization. It requires a permanent communication between all the stages of the product development, manufacturing, assembly and selling through a system that allows sharing all the necessary information in order to end up with the exact product that the client wants and needs.

According to Tseng and Jiao (2001) there are three main challenges that shortly lie on maximizing reusability, creating a product platform and creating an integrated product life-cycle. Without deepening the challenges it is worth to note that the concept lies in a duality: *mass production*, which means a process of repetition, producing to stock *versus customization*, which on the other hand means individualization, producing singular products. This way, it is essential to meet the right ratio between keeping the cost down (through mass production concepts and modularity) and fulfil the customers' different needs (through maximizing personalization). Finding this balance between two opposing forces requires a very solid organisational structure and an almost perfect management and control of the flow of information in all of the stages of the product life. This balance can be made by using some enablers such as lean manufacturing, agile manufacturing, having a good supply chain management and using product modularity/standardization.

With the concept of mass-customization a firm, besides lowering costs on inventories due to zero stock, reducing material waste and having a better control over the products' quality (through modularity), is able to reach a wider range of customers by meeting their exact needs. This reflects on an efficient way to widen the market share, adapting quickly to different demands and achieving high customer satisfaction rates.

In order to take advantage of the benefits of the presented notion, a Gantry system should be designed in a way that uses standard concepts adaptable to different sub-systems or even to different products. At the same time, it should have a modular construction to cover the maximum amount of configurations. The goal in a design having mass-customization in mind is to be able to create a product matrix that can cover the greater amount of different clients' needs. In order to have a smart modular, configurable system, the design should be greatly focused on the manufacturing stage.

2.3.2 Manufacturing Process

In this section the manufacturing process of Gantries, as well as Cantilever and Masts it will be discussed.

To produce the entire system, regarding all the necessary structural and functional components (not concerning purchased parts like for example screws or nuts) it is not viable to resource only to one process. Concerning the production of elements like beams, columns, small poles or any profiles with a constant section throughout all the length, the adequate manufacturing process is the extrusion.

In summary, columns for rigid framed Gantries, beams for the masts or for the boom of trussed Gantries or Cantilevers, simple poles or masts, are all the result of extruded profiles that subsequently are joined to structural systems. Of course the extrusion itself will not be enough to produce the final element, there are sequential operations that adapt each extrusion to its end. Operations of transversal cutting and drilling are dominant after the extrusion. However, since the main operation that gives shape to the structural members of a Gantry is the extrusion, this will be the main focus of this section.

Extrusion

Below, the basic principles of extrusion will be addressed; the main manufacturing process to produce the main parts of the traffic support structures.

First extrusions were made at the end of the eighteenth century in the manufacturing of lead pipes (Santos, 1998). Nowadays, many different industries use the extrusion process for creating the vastest collection of sections using a wide range of materials.

Regarding the aluminium extrusion, its application and demand grew rapidly in many industries like the automotive one, aviation, machine components, structural constructions, and architecture (Saha, 2000).

The extrusion is a plastic deformation process where a billet of certain material is forced under high pressure to pass through an opening (a die) with a smaller cross section area in order to reduce the original cross section or/and to reshape the cross section. This way, an extruded piece has a constant profile section. Therefore, this process is optimal for products that besides demanding a constant section need to have a long aspect ratio (length over width and height) or to put I bluntly, long lengths. It can be used to produce both solid and hollow sections and the shape of the extruded piece is given by the die, from simple circular profiles to very complex and detailed sections. Therefore, the design and manufacturing of the die has a big role to play on the extrusion process. According to the material extruded and the type of extrusion, the process can be cold or hot.

There are two main types of extrusion, direct and indirect extrusion. In direct extrusion the solid pressing piston (ram) pushes the billet inside a container that holds the opening die at the end, forcing the material to exit through the die. This way, the movement of the ram and the flow of material have the same direction. During the direct extrusion the billet has to slide with the walls of the container, which requires an increase of pressure by the piston. At the end of the extrusion of one billet, as the ram doesn't reach the die, when it gets to the end of its course there is a portion of non-extruded material that has to be removed from the extruded piece. Therefore the direct extrusion results in material waste, which doesn't contribute to the efficiency of the process. Below, a schematic figure of the described process is shown.

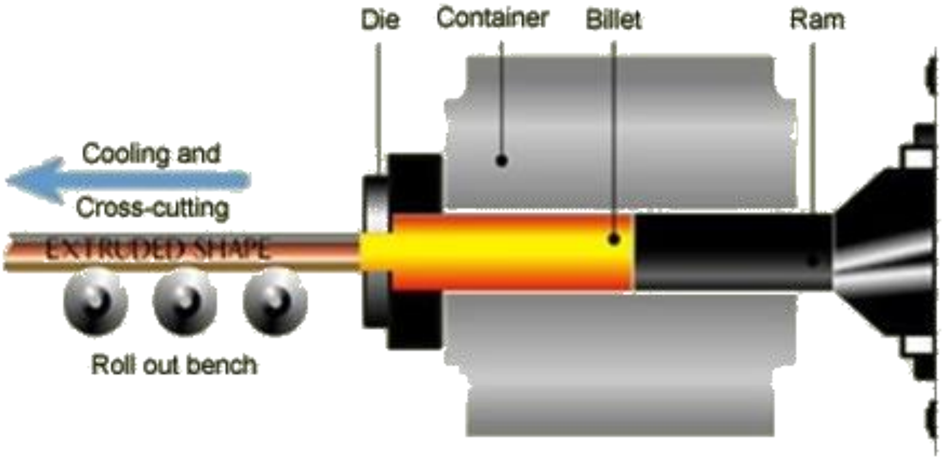


Figure 2-14: Direct Extrusion – In *Finkelstein-casting*

The indirect extrusion process is characterised by a closed container and a ram that is hollow and has the die within it. This configuration results in an opposite movement between the ram and the flow of material that exits through the hollow ram, which acts also as die. In indirect extrusion, there is no relative movement between the container and the billet as it was in the case of direct extrusion, which results in much less friction. Accordingly, the pressures required for the progress of the ram are smaller than in the equivalent process with direct extrusion. Through indirect extrusion it is also possible to be more efficient on the material use, since there is less waste inside the container. Below, a schematic figure of the indirect extrusion process is shown.

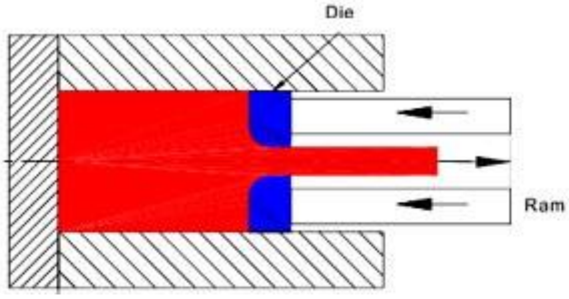


Figure 2-15: Indirect Extrusion – In *Industrialextrusionmachinery*

In the figure below, are shown some examples of extruded profiles.

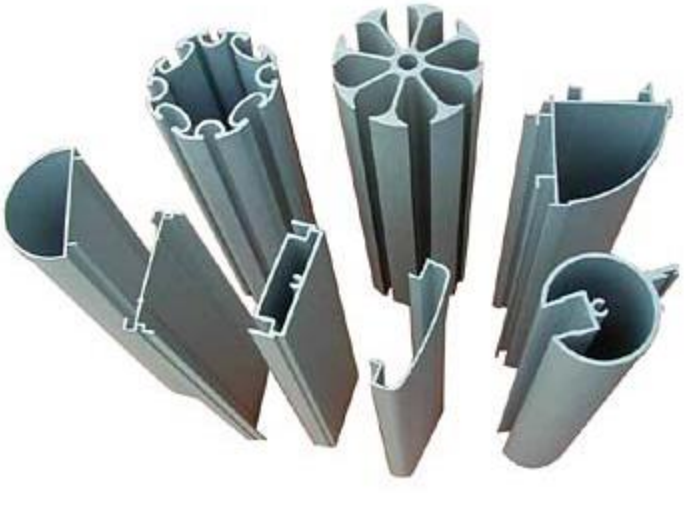


Figure 2-16: Example of aluminium extruded profiles – In *Made-In-China*

During the stages of product development, the design should consider the potentials of the manufacturing process in order to increase the product functionality, instead of adding future costs coming from the restrictions and conflicts between manufacturing and the design (Støren & Moe, 2003). The production process can add functionalities to the product. So, having a wide vision of all the product development process, several features can be enhanced and integrated to the design so that the final product can have more value. In other words, if the capabilities of the manufacturing process, in this case extrusion, are maximized, namely if the design includes some integrated details in the section profile, forward processes like assembly can be simplified. This would be possible by smart ways to direct fit different profiles or simply minimize the use of extra parts for connecting purposes. This way a design that considers the potentials of the manufacturing process can minimize the total cost just by reducing the system's total number of parts.

Concerning the extrusion performance, there are some factors that define it, such as the die life, the extrusion speed, the surface quality, the geometrical tolerances, and the material properties. Regarding the productivity and production cost of extrusions, the design should also consider several aspects that can maximize the first and minimize the second. The productivity of an extrusion process is governed by numerous factors, as for example feed speeds, number of cuts after the extrusion, time for the die change, quantity of scrap per billet, among many other aspects. The sections' design should also consider the cooling phase, by maximizing the uniformity of cooling speed rates throughout the section and minimizing the overall cooling time. This topic will be resumed ahead, when some limitations of the profile design will be presented.

About the total cost minimization regarding the manufacturing process, the profiles should be designed in a way that considers the fabrication of the die and its cost. A complex die is usually more expensive to produce. A die will thin walls (in order to produce thin hollow sections or thin slots in the profile) will be exposed to higher stresses, which can result in a small working life and on an uneven section over the length of the extruded piece due to the weak walls' rapid wear. Therefore, the design of the profile should maximize the working life of the die, considering its production and avoid details that can induce defects on the extruded piece.

The main recommendations state that the geometry of the profile should have as many constant wall thicknesses as possible and also maximize symmetry. This will enable an even cooling speed and also an even speed flow over the die that can prevent distortions or bending. Also, regarding the cooling phase, the use of hollow sections inside the profile should be avoided. It is very difficult to control the cooling process inside these sections. In order to improve the stress flow of the piece during the working life, live corners should also be avoided. With smooth transitions the stress concentrations can be lower and the strength of the piece can be enhanced as well as the fatigue life. Lastly, thin isolated flanges should be avoided due to the risk of deformation during stacking the profiles after the extrusion.

Within this section the importance of a manufacturing orientated design process was underlined. By using the capabilities of extrusions, some assembly problems can be reduced and simplified, and by this, an efficient design should be made in order to explore and maximize the advantages of the process.

2.4 Material Choice

In this chapter, the different materials that structural truss or frame systems may adopt, the most common used in Gantries and the justification of using aluminium for the Gantry to be designed in this work will be addressed. In the second part of this chapter the different aluminium alloys and some of their basic properties will be approached.

2.4.1 Why Aluminium?

Depending on the application and the loads to be applied, a truss or frame system can be made of timber, concrete, steel, aluminium, or even composite materials (Nageim, Durka, Morgan & Williams, 2010).

A gantry needs to cover a considerable span of at least ten meters and for this, it needs to have the stiffness to avoid big deflections in the middle of the transom. This makes the use of timber unfeasible, as timber has a very low Elasticity Modulus and besides the structural weakness it is sensible to the elements' exposure. The use of concrete is more reserved for civil engineering applications and sometimes as reinforcement. Concrete opposing timber has a very high brittle behaviour that makes it impracticable to use for high span structures. Therefore, it's used more often in structures that carry compressive loads. As to composite materials, there are vast combinations of materials that can be used in many applications, where the light-weight and the high values of strength are the main advantages. The problem of using these materials widely lies in the high manufacturing costs and time. This makes the industry of composites more suitable for high performance components such as, for example aviation, automotive racing, sports equipment, etc.

In this short introduction, there are also steel and aluminium to consider.

The majority of truss and frame structures, both in civil engineering or smaller applications are made of steel due to the versatility of the material and the wide range of alloys available. Regarding Gantry applications, the trend is the same. It is more common to encounter steel structures over the road than aluminium ones. This can be justified by the ease of access and production of steel by many countries and, relatively good extrudability (the apt manufacturing process for these structures), and also by the versatility of joints that can be made to connect steel elements.

There are many existing steel alloys and aluminium alloys, but, in a general way aluminium presents a density about three times lower than steel and an Elasticity Modulus also about three times lower (Mazzolani, 1995). This means that in a structure made of steel and another with the same dimensions but made of aluminium, the latter will have about one third of the total weight and the triple of capacity to displace before plasticity occurs. Both materials have a wide combination of alloys, where the adding of other elements can significantly change their baseline mechanical properties.

Besides the advantage of the structural behaviour that the lower density offers to aluminium structures having a lower self-weight (compared to steel), this characteristic and also its higher elasticity makes the extrusion process more versatile regarding the shape of the sections, due to the lower forces generated during the process (Støren & Moe, 2003). In other words, the use of aluminium offers a wider range of possibilities for the shape of the sections to be extruded. On the contrary, steel profiles are more conservative, having simpler geometries, due to manufacturing limitations. Another key aspect of aluminium that overtakes steel is the fact that aluminium has a high corrosion protection (when in contact with air, an aluminium oxide layer is formed, which protects the aluminium against corrosion), which is an important advantage for a structure exposed to the weather like a Gantry. This way, an aluminium structure can be used without protective coating or any paint, which is another economical advantage over steel structures, which oxidize in the presence of oxygen. In other words, they rust without any protective coat (except in the case of self-protecting steels).

Taking into account the presented advantages of the use of aluminium over steel for a Gantry application it was decided that aluminium would be the material to be used. The requirements for the design of the Gantry will be later discussed in this document, but it is convenient to anticipate one of the main ones that is the focus on a light-weight structure. This would be achievable more efficiently with an aluminium structure. The next section will introduce the different families of alloys and treatments that can be made after the extrusions.

2.4.2 Aluminium Alloys

Aluminium in its pure state is not a strong material. Thus, for structural purposes the addition of reinforcement elements is needed.

There are seven series of aluminium alloys regarding the added elements (named alloying elements) and they differ mainly in mechanical properties, corrosion resistance and ease of manufacturing, which, in the context of this work, is focused on extrudability. The alloys can be heat treated after the manufacturing process, in order to strengthen their mechanical properties. However, not all the alloy series can be treated. Below, the seven series with their main alloying elements are listed.

- Non Heat Treated Alloys
  - 1xxx Series – Pure (greater than 99%) aluminium;
  - 3xxx Series – Manganese (Mn);
  - 4xxx Series – Silica (Si);
  - 5xxx Series – Magnesium (Mg).
- Heat Treated Alloys
  - 2xxx Series – Copper (Cu);
  - 6xxx Series – Mangnesium and Silica;
  - 7xxx Series – Zinc (Zn) and Magnesium.

Figure 2-17: Seven aluminium alloy Series and their main alloying elements

1xxx Series alloys – pure aluminium / low alloy content

As referred before, aluminium in its pure state or very close to it has very weak mechanical properties. Therefore, this family of alloys is not suitable for structural applications. Since the higher the aluminium purity is, the higher the corrosion resistance (and also the higher its ductility), the 1xxx Series alloys are appropriate for non-structural applications under harsh environments.

2xxx Series alloys – aluminium-copper

The main alloying element of the 2xxx Series family is copper, but also other elements may exist, such as magnesium, silica and manganese. These alloys can be heat-treated which increases their strength but still presents relatively high values of ductility. Their resistance to corrosion is poor, which requires the use of protective coats if needed. This family has the characteristic of having a bad extrudability and not being suitable for welding. They are mainly used in the aeronautical industry.

3xxx Series alloys – aluminium-manganese

This family of alloys is characterized for having more strength that the 1xxx Series but still in relatively low values, and high ductility. Though, these alloys are corrosion resistant. Welding is possible for 3xxx Series alloys and they are more common in the form of sheets and not profiles due to their high values of strength at high temperatures, which complicates the extrusion process.

4xxx Series alloys – aluminium-silica

The 4xxx Series is mostly used in casting and thus these alloys are not used as structural members such as beams or columns.

5xxx Series alloys – aluminium-magnesium

The Al-Mg alloys have in general the better mechanical properties of the non-treatable alloys and ductility similar to the 2xxx Series. Hence these are the most non-treated alloys used for structural purposes. They have good corrosive resistance, welding is possible and frequently used due to the low loss of mechanical properties in the heat-affected zone. This family doesn't have a good extrudability, therefore the most common manufactured shapes are sheets and plates.

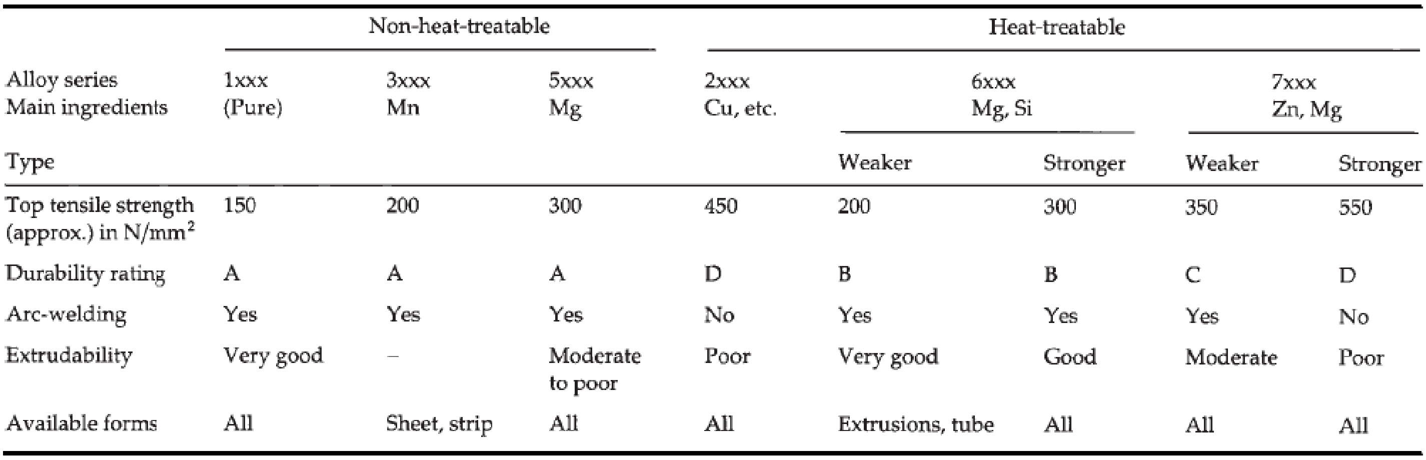
6xxx Series alloys – aluminium-magnesium-silica

The 6xxx Series family is corrosion-resistant and before the heat treatment they are easily formed, which makes these alloys very suitable for extruding. After the heat treatment, they increase their strength considerably, making them very proper for structural application. The values of ductility are similar to the 5xxx Series. About weldability, it is possible to weld but the heat-affected zone suffers a drastic loss of properties, which can weaken the structure to be applied considerably. These alloys can be divided in two sub families, the stronger and the weaker types. The former are more appropriated for high strength demanding structures, whereas the latter group in other hand is more suitable for structures with a higher priority of stiffness over strength, and are the most appropriate of all the alloys for extrusion.

7xxx Series alloys – aluminium-zinc-magnesium

This family of alloys is also divided into two groups. The stronger has very good mechanical properties with high values of strength, but they are not corrosion-resistant or proper for welding and are difficult to extrude. They are mostly used in the aviation industry with protective coating applied. The second group, the weaker one, has similar characteristics to the stronger 6xxx Series, but with higher mechanical properties. Nevertheless, they present a worst extrudability and corrosion resistance (however still higher than the stronger 7xxx group). This group contrarily to the first one is suitable for welding.

The next table, found in *Aluminium Design in Construction* by John Dwight (1999), sums up the main characteristics of the different families of alloys that have structural applications.



	Non-heat-treatable			Heat-treatable				
Alloy series Main ingredients	1xxx (Pure)	3xxx Mn	5xxx Mg	2xxx Cu, etc.	6xxx Mg, Si		7xxx Zn, Mg	
Type					Weaker	Stronger	Weaker	Stronger
Top tensile strength (approx.) in N/mm^2	150	200	300	450	200	300	350	550
Durability rating	A	A	A	D	B	B	C	D
Arc-welding	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Extrudability	Very good	–	Moderate to poor	Poor	Very good	Good	Moderate	Poor
Available forms	All	Sheet, strip	All	All	Extrusions, tube	All	All	All

Table 2-1: Characteristics of the aluminium alloy Series – In *Aluminium Design in Construction*

After the previous presentation, concerning the main principles of the different aluminium alloy families it is now time to reveal the chosen series for applying to the Gantry's design. The main concerns regarding the choice of one alloy series was extrudability, which eases the manufacturing process, and the strength and stiffness required for a structural application. It is believed that the best balance between these characteristics is found in the 6xxx alloys.

The chosen alloy family, the 6xxx Series, belongs to the heat treated alloys group. Therefore, it is relevant to address, even if shortly, the topic regarding heat treatment.

The heat treatment stage is referred to by the letter "T", and, according to Mazzolani (1995), regarding the combinations of operations, the range goes from T1 to T12. The heat treatment phase has the goal of increasing the strength of the extruded element and can be divided into two major stages, the solution treatment and the ageing period.

For the relevance of this work, only the heat treatments used in pieces for structural purposes will be addressed. These are the T4, T5 and T6. The T4 alloys are treated in a solution and then naturally aged, resulting in a piece with more ductility. The T5 group is air cooled and artificially aged, without going through the solution treatment. This treatment is specially fit for thin extruded sections. Lastly, the T6's are solution treated and then artificially aged. This gives the alloys of this group high strength.

Below, it is presented a summary of the basic treatments for each T group, adapted from Mazzolani's *Aluminium Alloy and Structures* (1995).

$$\begin{array}{c}Solution\\ and\ Heat\\ Treatment\end{array}\begin{cases}\begin{array}{c}without\ work\\ hardening\end{array}\begin{cases}naturally\ aged & T4\\ artificially\ aged & T6\end{cases}\\ \begin{array}{c}with\ work\\ hardening\end{array}\begin{cases}work\ hardened\begin{cases}naturally\ aged & T3\\ artificially\ aged & T8\end{cases}\\ artificially\ aged\left\{work\ hardened\right. & T9\end{cases}\end{cases}$$

$$\begin{array}{c}Heat\\ Treatment\end{array}\begin{cases}\begin{array}{c}without\ work\\ hardening\end{array}\begin{cases}naturally\ aged & T1\\ artificially\ aged & T5\end{cases}\\ \begin{array}{c}with\ work\\ hardening\end{array}\begin{cases}work\ hardened\begin{cases}naturally\ aged & T11\\ artificially\ aged & T12\end{cases}\\ artificially\ aged\left\{work\ hardened\right. & T10\end{cases}\end{cases}$$

Figure 2-18: Basic treatments to aluminium alloys – In *Aluminium alloy and Structures*

For the Gantry application, where structural integrity is a priority, namely by enhancing the strength and minimizing deflections due to high spans, the recommended heat treatment group for the 6xxx Series alloys after the extrusion will be the T6.

2.5 Connecting Structural Elements

A structural system is not made in a single piece. It is the result of the assembly of individual elements. This way, the connections between the elements, or joints, are an important topic, which plays a major role in the designing phase.

The first step is to choose a type of connection regarding the application, thus the load types, the material and alloy and finally the manufacturing process. As was discussed before the selected manufacturing process, extrusion, makes it possible to have details in the sections that can maximize the connection potential between the elements.

In this chapter, the main types of connections will be addressed. Some of the main advantages and challenges according to the selected processes, which have been described in the previous sections, namely, the manufacturing process (extrusion), the material (aluminium), the alloy (6xxx series) and the heat treatment (T6) will be addressed. This topic will also consider that the application for the connections is a Gantry, namely a structural system made from extruded profiles. In other words, connections fitted for thin walled profiles or plates will not be considered.

There are three types of joints regarding the contact area: point, line and surface connections. The point connections can be achieved by bolts or rivets, the line connections by welding and the surface ones by bonding processes like adhesives.

Fusion welded joints

In the fusion welding process two components are joined by melting them at their interfaces or with the addition of a third material. There is a wide range of weld processes. These are chosen concerning the material and alloy to be welded and many other requirements as the propensity for defects, the type of surface finish, strength, labour and equipment cost, among others (Höglund, 2007). The different processes vary mainly in the heat source and heat intensity. The overall goal of these technologies is to link several elements in order to produce a single but more complex piece.

In general, aluminium is not an easy material to weld due to the high thermal and electrical conductivity which requires the use of high values of electric current. Being the selected alloy the 6xxx Series (aluminium-magnesium-silica alloys), crucial mechanical properties are weakened in the heat-affected-zone, which is the surrounding area of the weld cord that is affected by the heat. For instance, the elastic limit drops 55%, the ultimate strength 45% and the ultimate elongation reduces 60% (Mazzolani, 1995).

As stated before, one of the main goals of this work is to design a light-weight structure. To achieve that, an efficient use of the material is necessary. If the connecting elements of the Gantry were welded together, independently of the process, the joints would lose about 50% of the strength. To balance that fact, the joints would have to be overdesigned, by an increase of the sections' dimensions, which would result in the addition of material and consequently weight to the structure. Because of this fact, the use of welding technologies is excluded for the purpose of this project. Below is presented an example of a welded aluminium structure.

Figure 2-19: Example of welded connections in an aluminium structure – In ***Made-In-China***

Riveted joints

A riveted connection is a permanent joint where the two interfaces are overlapped and connected punctually by a rivet.

The main concern about the use of rivets is that a rivet is designed to resist shearing forces and has, on the other hand, low capacity for tensile forces (Mazzolani, 1995). This fact requires a good preview of the type of loads that the structure to be riveted will be subjected to.

The picture presented below shows a riveted joint cut by the rivets plane.

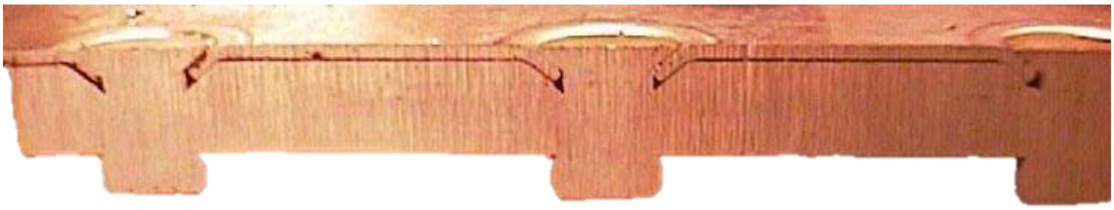
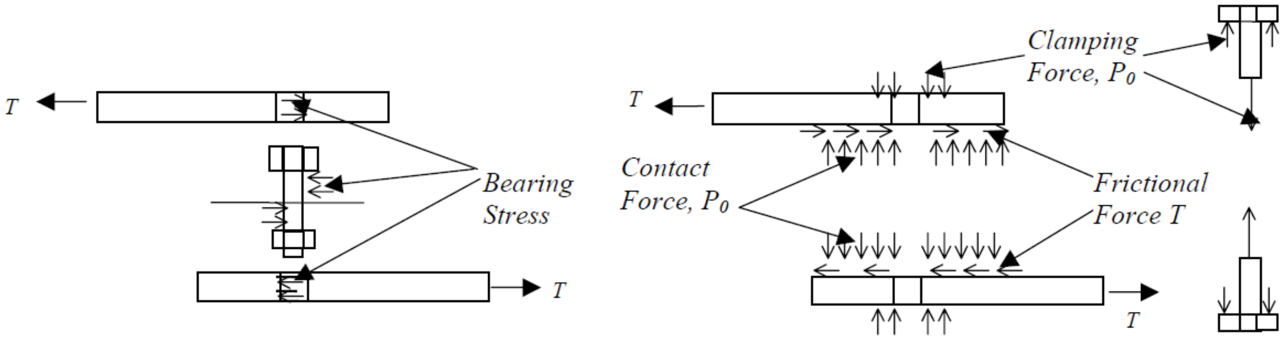


Figure 2-20: Example of a cut view from riveted joint – In *n36sx*

Bolted Joints

A bolted connection offers a non-permanent joint that can be disassembled if needed.

The bolts used for aluminium structures can be made of aluminium, steel, or stainless steel. Regarding the use of steel bolts, the corrosive protection must be taken in account. There are two main types of bolts, the bearing bolts and high strength friction grip (HSFG) bolts. The two bolt types are exposed to shearing, but with HSFG the existing friction between the interface of the element and the bolt prevents the bearing stresses between the bolt and the hole surface (if the external forces are smaller than the friction contact). This means that the second type of bolts offers a higher rigidity to the joint, since the bolt only slides within the tolerance with the hole if the levels of friction would be exceeded and only then the behaviour is similar to the bearing bolts. The next figure, adapted from *Connection Design* – Design Requirements by Narayanan et al, shows a scheme with the forces represented.



Bearing Bolt

HSFG Bolt

Figure 2-21: Representation of the forces in a Bearing and HSFG Bolt – In *Connection Design – Design Requirements*

Huckbolts

It was considered relevant to introduce one type of bolts that differ from the ordinary concept of bolting, having some notions similar to a riveted connection. These are the *Huckbolts* and they don't use a thread, but parallel grooves that enable a collar (or collet) to deform and be force fitted to the grooved bolt.

This type of connection has several advantages regarding process productivity and structural behaviour, namely an easy installation with high rating operations, the bolt heads apply a constant clamping force, the self-locking joint offers high shear, tensile and fatigue strength and are not loosened by vibrations and lastly this joint isolates the connecting interfaces from gas and fluids (Höglund, 2007). Below, the schematic shows principle of the fixation of the collar in the parallel grooves.

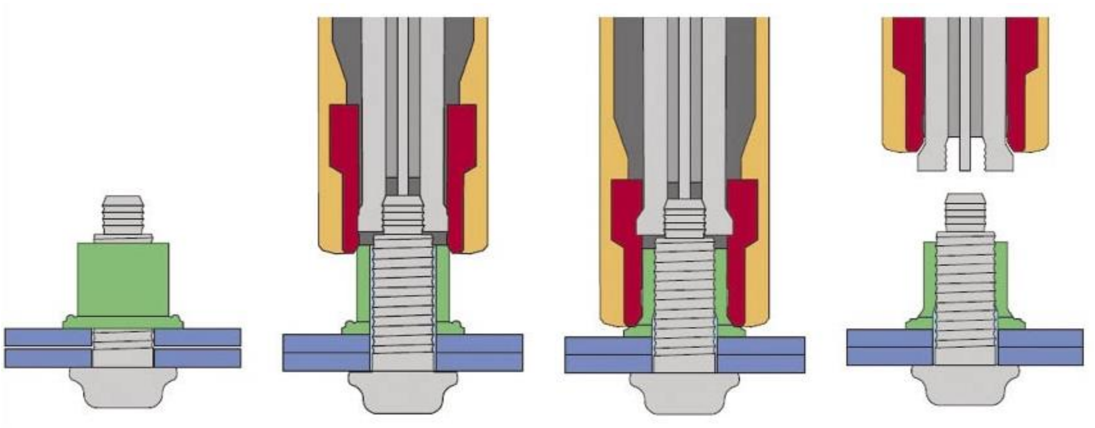


Figure 2-22: *Huckbolt*: Cut view of the collar to the grooves – In *Windpowerengineering*

Adhesive Joints

The use of adhesives enables a surface contact between the bonded surfaces. This type of bonding allows a wide range of options for a joint's configuration and has the advantage of virtually not adding weight to the structure and can also result in visual appealing connections.

The adhesives are designed to deal with pure shear, pure tension or compression forces, thus, any forces that induce cleavage or peeling could provoke a joint failure. The cleavage forces can be avoided by the simultaneous use of other type of mechanical connection, like rivets.

The application of adhesives requires a very good surface treatment from the two elements to be joined. These cleaning operations must be taken in a very controlled environment to prevent the presence of any particle that may queer the integrity of the joint. These operations, requiring high quality guarantee, result in additional labour hours and additional cost by controlling the whole process. Another big disadvantage is the fact that the process of cure can be long and being a key procedure for the mechanical characteristics of the joint also needs a high controlled environment.

The picture below shows an example of a bolted flange joint being reinforced with an adhesive. This is an example of a hybrid joint.

Figure 2-23: Example of a hybrid joint: Adhesive plus Bolts – In *ptfe-sheet*

At this point, some types of connection were excluded for the purpose of the Gantry's design, due to some of the challenges addressed. It was not decided to use welding technologies to preserve all the mechanical properties of the material in order to have an efficient material usage leading to a more light-weight structure as possible. Analogously, adhesives bonding were also excluded, but because of the necessary logistic procedures that would increase the structure's production costs. Between the remaining processes, it was given avail to the use of bolted connection (either conventional or with *Huckbolts*). This decision was based on the fact of rivets produce a permanent joint, but more importantly they are weak when subjected to shear forces. The majority of the connections between the Gantry's parts are subjected to different type of forces, including shear, which give the advantage of bolted joints over riveted ones.

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3. Methods and Approaches

This chapter will address the tools used in this work.

Firstly, a Cost Model applied to Gantry structures will be discussed. Then the applied approaches as Quality Function Deployment and House of Quality, the *Pugh Matrix* concept, and lastly the *CAD* and *FEA software* tools will be introduced.

3.1 Gantry Cost Model

The main goal of this work is to develop an aluminium Gantry system, which has lower cost than the present solution. Since the cost is a key factor in terms of competiveness for the final product, it is very relevant to be able to access the costs thorough each step during the product fabrication. For this study, the following Gantry's fabrication steps will be considered: Extrusion, Fabrication of components, Assembly and Installation, which complete the product live, from the aluminium billets to the assembled Gantry, ready to use.

The development of a cost template has two big goals. First, by applying it to the current solution, the cost distribution in each step might be visible and it can be evaluated where there is potential for improvement during the conception of the new Gantry solutions. The second goal is to be able to predict the cost by comparison of different solutions during the concept phase of this work. This tool can have a very important role during the design stage, since is through decisions taken in the primary product development phases (as concept proposals and the evaluation between them) that the highest amount of the final product cost as well as quality are determined (Andreasen & Hein, 1987).

The cost model used in this work divides the Gantry cost into five major categories: material (extruded aluminium), parts (connection plates, screws and nuts and foundations), assembly, dies (different extrusion dies required) and production (operations after extrusion; cutting and drilling). The more detailed cost model that was taken as a reference, developed by Harald Vestøl (1998), was slightly adapted to comply with a Gantry structure and is presented in the Annex I. it enables, through the required introduction of many real input data, to perform a more detailed cost breakdown.

3.2 Quality Function Deployment – *House of Quality*

This section will address the concept of Quality Function Deployment (*QFD*) and its importance in the early stages in product development.

QFD was developed in Japan in 1966, by Yoji Akao, a planning specialist also developer of the Hoshin Planning. *QFD* is an approach used in order to achieve a product that meets the exact needs of the customer. It is a tool (matrix) used to convert subjective wants and needs into objective engineering specifications. Thus, the major goals are to rate and prioritize the customers' demands, convert them into technical specifications, and lastly be able to deliver a quality product aiming for the ultimate customers' satisfaction.

There are four main phases, each one corresponding to a matrix, considered in this approach: Product Planning, Product Design, Process Planning and Process Control. The first phase, also called House of Quality, consists of the correlation between the customer's needs or requirements with the technical descriptors, which the company will use to meet those demands. The second phase, Product Design, is used for the concept generation and selection of those which meet the customers' requirements the best. The third phase, Process Planning, as the name suggests corresponds to the planning of the manufacturing operations. Lastly, the Process Control consists of the control procedures done during the production to assure the product's target quality levels.

The application of the *QFD* in this work will only focus on the first phase, the House of Quality. During the evaluation of different concepts it will be important to have a rating of the performance parameters, which are governed by the requirements and needs. The *House of Quality*, by correlating the customers' needs and wants (the requirements) with technical characteristics, makes possible to have a relative weight for all those parameters used to compare concepts. Regarding the phase of comparing solutions and concepts, a simple systematic evaluation method will be adopted: a *Pugh Matrix* type, which will be addressed in the next section.

The House of Quality is a matrix that can be summarized in eleven major sections. A typical *House of Quality* has the layout presented in the figure below, with the different numerated sections.

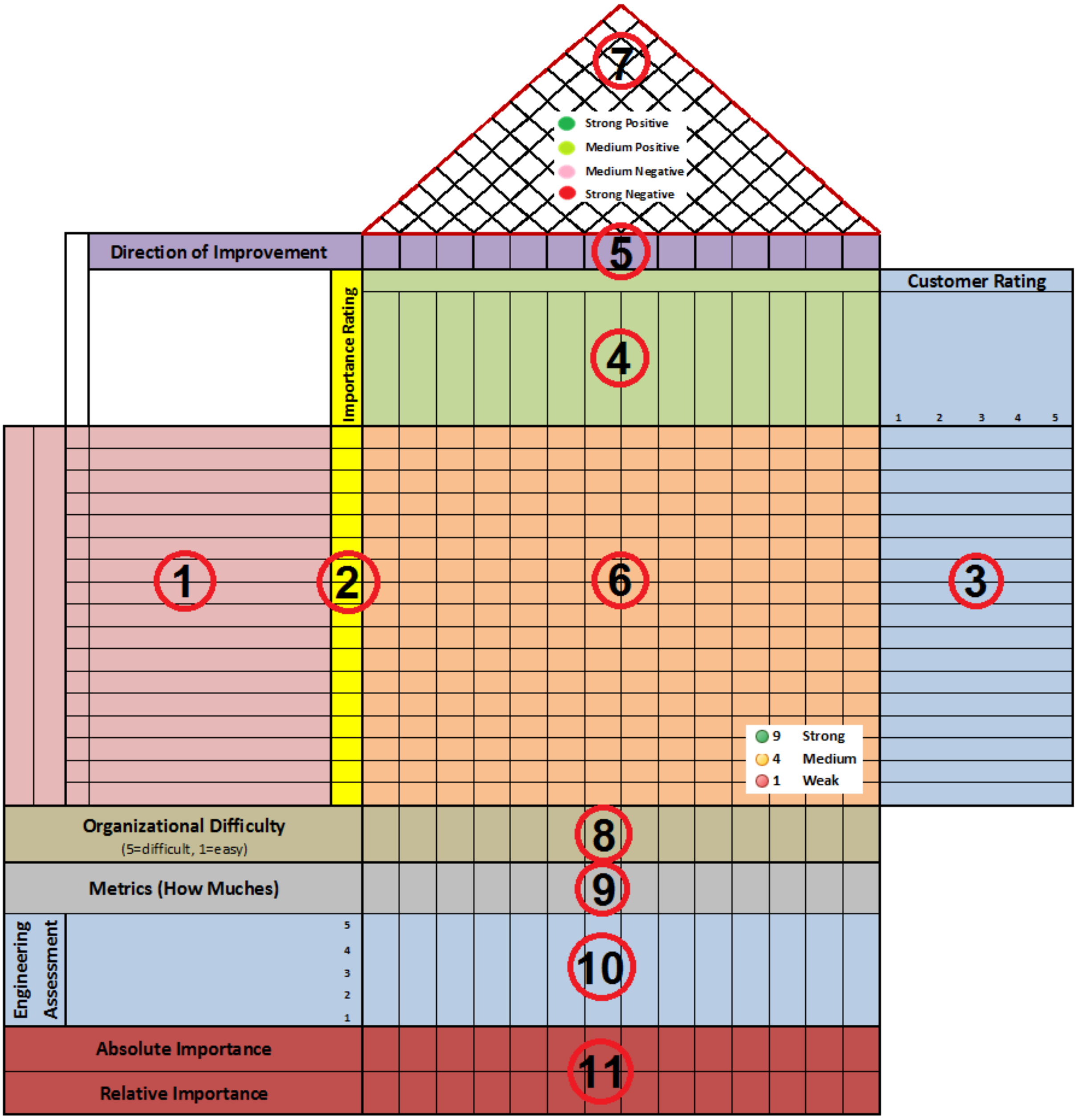


Figure 3-1: ***House of Quality*** **matrix: the eleven sectors**

Below the contents of the different parts will be summarized.

1) **Customer Requirements:** This section is the list of the customer's needs and wants that correspond to the project's requirements.

2) **Importance Ratings:** The customer shall rate each requirement in a scale from 1 to 5 according to the importance.

3) **Customer Rating (of the company and competition):** In this section, the customer can rate the degree of satisfaction (1 to 5) of each need, perceived from the company or/and from the competition.

4) **Technical Descriptors:** This section consists in the attributes that will quantify and measure the customer's requirements. In other words, these are the means to achieve customer satisfaction.

5) **Direction of Improvement:** Here, is defined the direction that each Technical Descriptors must meet to improve the product. Usually this is used to meet the "minimize" or "maximize" type of requirements.

6) **Relationship Matrix:** In this section is quantified the strength of the relationship between the requirements and the technical attributes. Therefore, it measures the influence of each attribute in the fulfilment of each requirement. The relation can the Strong, Medium or Weak, and be rated with 9, 4 or 1, respectively.

7) **Correlation Matrix:** This section is a matrix that reflects the relationship between the Technical Descriptors and impact they have on each other. Here is identified the attributes that "push" in the same way (the positives) and the ones that originate contradictions (the negatives).

8) **Organizational Difficulty:** Here is rated the difficulty that the company has in implement in the design each attribute. Because of the contradictions revealed by the previous section, there are attributes that are much more difficult to implement (and be able to follow the improvement direction) than others.

9) **Target/Reference Values:** This section consists in reference values for the Technical Descriptors. The target or reference values of each attribute can also be compared with other company's products, or be used as a baseline to compare different solutions or concepts.

10) **Engineering Assessment (of the company and competition):** This section is a rating of the attributes (Technical Descriptors) of the company or/and the competition.

11) **Absolute and Relative Importance:** This is the section that reveals the most important technical attributes that most matter for the customer. The Absolute Importance assessment is the product of the value in each cell of the Relationship Matrix (6) with the correspondent Importance Rating (2).

In the last section of the *House of Quality*, the Relative Importance for each attribute of the design is calculated. This will be significant to evaluate different concepts in a qualitative way, since the different technical parameters don't have the same importance to achieve maximal customer satisfaction.

3.3 *Pugh Matrix*

The method presented in this section will be used during the phase of the concepts' evaluation.

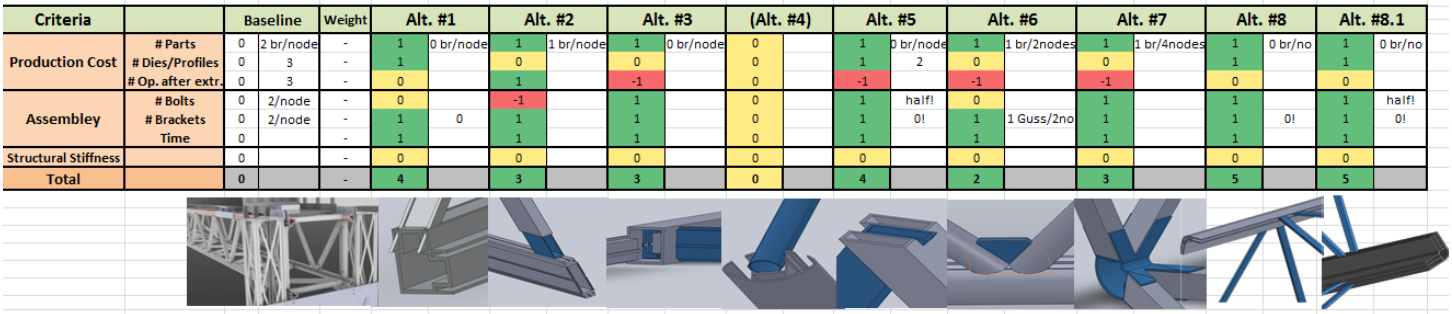
During that phase is important to generate different concepts and solutions, in order to be able to evaluate their weaknesses and strengths. By having a concept evaluation method, the proposed solutions with less potential can be excluded and the best ones be identified, giving this way origin to new and optimized concepts. This iterative process will eventually end up in one or two concepts that with further development and optimization may originate the final solution.

In order to perform a simple and time efficient evaluation between the alternative concepts it will be used a *Pugh Matrix* type, created by Stuart Pugh. This Matrix contains the performance factors of the product (stiffness, number production operations, assembly time, cost, etc.) and each proposed solution will have a rating for each of those performance factors. The rating will be qualitative, hence in this phase no major calculations will be done because it refers to the concept selection and not the concept optimization. The comparison between the solutions that allows the rating process will be done according to a baseline solution, which corresponds to the actual product to be improved, for example. The baseline solution will have a "**0**" on all of the performance factors, corresponding to the reference. Each proposed solution's performance factor needs to be evaluated regarding the baseline and if it has a better performance it will have a "**+1**" and, on the other hand if it's worse, a "**-1**". If the performance is the same it gets a "**0**".

Each performance factor has a different weight, which were defined in the *House of Quality* matrix. This allows giving more importance to some characteristics than other and the “**+1’s**” and “**-1’s**” shall be multiplied by those weight values. This way, all the performance ratings of each proposed alternative can be summed and compared with each other. If the sum is negative means that globally the solution is worse than the baseline one, but if is positive it means that there is a potential for an improvement.

This way, the concepts with the sum’s lower values shall be eliminated and the best solutions combined in order to originate more solutions with as higher sum values as possible, until reach the final one or two best concepts. This constitutes the iterative concept evaluation that is possible due to a *Pugh Matrix* type.

Below is presented a simple example of a *Pugh Matrix* used to evaluate early concepts for the connection of the beams in a Gantry’s Boom.



Criteria		Baseline		Weight	Alt. #1		Alt. #2		Alt. #3		(Alt. #4)		Alt. #5		Alt. #6		Alt. #7		Alt. #8		Alt. #8.1	
Production Cost	# Parts	0	2 br/node	-	1	0 br/node	1	1 br/node	1	0 br/node	0		1	0 br/node	1	1 br/2nodes	1	1 br/4nodes	1	0 br/no	1	0 br/no
	# Dies/Profiles	0	3	-	1		0		0		0		1	2	0		0		1		1	
	# Op. after extr.	0	3	-	0		1		-1		0		-1		-1		-1		0		0	
Assembley	# Bolts	0	2/node	-	0		-1		1		0		1	half!	0		1		1		1	half!
	# Brackets	0	2/node	-	1	0	1		1		0		1	0!	1	1 Guss/2no	1		1	0!	1	0!
	Time	0		-	1		1		1		0		1		1		1		1		1	
Structural Stiffness		0		-	0		0		0		0		0		0		0		0		0	
Total		0		-	4		3		3		0		4		2		3		5		5	

Figure 3-2: Example of a *Pugh Matrix* type used for concept evaluation

3.4 *CAD software*

This section addresses the importance of *CAD software* tools and its function within this work.

CAD means Computer Aided Design. These *software tools* allow the modelling of technical designs. They are used broadly in all the engineering departments but also on many other subjects. *CAD software* permits to draw 2D or 3D models. By modelling the product to be developed one can preview and see the real dimensions and the couplings between the different parts of the total assembly and some problems can be identified already in the modelling stage. It consists in a very good tool to see a virtual version of the real product before it actually exists, that helps the designer but can also be used for presenting the product to the public. These *softwares* usually allow dimensional changes after the modelling being complete with the update of the total structure, which is very convenient during the optimization of the model.

The *CAD* models, besides being important for the preview of the assembly between all the structure's parts and giving a visual image of the product to be produced or developed, they can be used in the subsequent stages of analysis. Normally, the Finite Element Analysis (*FEA*) *softwares* allow the import of the *CAD* files with the model to be analysed. *CAD* models can be used in *FEA* to predict the structural behaviour, or to preview the production processes but they also can be used in *CAM* (Computer Aided Manufacturing) *softwares* which preview the machining of the model to be used in a CNC (Computer Numerical Control) machine.

CAD files will be vastly used during this work. It will be used to model the different parts and to build up the Gantry's assembly and with this compare different alternatives. Finally they are used to make a structural analysis, which is required to access the performance of the solutions.

The *softwares* used for modelling were *DDS*'s *Solidworks* and *Siemens' NX*. The first was used mainly in the early stages since the *NX* would be the *FEA software* to use. So it was preferred to model and analyse in the same *software*, therefore the chosen one for the major part of this work was the *NX*.

3.5 *FEA software*

As already mentioned in the previous section, the *FEA software* will be the tool used to perform the structural analysis and predict the behaviour of the structure under the work loads.

The Finite Element Method decomposes the structure into small elements that are connected at nodes, through the application of a mesh. The mesh will transform a continuous domain into a finite domain that enables the calculation of simultaneous algebraic equations. This method requires the application of boundary conditions such as fixed or pinned constrains and the application of external loads and/or gravity in order to consider the self-weight of the structure.

The *FEA* can be performed in a structural application but also in thermal or fluid flow problems. As this work is focused on the design of a Gantry system, only structural analysis will be considered.

The structural analysis can be linear or non-linear. If the interest of the analysis is to preview the behaviour of the structure in the elastic domain then is used a linear analysis. On the other hand, if the work loads are probable to overcome the yield stresses in some areas of the model, some hardening will happen and the material properties will differ along the model, therefore a non-linear analysis shall be performed. In this work, the structure is expected to work below the plasticity domain, or in other words, work only in the elastic domain, so the analyses to be performed will be linear. The goal of these linear analyses is to be able to preview the main results such as the maximum displacements.

4. Concept Design

This chapter covers firstly the requirements that will govern the design of a new Gantry system. Then the different concepts generated and the evaluation between them will be presented.

4.1 Requirements

4.1.1 Introduction

The product development phase has to be conducted aiming to meet the requirements that the product has to fulfil. This way, through the restrictions to the design it is possible to achieve a solution close to the optimum one. Without requirements, it would not possible to define a certain number of solution possibilities and the design options would be infinite.

The design of a product can have three types of implemented features or characteristics: the *Must Have*'s, the *Should Have*'s and the *Could Have*'s. A *Must Have* corresponds to a requirement, which defines the minimum level of customer's satisfaction. The *Should Have*'s correspond to additional features that cover extra needs of the client and add value to the product. The implementation of *Should Have*'s requires a proportional effort and resource consumption to the expected customer's satisfaction and corresponds to the expected quality of the product. Lastly, the *Could Have*'s are extra features that are added to the product to differentiate it from the competition and make the customer recognize its added value. The implementation a *Could Have* requires an exponential effort comparing to the customer's satisfaction and work a delighter.

The graph presented below (*Kano Model*) distinguishes qualitatively the three types of implementations that can be done during the design of a product. It relates the degree of implementation to the customer's satisfaction.

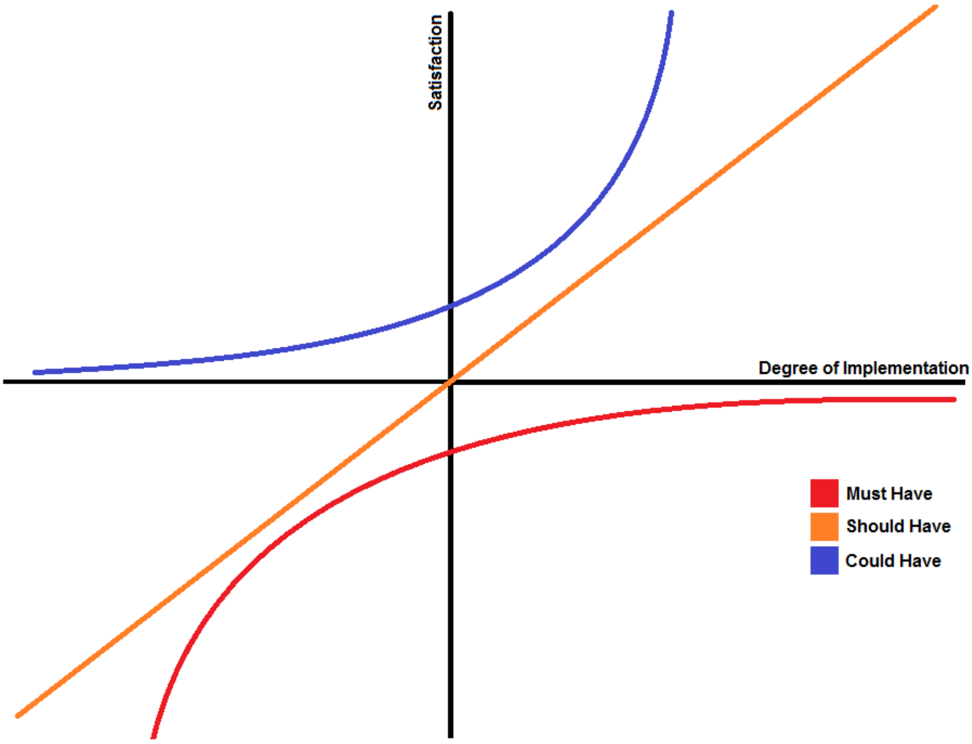


Figure 4-1: *Kano Model – Must*, *Should* and *Could Have*’s: Degree of Implementation vs Customer’s Satisfaction

The next section will cover the requirements that the Gantry’s design must meet. These requirements are mostly stated by *Highways Agency*’s norm BD 51/98 and also from *Lattix*. Therefore, the External Requirements, given by the customer that is obliged to comply with the norm, and the Internal Requirements, given by *Lattix*, where are addressed issues that don’t concern directly the customer, will be distinguished. Only the requirements that are directly related to the aluminium structure will be addressed, leaving apart the requirements related to the site location, the signs or signals, the foundations, the crash simulations (due to the scope of this work the collision loads to simulate an impact from an errant vehicle won’t be addressed, hence crash analyses won’t be performed), or the technical approvals.

Each requirement will be categorized as a *Must Have* (M), *Should Have* (S) or *Could Have* (C).

4.1.2 External Requirements

This section will deal with the requirements stated by the customer. It is relevant to refer that most of the External Requirements are given by legislative norms beyond the customers’ needs, which must be achieved in order to the Gantry be homologated.

Below, the requirements given by the customer are listed.

(M) A Gantry is designed to have a **life of 60 years**, at least.

(S) The Gantry must be material efficient aiming to a **light-weight** structure.

(M) Span: from **20m** to **30m**;

(M) Height: from **5.5m** to **7.5m**;

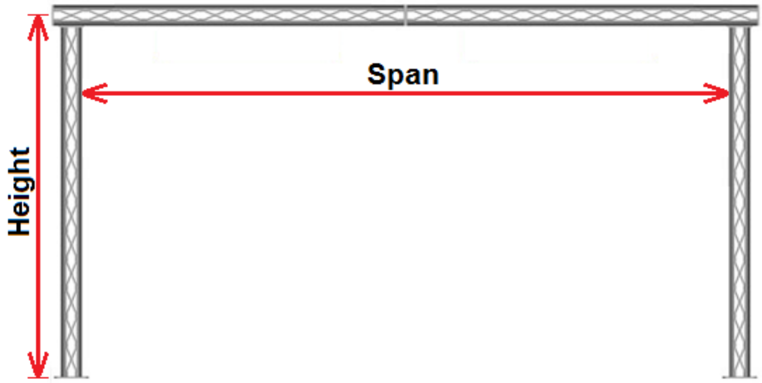


Figure 4-2: Gantry's Span and Height

(M) Variable Message Sign:

- Maximum sizes [l x h] and Weights [W]:
  - Sign 1 – **[8.5 x 2] m** and **W = 3.4 kN**;
  - Sign 2 – **[10 x 2.7] m** and **W = 15 kN**;
  - Sign 2 – **[10 x 3] m** and **W = 6 kN**.

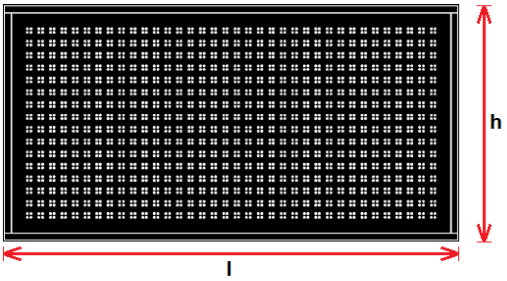


Figure 4-3: Variable Message Sign's dimensions

- Position in the Boom:
  - Centric;
  - Above.

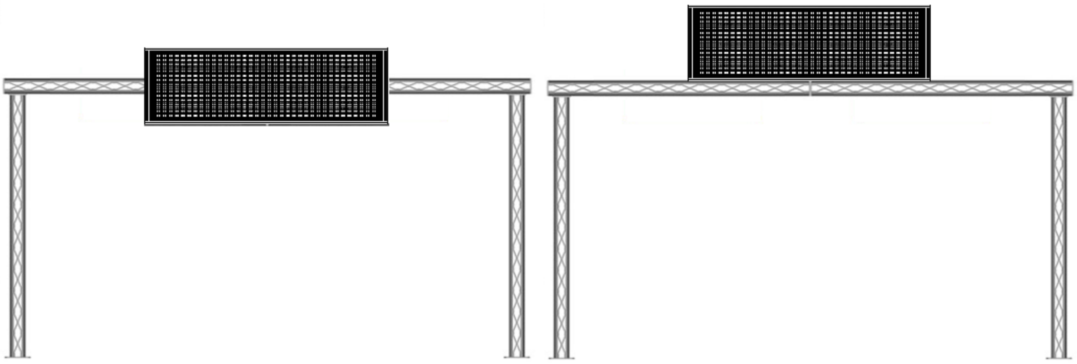


Figure 4-4: Variable Message Sign Position: a) Centric on Boom; b) Above Boom

- Minimum clearance from the road to the sign: **5.5m**;

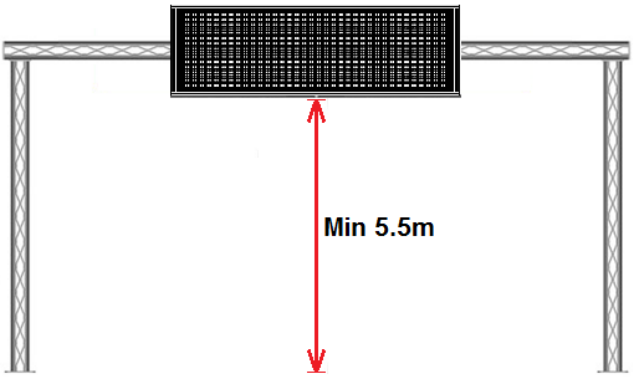


Figure 4-5: Gantry’s minimum clearance

(M) Loads:

- **Gantry’s self-weight**;
- **Sign’s weight**;
- **Wind**: from 1 to 2.2 kN/m^2;
- **Snow**: 1 kN/m^2;

(M) Connections between structural elements:

- Vibrant resistant fasteners shall be used;

(M) Access: to maintenance purposes shall be installed a walkaway or a ladder.

(S) Pre-Camber:

In order to counteract the displacement due to the structure’s own weight a pre-camber shall be applied.

(M) Maximum Displacements:

Boom’s Vertical (y) Displacement: S/200;

Boom’s Horizontal (z) Displacement: S/100;

Legs’ Horizontal (z) Displacement: $H_y/200$;

Legs’ Horizontal (x) Displacement: $H_y/200$.

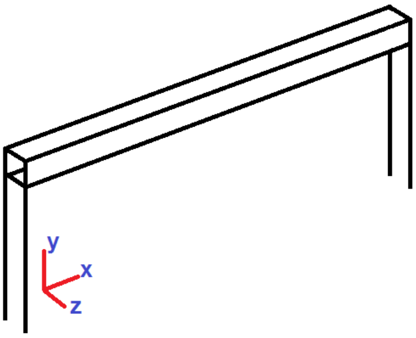


Figure 4-6: Referential of Coordinates

(M) Maximum Torsion:

Boom or Legs’ maximum torsion: 2.3º.

(S) Simple sign fixing:

The design should consider the fitting of the sign with the boom, and this should be simple, allowing a quick installation, maintenance or sign replacement.

(S) Minimize the risk of theft:

Measures should be taken to minimize the risk of material theft and vandalism. If necessary a risk assessment should be taken to prevent illegal access to the ladder.

(S) Minimize the need for inspection:

The Gantry’s design should consider means to avoid the need of regular structural inspection. Therefore is not recommended to use welds in the aluminium structure.

(C) Aesthetics:

A Gantry should have an appearance in continuity with other highway structural elements. It should reduce the visual impact as much as possible by having a simple and innovative design. The colour should be appropriate to assist and promote the function of communication. The accessories like walkways should be hidden from the road users.

(S) Avoid supports in the central reserve (the 3rd Leg):

Related to the aesthetics recommendations, a Leg in the central reserve (in the middle of the Gantry) should be avoided. This not only reduces the structure’s visual impact but also reduce the material use, weight and therefore the cost.

(C) Environmental responsibility and End of life:

Since the material to be used is aluminium, no paint or chemical are needed for maintenance. A Gantry as light-weighted as possible, requires less energy consumption during the transport and installation on site. The Gantry's material should be recyclable.

4.1.3 Internal Requirements

This section will address the requirements that *Lattix* dictates.

(M) Main manufacturing process: Extrusion;

(M) Maximum extrusion section dimensions: [420 x 230] mm;

(M) Minimum thickness for aluminium alloy sections: 4 mm;

(S) Minimum thickness of the end plates: thickness of the profile or 8 mm;

(M) Hollow sections shall prevent the retention of water inside the profiles;

(S) Extrusion profiles' good stacking:

The design of the structural parts' profiles should consider the stacking at the factory plant and during the transport. The aim is to improve the pilling potential and avoid bending and thus not deliver bad parts.

(S) Maximize Customization:

The design should use mass-customization principles in order to allow each customer to have a degree of freedom in adapt the final design to his specific needs, while keeping controlled production costs. This would increase the value of the product in the customers' eyes.

(S) Modularity/Standardization:

The design should use a modular philosophy in order to extend the applications of the same Gantry's model and also to reduce the costs.

(S) Minimize the number of manufacturing operations:

The design of the structural parts should take in account the required number of production operations needed, with the goal to minimize them and thus its cost.

(S) Minimize extrusion cost:

The design of the beams' profiles should consider the extrusion process, in order to prevent high die costs, low productivity and high scrap production.

(S) Minimize production cost:

The design should minimize the number of operations after the extrusions, like for example cutting and drilling.

(S) Minimize purchased parts cost:

The number and complexity of purchased parts used in the structure should be minimized.

(S) Minimize assembly cost:

The design should consider profiles that simplify the assembly and also minimize the total number of connections, in order to keep down the assembly costs.

(S) Minimize installation time and cost:

The design should consider the installation phase and have simple and direct fittings between the subassemblies and the foundations. This enables to minimize the installations time and thus its cost.

(S) Installation Requirements:

- **Installing the Legs:** The Legs will arrive on site ready to be mounted. Each Leg is bolted to a baseplate with is also bolted to the foundation;

- **Boom total assembly:** The Boom will arrive on site in modules (the maximum length allowed to transport in public roads in Norway is 13 m). They will be placed in supports and connected thought end plates;
- **Installing the Boom:** The boom is lifted as one piece, with the sign fasteners installed, then it is lowered into position, locked and fixed;

- **Attachment of the Signs:** The *VMS*'s will be lifted and fixed to the Boom.

4.1.4 *House of Quality*

A product must comply with the requirements, mainly the customer's needs and demands, in order to be valuable and desired. The translation of the requirements into measurable parameters that define the product is a very important task.

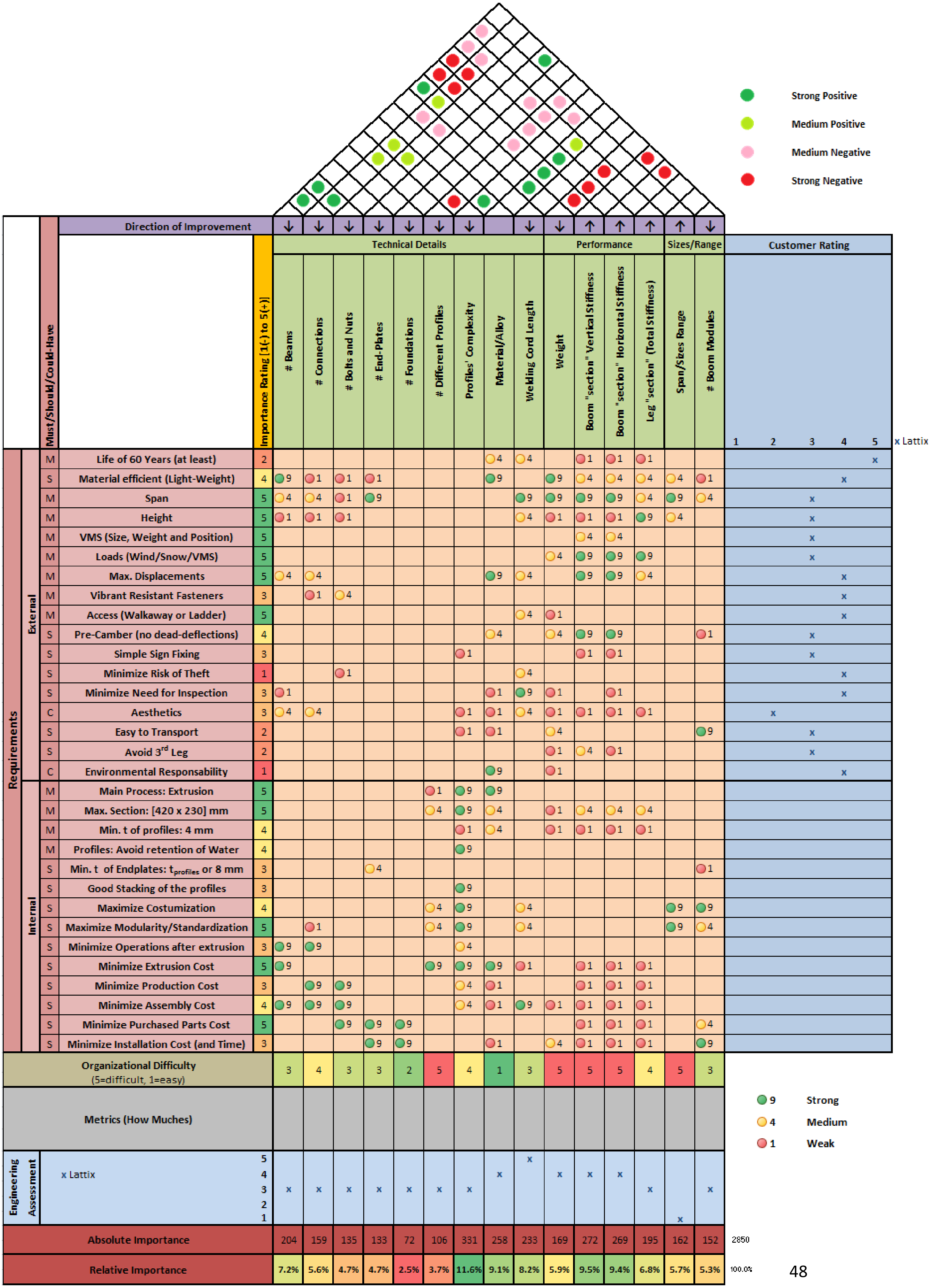
The requirements are achieved by the performance of the technical characteristics of the product. This way, it is very important, firstly, to decompose a generic Gantry into its several technical parameters. After that, list all the external and internal requirements and rate them accordingly with their importance (from 1 to 5). Then, it is needed to relate each requirement with each technical parameter (technical descriptor) in one of the three relations: Strong, Medium or Week. This way, through the *House of Quality* matrix, introduced in the third chapter, it can be known the relative importance or weight of each technical parameter regarding the ability of fulfilling all the requirements.

Since the requirements were introduced in the previous sections, below the technical parameters that allow characterising a Gantry in terms of its structural configuration are listed.

- Number of Beams;
- Number of Connections;
- Number of Screws (and Nuts);
- Number of End-Plates (longitudinal connectors);
- Number of Foundations;
- Number of Different Profiles;
- Profile's Complexity;
- Material/Alloy;
- Welding Cord Length;
- Weight;
- Boom's Vertical Stiffness;
- Boom's Horizontal Stiffness;
- Leg's Total Stiffness;
- Span/Sizes Range;
- Number of Boom Modules.

The figure below presents the *House of Quality* matrix with the requirements' importance rated, as well as their relationship with each technical descriptor. These two values will originate the absolute and consequently the relative importance of each technical parameter, which is the goal of this exercise. The *House of Quality* matrix is a more complex tool, which represents just a step in the *Quality Function Deployment* approach. Therefore, it also represents (in the "roof") the impact of the implementation of each technical descriptor in each other, regarding the correspondent directions of improvement. These relations will define the organizational difficulty in implement each technical descriptor. The matrix also has a field where the customer (or customers) can evaluate currently the perceived capacity of the company and also the competitors to fulfil each requirement (this evaluation was assumed, because there was no contact to specific customers). Regarding the metrics, it was not considered any baseline values, because it is not being studied a specific Gantry size. Therefore, in short, the relevance of this implementation is to get the relative weights of each technical parameter, in order to use them in the *Pugh Matrix* type to be used to compare the different Gantry models and concepts.

One of the goals of this work is to present the method used to take decisions and to evaluate different concepts. Therefore, the focus here is not the specific values used to rate the requirements' importance or the relationships between them and the technical descriptors.



		Must/Should/Could-Have	Direction of Improvement		↓	↓	↓	↓	↓	↓	↓		↓	↓	↑	↑	↑	↑	↓					
					Technical Details									Performance				Sizes/Range		Customer Rating				
				Importance Rating [1(-) to 5(+)]	# Beams	# Connections	# Bolts and Nuts	# End-Plates	# Foundations	# Different Profiles	Profiles' Complexity	Material/Alloy	Welding Cord Length	Weight	Boom "section" Vertical Stiffness	Boom "section" Horizontal Stiffness	Leg "section" (Total Stiffness)	Span/Sizes Range	# Boom Modules	1	2	3	4	5
Requirements	External	M	Life of 60 Years (at least)	2								4	4		1	1	1							x
		S	Material efficient (Light-Weight)	4	9	1	1	1				9		9	4	4	4	4	1				x	
		M	Span	5	4	4	1	9					9	9	9	9	4	9	4			x		
		M	Height	5	1	1	1						4	1	1	1	9	4				x		
		M	VMS (Size, Weight and Position)	5											4	4						x		
		M	Loads (Wind/Snow/VMS)	5										4	9	9	9					x		
		M	Max. Displacements	5	4	4						9	4		9	9	4						x	
		M	Vibrant Resistant Fasteners	3		1	4																x	
		M	Access (Walkaway or Ladder)	5									4	1									x	
		S	Pre-Camber (no dead-deflections)	4								4		4	9	9			1			x		
		S	Simple Sign Fixing	3							1				1	1						x		
		S	Minimize Risk of Theft	1			1						4										x	
		S	Minimize Need for Inspection	3	1							1	9	1		1							x	
		C	Aesthetics	3	4	4					1	1	4	1	1	1	1				x			
		S	Easy to Transport	2							1	1		4					9			x		
		S	Avoid 3rd Leg	2										1	4	1						x		
		C	Environmental Responsability	1								9		1									x	
	Internal	M	Main Process: Extrusion	5						1	9	9												
		M	Max. Section: [420 x 230] mm	5						4	9	4		1	4	4	4							
		M	Min. t of profiles: 4 mm	4							1	4		1	1	1	1							
		M	Profiles: Avoid retention of Water	4							9													
		S	Min. t of Endplates: $t_{profiles}$ or 8 mm	3				4											1					
		S	Good Stacking of the profiles	3							9													
		S	Maximize Costumization	4						4	9		4					9	9					
		S	Maximize Modularity/Standardization	5		1				4	9		4					9	4					
		S	Minimize Operations after extrusion	3	9	9					4													
		S	Minimize Extrusion Cost	5	9					9	9	9	1		1	1	1							
		S	Minimize Production Cost	3		9	9				4	1			1	1	1							
		S	Minimize Assembly Cost	4	9	9	9				4	1	9	1	1	1	1							
		S	Minimize Purchased Parts Cost	5			9	9	9						1	1	1		4					
		S	Minimize Installation Cost (and Time)	3				9	9			1		4	1	1	1		9					
			Organizational Difficulty (5=difficult, 1=easy)		3	4	3	3	2	5	4	1	3	5	5	5	4	5	3					
			Metrics (How Muches)																					
Engineering Assessment		x Lattix		5									x											
				4								x		x	x	x								
				3	x	x	x	x	x	x	x						x		x					
				2																				
				1														x						
			Absolute Importance		204	159	135	133	72	106	331	258	233	169	272	269	195	162	152	2850				
			Relative Importance		7.2%	5.6%	4.7%	4.7%	2.5%	3.7%	11.6%	9.1%	8.2%	5.9%	9.5%	9.4%	6.8%	5.7%	5.3%	100.0%				

x Lattix

● 9	Strong
● 4	Medium
● 1	Weak

Figure 4-7: *House of Quality*

4.2 Concept Generation

This chapter will deal with concepts for a new light-weight Gantry system with the purpose of having a significant cost reduction comparing to the current models.

4.2.1 *Lattix*'s Current Gantry Model (*LWG 1000*)

Before start to deal with new proposed concepts for future Gantries, it is necessary to discuss the current model. The type of sections and the connections between the parts will be introduced briefly.

Figure 4-8: *Lattix*'s current Gantry model - overview

The current solution uses the *Lattix*'s Standard Masts. Each Mast is made of one extrusion, then slotted longitudinally in order to be then stretched, resulting in a "X" lattice pattern all made in a single piece. Each of the Gantry's Leg comprises two standard masts that are connected by a plate at the top.

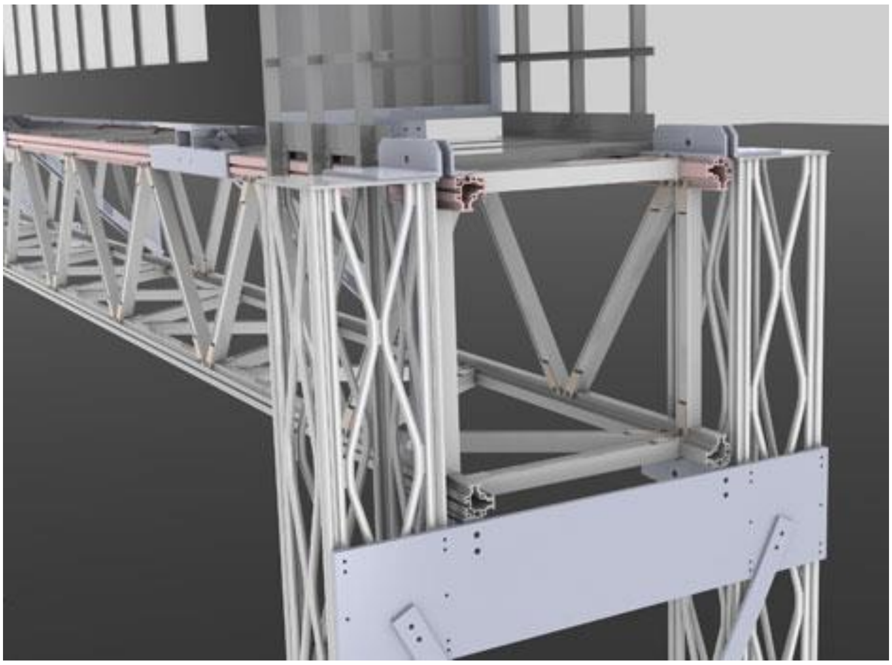


Figure 4-9: ***Lattix*****'s current Gantry model**

The Boom has a square transversal section with about 1m of width. There are four main beams that outline the 90 degree connections between the diagonal beams from two adjacent planes.

The connections between the diagonal beams and the respective main beam are done by the use of brackets that have two bolts each; one linking it to the diagonal and the other linking it to the main beam. The bolts transfix the beams from one side to the other, therefore, each connection between one diagonal with the main beam requires two brackets (one for each side) and two bolts.

The Boom is built in longitudinal sections of about 7m that are connected on site, during the installation phase, by 180 degree connectors. The Total Boom is then connected to the Legs by 90 degree connectors.

Regarding the Legs, the standard masts offer a good structural behaviour, but mainly they give to the Gantry a status of a passive safely structure, which means that in case of a collision from an errant vehicle, the masts absorb the energy from the impact in order to protect the occupants. The problem is that the production of these masts requires a high number of operations and thus higher associated cost.

Despite the Boom's light-weight, provided by the relative small sections, due to a considerable large amount of parts the assembly costs have a substantial proportion on the Gantry's total cost.

In order to improve the current model, the focus will be to create a model that can reduce the total number of parts but at the same time keep a light-weight philosophy that enables to minimize the material usage.

4.2.2 The Models

This section has the goal of study new configurations and evaluates their potential as new Gantry models. Therefore, the focus is not the use of determinate sections or to study all the load cases, but to compare several proposed models, having as a reference the current *Lattix*'s model. In addition to it, another model from the competition will be added, since it uses a different structural approach. For reasons of confidentiality, this model will be named *Model W*.

The design philosophy behind the proposals was the focus on the vertical and horizontal stiffness, in order to prevent Boom's deflections close to the allowable limits, but also a structure that has better visual appealing to the road users than the current Gantry models.

1) *Model I*:

The first proposed model was designed having a singular frame structure in mind, but supported by a triangular truss structure that increases the Boom's inertia moments in both vertical and horizontal directions. Since near both Legs, the Boom's deflections don't have great magnitudes, the Boom's truss reinforcement is not applied in the entire horizontal frame's length, enabling this way some material save.

The figure below shows the Model I's structure configuration. The image was retrieved from the *NX*'s *FEM* file, where the Mesh is applied to the 1D beam elements.

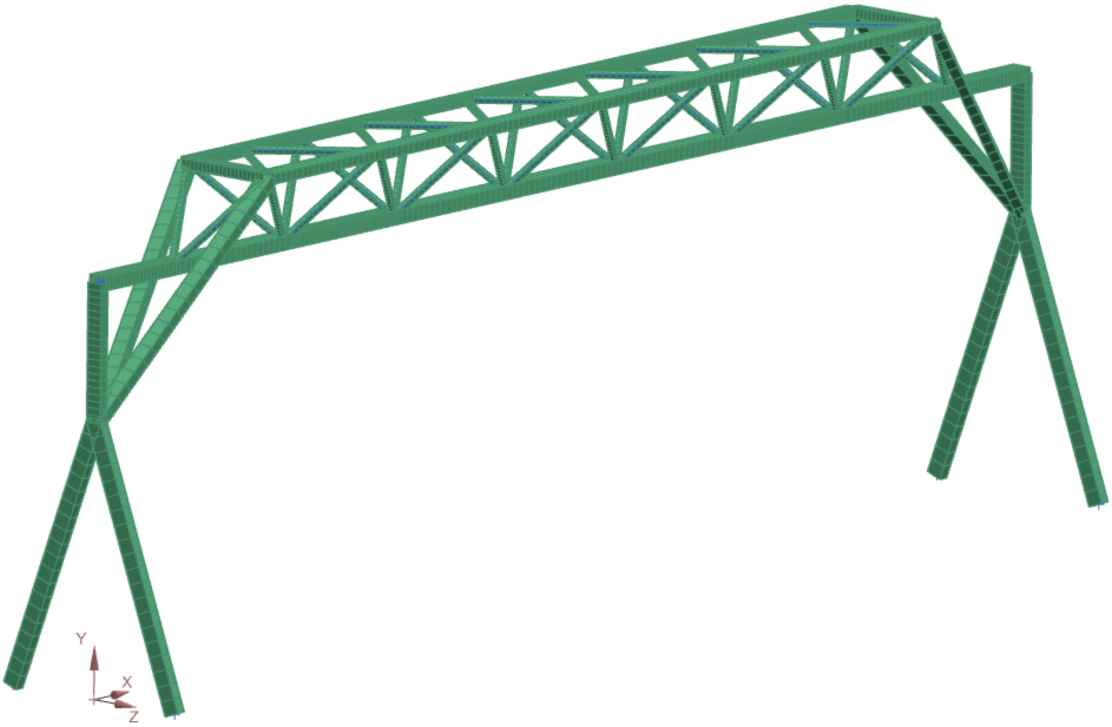


Figure 4-10: ***Model I*** **with 20m Span**

2) ***Model II*:**

The second model to be presented was designed as an evolution of the *Lattix*'s proposed concept, to be presented ahead. It was given a Boom with three steps, in order to give a curvature that counteracts the vertical displacements. One advantage of a Boom like this is that this way there is no need of applying a pre-camber to cancel the visible vertical deflections due to the self-load. The structure consists of two parallel main beams connected in the Boom's three steps by diagonal beams. The main structure is reinforced by four Legs in an angle, having this way six contact points with the ground.

The goal with this design, besides the focus on minimizing the deflections, was to create a Gantry that could be more harmonic with the environment and more visual appealing by being slightly less geometric (as a simple rectangular frontal view).

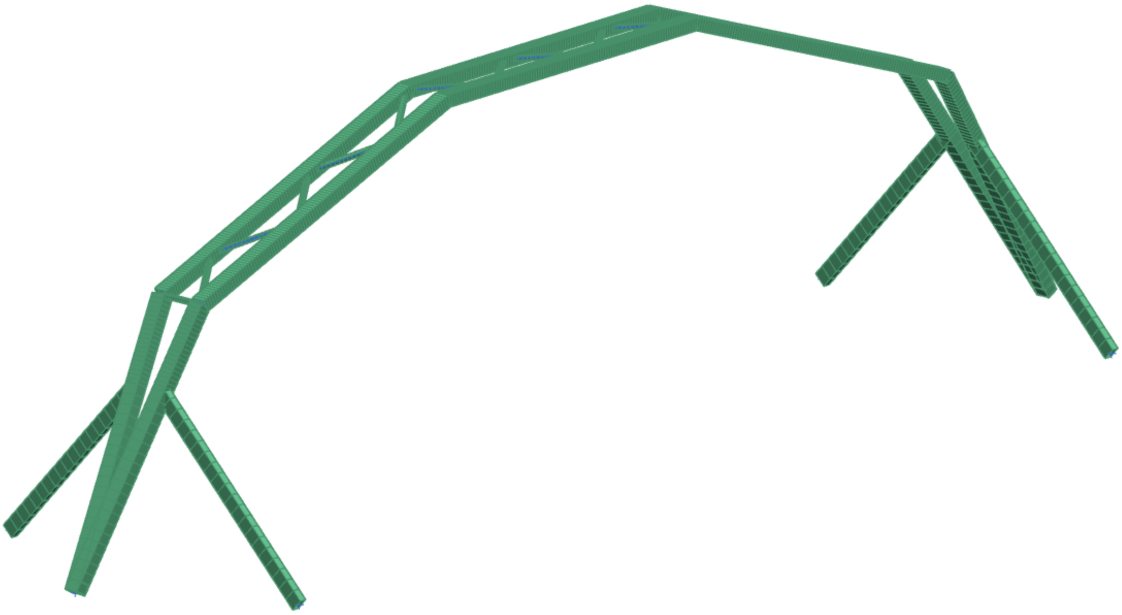


Figure 4-11: ***Model II*** **with 20m Span**

This configuration allows reducing the number of beams comparing to the *Model I,* which consists is the main advantage. This is equivalent to a lower assembly cost and lower number of parts required to produce the Gantry. But in order to comply with the displacement requirements in the same order as the *Model I* it is expected that this structure requires the use of more material, resulting in a higher total weight.

3) ***Lattix's*:**

The proposed new Gantry by *Lattix* is composed by a Boom with just one section, in other words, instead of having four main beams and a quadrangular boom section it has two bigger main beams and a planar boom section. The Leg masts have the same profiles of the Boom's main beams. The two parallel main boom's beams are connected through smaller diagonal beams. The Leg's masts are also connected by diagonal beams but in an array with straight beams.

The previous brief description can be better understood by observing a picture of the model, which is present below.

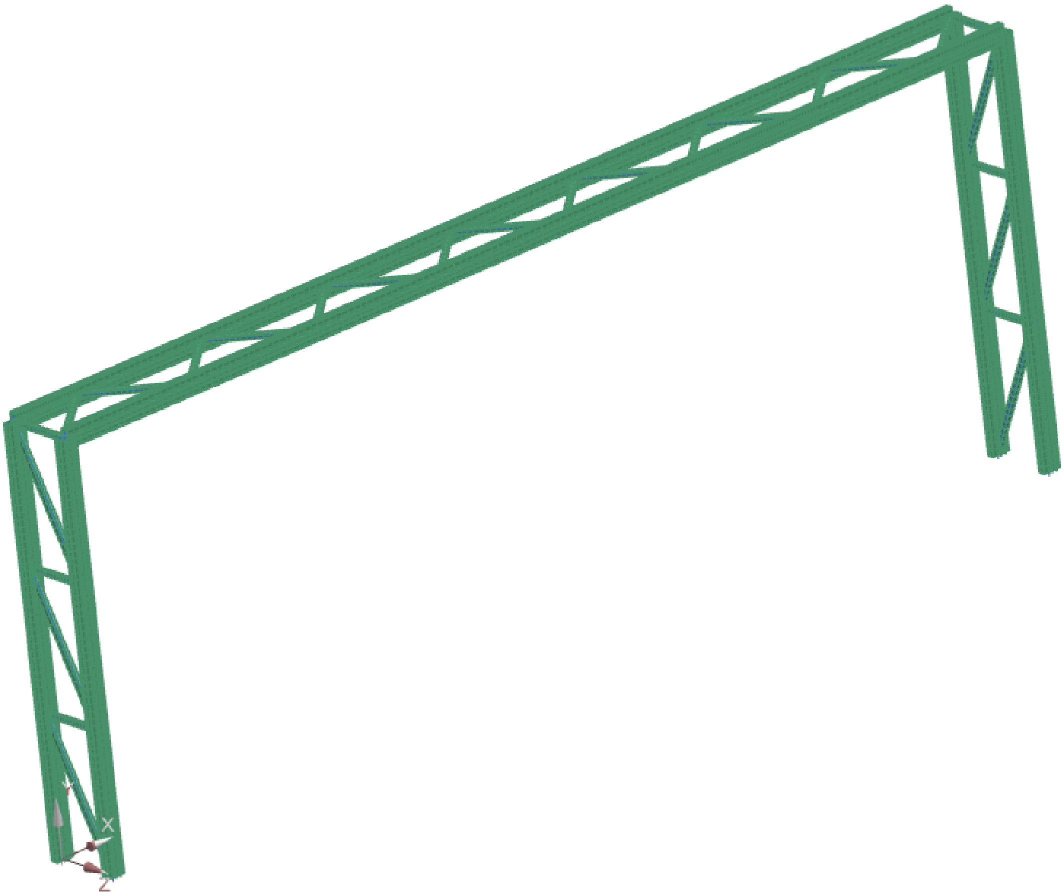


Figure 4-12: *Lattix's* Model with 20m Span

A structure like this, by having a planar Boom instead of a square section, result immediately in a smaller total number of parts, because the number of diagonal beams is reduced in one fourth, comparing with the current Gantry model scheme (*LWG 1000*). This would enable a faster and thus more economical assembly, due to the fact that the fewer number of parts, the fewer connections are to be made.

This doesn't represent automatically also less material use and extrusion cost savings. In order to maintain the structural integrity and comply with the stiffness requirements the Boom sections have to be large enough to have the minimum required Inertia Moments to meet the displacements' requirements. The sections for this model were also given and have an overall dimension of [340 x 210] mm.

Some studies performed to this model can be found in the Annex II, where are assessed different section sizes and different load cases.

4) *LWG 1000*:

This model was addressed in the chapter 4.2.1. Below the modelled structure is shown.

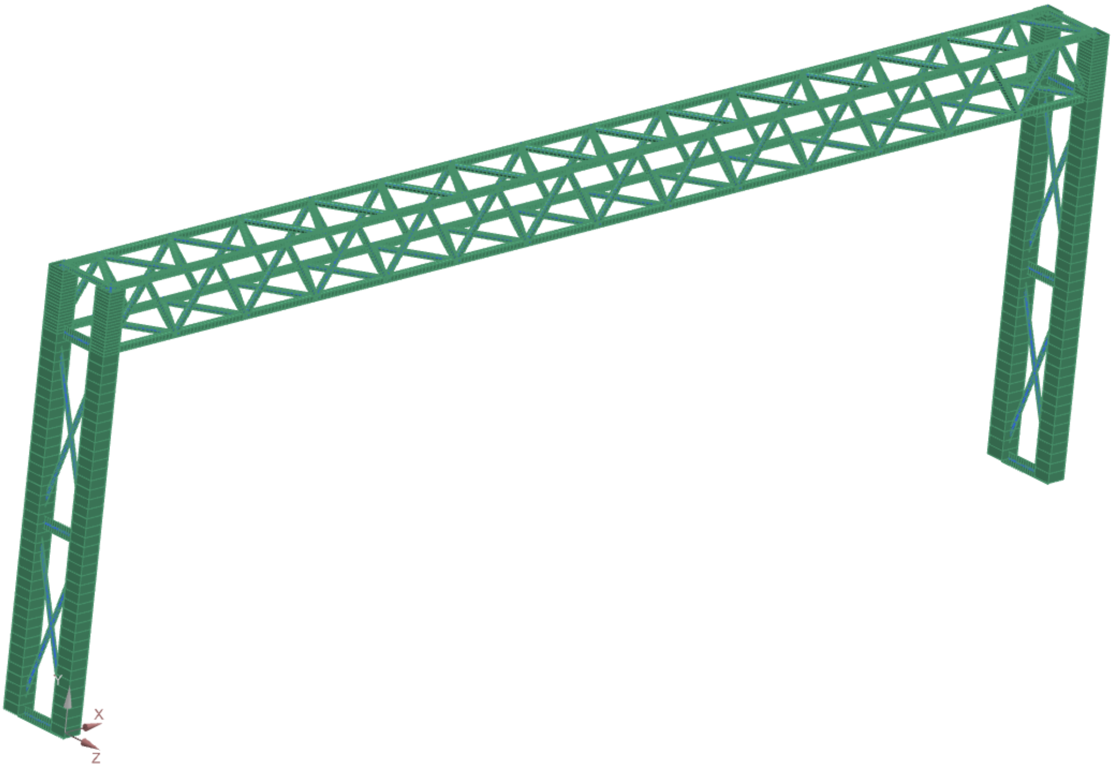


Figure 4-13: *LWG 1000* with 20m Span

The modelling of *the LWG 1000* had some simplifications due to the goal of the analyses, which is to evaluate the range of the Boom's deflections, and due to the use of 1D beam elements.

First of all, the *Lattix Masts 4438*, used in this model, where approximated to a hollow square box profile with the same bending stiffness. This Mast, with [375 x 375] mm of outer dimensions, has a weight of 22.13 kg/m. The bending stiffness (EI) of the 4438 Mast model is 5069 kNm^2 (Lattix Produktkatalog, 2010) which results roughly in 7200 cm^4 of Inertia Moment. Thus, to get an identical inertia value the Masts were approximates to box sections with [305 x 305] mm profiles with a wall thickness of 4mm.

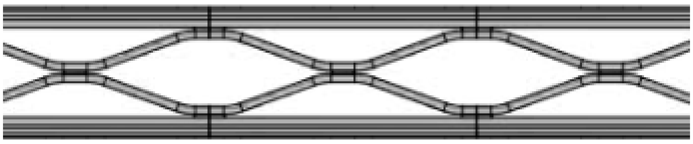


Figure 4-14: *Lattix* Mast pattern detail

Another simplification done during the modelling of the *LWG 1000* Gantry was that the Leg's connecting plates and stiffening bars were considered in a central position. In reality, there are one set of these at each side of the Masts. This had to be done because of the use of 1D elements, which only allow a punctual connection to each Mast (represented by a line).

This model represents the baseline to the comparison to be done. In other words, the costs of the other Gantry models will be compared to the *LWG 1000*'s costs by calculate the 'savings', in order to evaluate the potential of each solution.

5) *Model W*:

The *Model W* doesn't consist in a specific Gantry model, but a solution that the company use to build up a Gantry in accordance to the customer's specifications. These Gantries, also made of aluminium, are assembled by using welding processes, which allow generating profiles bigger than the ones possible to extrude. These Gantries consist of a simple portal frame. Both the Legs and the Boom consist in two extruded profiles connected (using welding chords) by two aluminium sheets, as the figure below suggests.

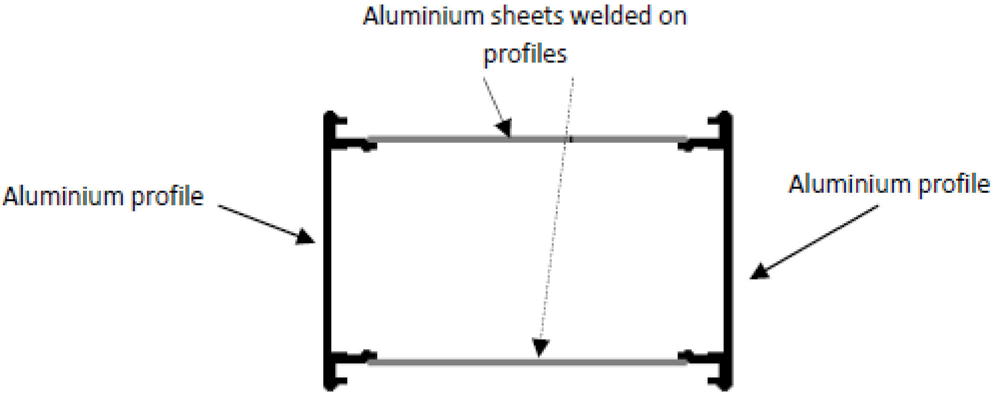


Figure 4-15: *Model W* Frame profiles

These Gantry models can have a walkaway built in on top of the Boom. This consists in a closed structure on top of the Boom, which allows to walk in safety on top of the Gantry and to access the *VMS*. The following figures show a typical *Model W* with and without a walkaway.

Figure 4-16: *Model W:* a) with walkaway; b) without walkaway

Normally, if the Gantry carries a *VMS*, a walkaway is required. Therefore, the walkaway will be considered for the cost calculations.

The walkaway is formed by welding vertical profiles to the Boom, which are connected by a perforated aluminium sheet forming the side walls. To build the ceiling, the profiles are welded to horizontal (or in a small angle) beams, with the same sections, and it is closed also by welding an aluminium sheet to the ceiling beams.

Figure 4-17: ***Model W:*** **Walkaway's vertical profiles and side perforated sheets**

Figure 4-18: ***Model W:*** **Walkaway's inside view**

The walkaway does not add stiffness to the frame structure. Therefore, there is no advantage in model it to get the Boom's displacement values. But its influence on the Boom has to be considered, namely its self-weight and the wind force that results from the bigger frontal area over the Boom due to the side perforated panels. To the contact area exposed to the wind pressure from the perforated panels it was considered 2/3 of the total area, due to the small holes, which reduce the drag force in the same proportion. This can be briefly explained by the drag equation.

$$F_d = \frac{1}{2}\rho v^2 c_d A \quad (4.1)$$

Where, $\mathbf{F_d}$ is the drag force, $\boldsymbol{\rho}$ is the density of the wind (in this case), **v** is the wind speed, $\mathbf{c_d}$ is the drag coefficient of the object (rectangular aluminium sheets) and **A** is the (projected) exposed area.

This way, in terms of modelling this Gantry corresponds to a very simple structure, as the figure below reveals.

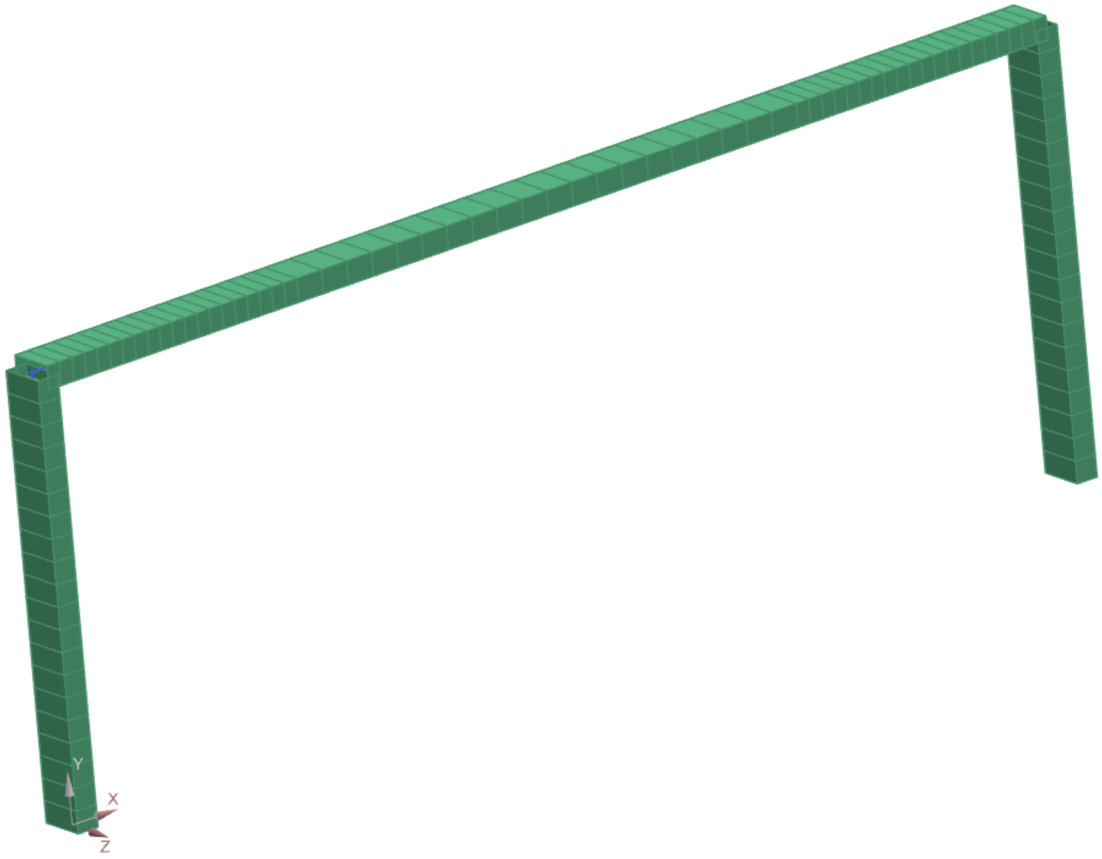


Figure 4-19: ***Model W*** **with 20m Span**

6) ***Model III*:**

The *Model III* was originated with the goal of enhance the vertical stiffness of the Boom. By this, the Boom has a vertical truss configuration. The lack of horizontal stiffness appears to be the weak spot of the structure, when exposed to the frontal wind pressures. Therefore, the bottom main beam is composed by two extruded beams side by side, which would be equivalent to a bigger extruded profile which cannot be produced due to the maximum die's dimensions limitation. These profiles would have details to enhance the lateral coupling and the bolting between both beams (for the calculations purposes, to this lateral coupling, it was considered a bolted connection for each meter). But since these subjects correspond to a much more detailed design, only the dimension of the beams (as box sections) and its weight will be considered in this section, being neglected this way the fitting between the two parallel main beams.

Below the structural configuration of the described model for a 20m span size is presented. It can be seen that this model has a relatively low number of beams, comparing to the other trussed models.

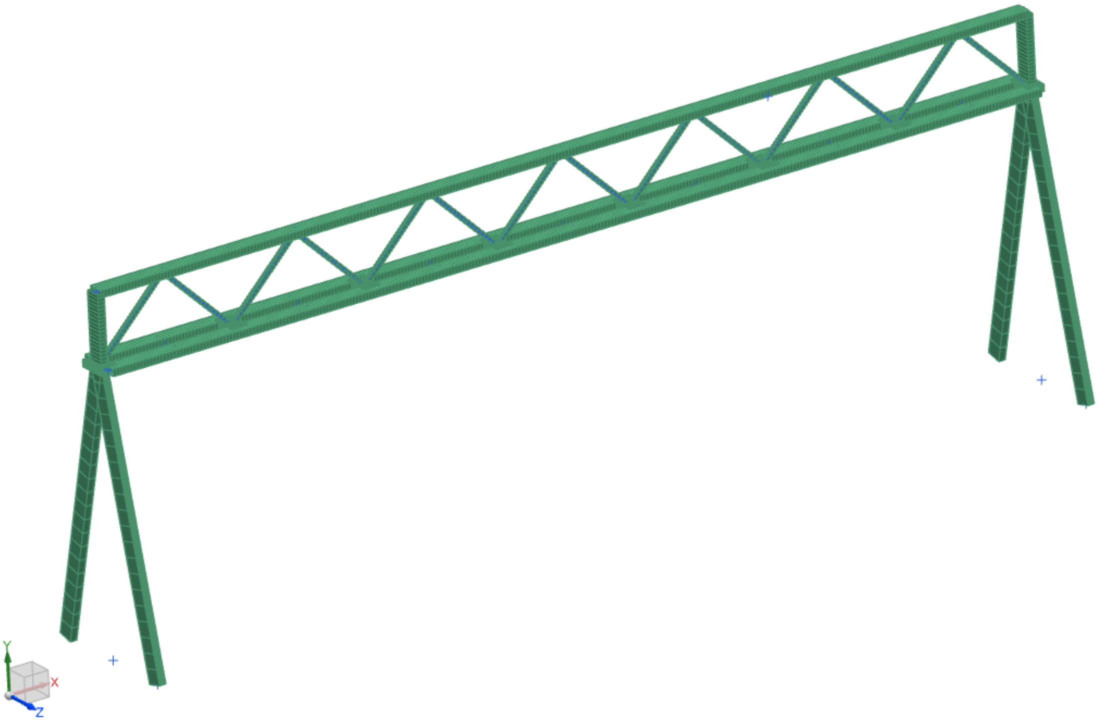


Figure 4-20: *Model III* with 20m Span

7) *Model IV*:

The *Model IV* was introduced as a variation of the *Model I*, where the top 'diagonals' of the triangular Boom section are connected perpendicularly to the main beams. This configuration, by slightly lowering the horizontal stiffness would enable to reduce the number of beams.

Below a figure with the proposed model is presented.

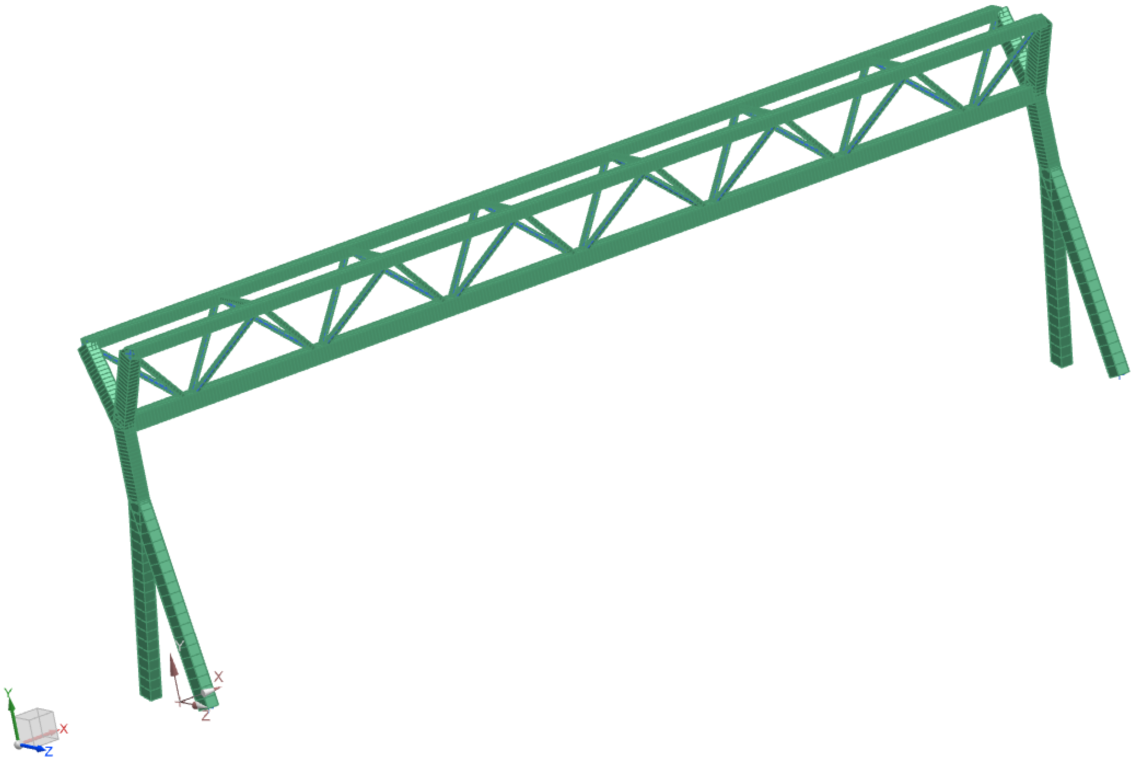


Figure 4-21: ***Model IV*** **with 20m Span**

4.2.3 Design Criteria

This section will cover the criteria used to perform *FEA*s and study the displacement results, in order to dimension the sections.

The goal is to dimension the models until get displacements in the range of the Span/200 range, in other words, for 20m span, within 100mm. Concerning the maximum torsion, a limit of 2.29º (0.04 rad) was used.

Regarding the load case considered, it was applied a snow pressure of 1 kN/m^2 combined with a frontal wind pressure of 1.1 kN/m^2. The *VMS* used was the heaviest one (Sign 2: [10 x 2.7] m; W = 15 kN). Regarding the vertical position of the *VMS*s on the Boom, to the *Model I*, *Model II*, *Lattix's* and *Model W* the sign was considered centred on the Main Beam of the Boom. The *LWG 1000* model uses the *VMS* on top of the Boom. The *Model III* used the *VMS* centre on the bottom Beam and the *Model IV* on the top main beam (as well and the *Model I*).

In terms of analyses, it was used (1D) beam elements. This type of analysis has the sufficient accuracy for the required results, enables an easy and quick tuning of the sections' dimensions and performs the calculations almost instantly. An analysis to a 3D model, besides the need of spend some effort improving the tetrahedral mesh, would take much more computational time, when compared to the use of beam elements.

The goal of this exercise is to evaluate the potential of different structural configurations. This way, the sections used for both structures were simple hollow box profiles, where the dimensioning lied on the width, height and side and top flanges' thicknesses. The approximation of using box hollow sections obviously has some limitations that must be considered. The virtual ideal box section would be the one with higher width and height and thinner walls as possible. The analyses ran to get the displacement results are static ones. Therefore, there's no consideration to the structure's stability, namely the possible buckling problems of the beams' walls. This way, in reality, many of this box sections considered, would have an inner wall to reduce the risk of buckling under compression forces. So the dimension of the wall thickness was performed having this in mind, in other words, the use of thin walls relatively to the sections dimensions was avoided.

The dimensioning of the different sections on the author's proposed concepts was performed to get displacement values inside the allowable requirement's range and in a way that all models present similar structural performances. In other words, the tuning of the sections was made until reach displacements for both models in the same magnitude (or as close as possible). This approach enables a fair comparison between the concepts, regarding the weight of each structure.

4.2.4 Sections and Displacements

1) *Model I*:

Below the sections used to the *Model I* and its displacement and rotational results are presented. For this 20m model, it was given to the Legs' profiles the same section as the Main Boom's beams, and not the Main Frame.

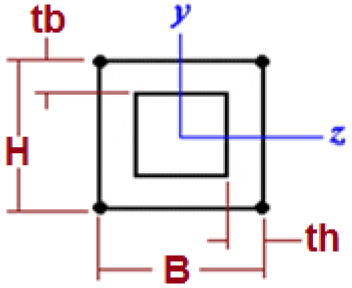


Figure 4-22: Nomenclature for the box section's dimensions

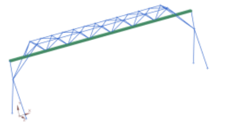
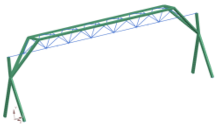
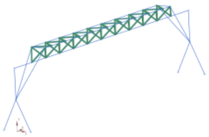
Beams	B	H	tb	th	Kg/m	
Main Frame (Boom)	310 mm	200 mm	6 mm	6 mm	16.2	
Main Boom, Boom-Leg connectors and Legs	250 mm	150 mm	6 mm	6 mm	12.6	
Diagonals	80 mm	80 mm	5 mm	5 mm	4.1	

Table 4-1: Sections used in the *Model I* – 20m

For the load case considered, the main results (vertical and horizontal displacements and maximum torsion) are shown below.

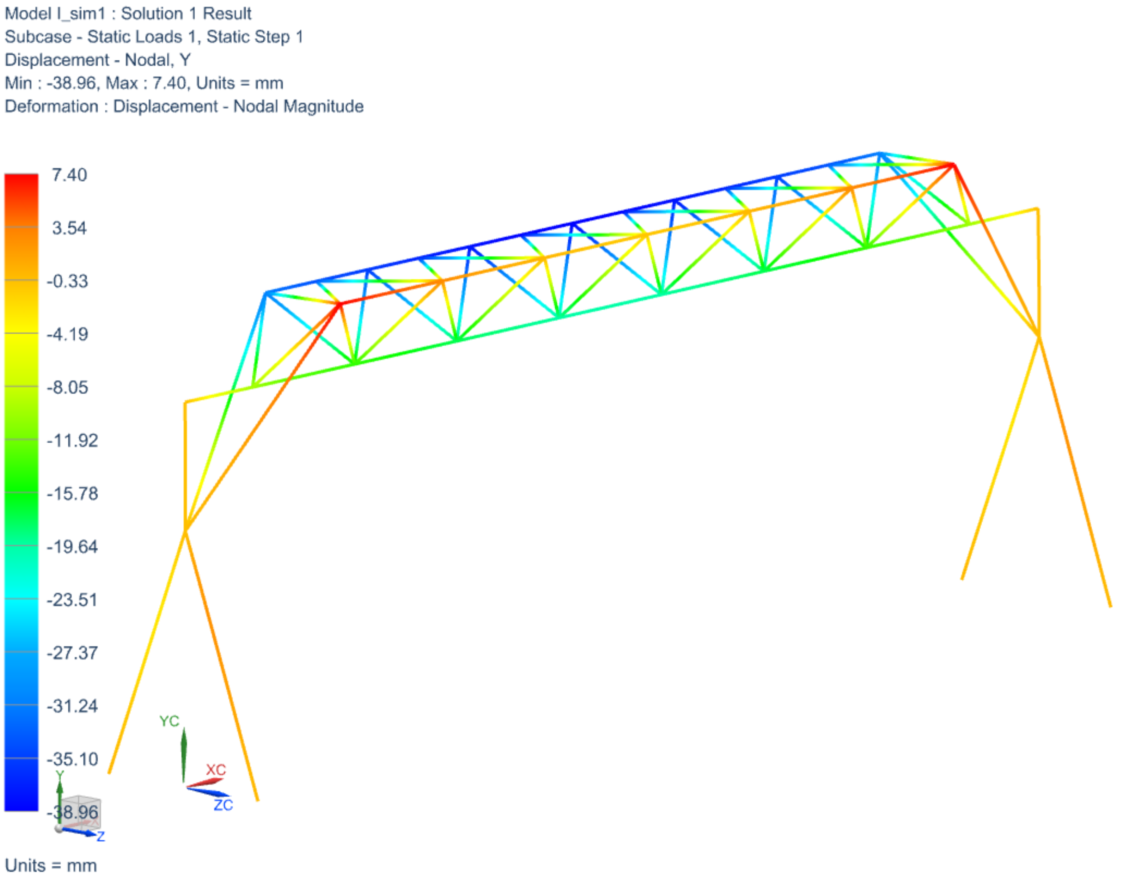

Model I_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Y
Min : -38.96, Max : 7.40, Units = mm
Deformation : Displacement - Nodal Magnitude

Figure 4-23: *Model I* – 20m: Vertical Displacement Results

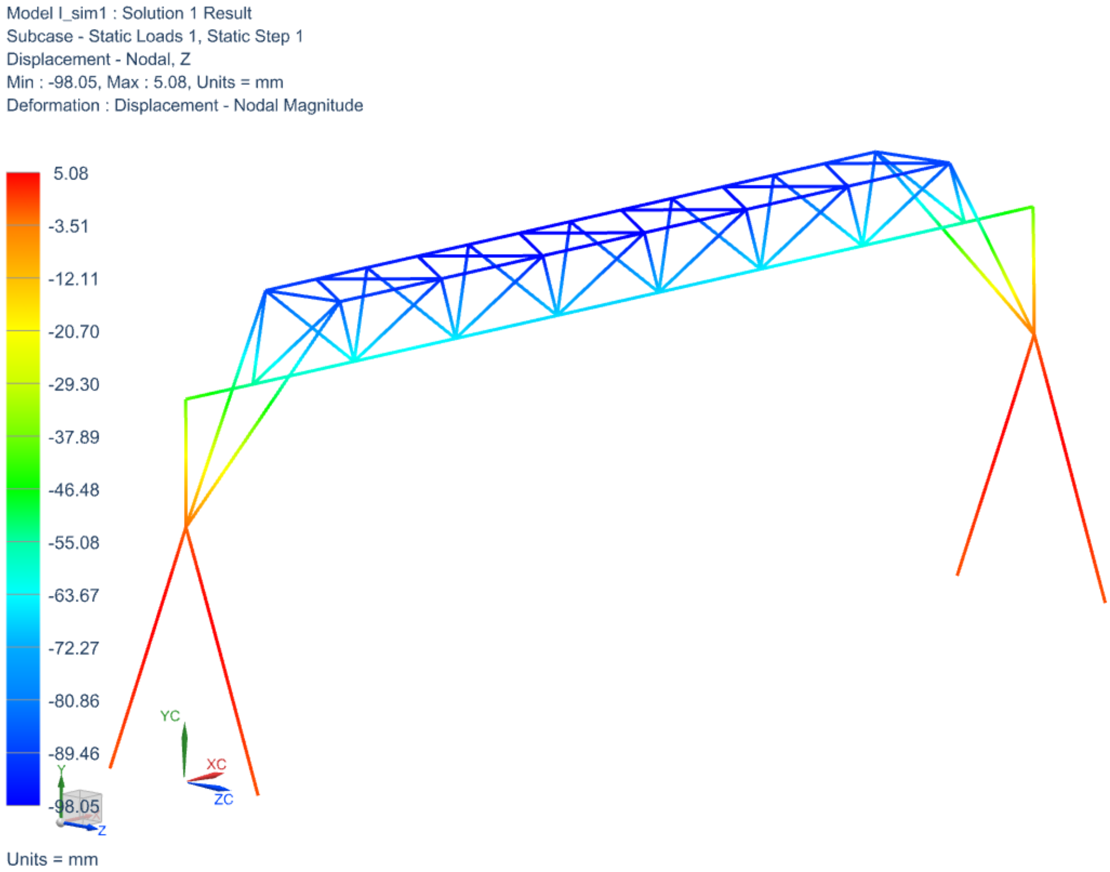


Figure 4-24: *Model I* – 20m: Horizontal Displacement Results

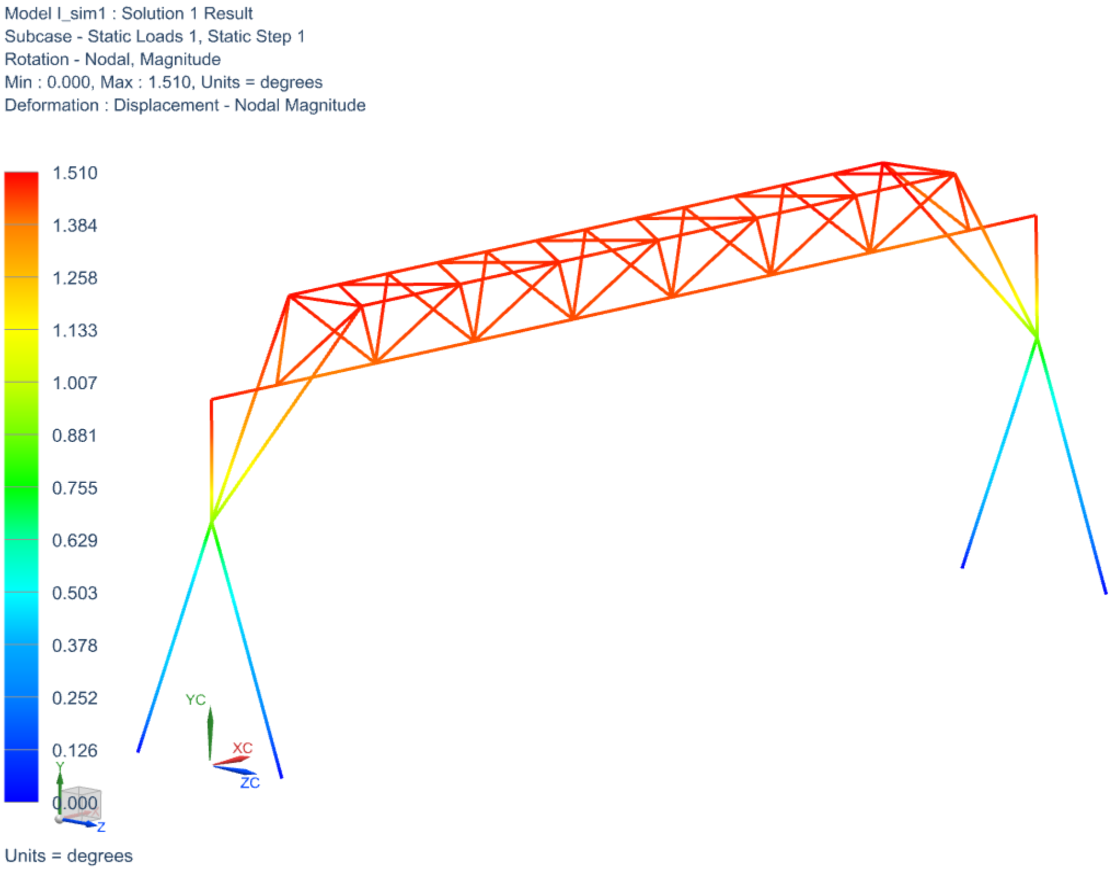


Figure 4-25: *Model I* – 20m: Torsion Results

Subsequently to the graphical results shown in the previous figures, the maximum results are summarized in the next table.

		Where
Maximum Vertical (y) Deflection	39 mm	Boom’s back main beam
Maximum Horizontal (z) Deflection	98 mm	Boom’s top
Maximum Torsion	1.5º	Boom

Table 4-2: *Model I* – 20m results summary

The triangular Boom section gives a high vertical stiffness. But this configuration suggests a *VMS* position centred in the Top Main Beam, which subjects the structure to torsional moments. Therefore the maximum rotational angle is quite high.

2) *Model II*:

Repeating the same arrangement as before, below, is presented the sections for the *Model II* with 20m.

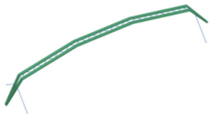
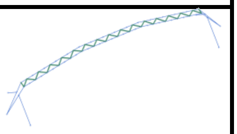
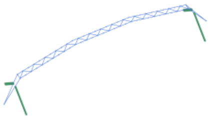
Beams	**B**	**H**	**tb**	**th**	**Kg/m**	
Main	320 mm	250 mm	7 mm	7 mm	21.1	
Diagonals	90 mm	90 mm	6 mm	6 mm	5.5	
4 Legs	300 mm	150 mm	7 mm	7 mm	16.5	

Table 4-3: Sections used in the *Model II* – 20m

The main displacement results are shown below.

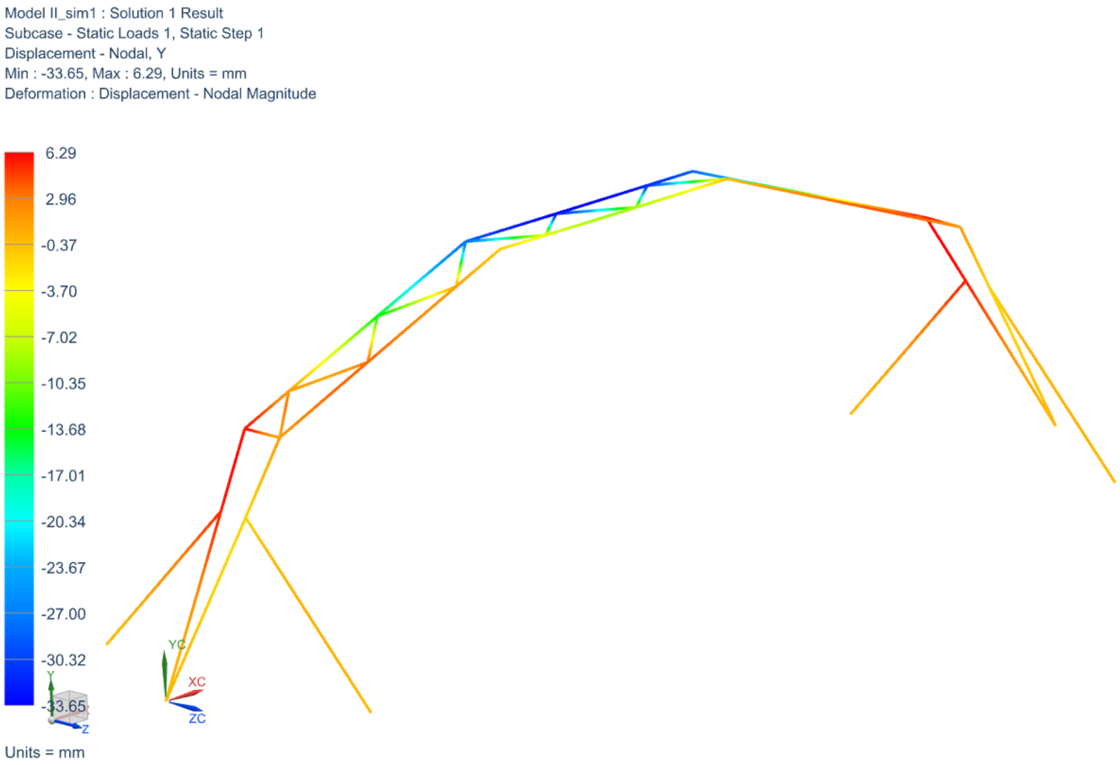


Figure 4-26: ***Model II*** **– 20m: Vertical Displacement Results**

Figure 4-27: ***Model II*** **– 20m: Horizontal Displacement Results**

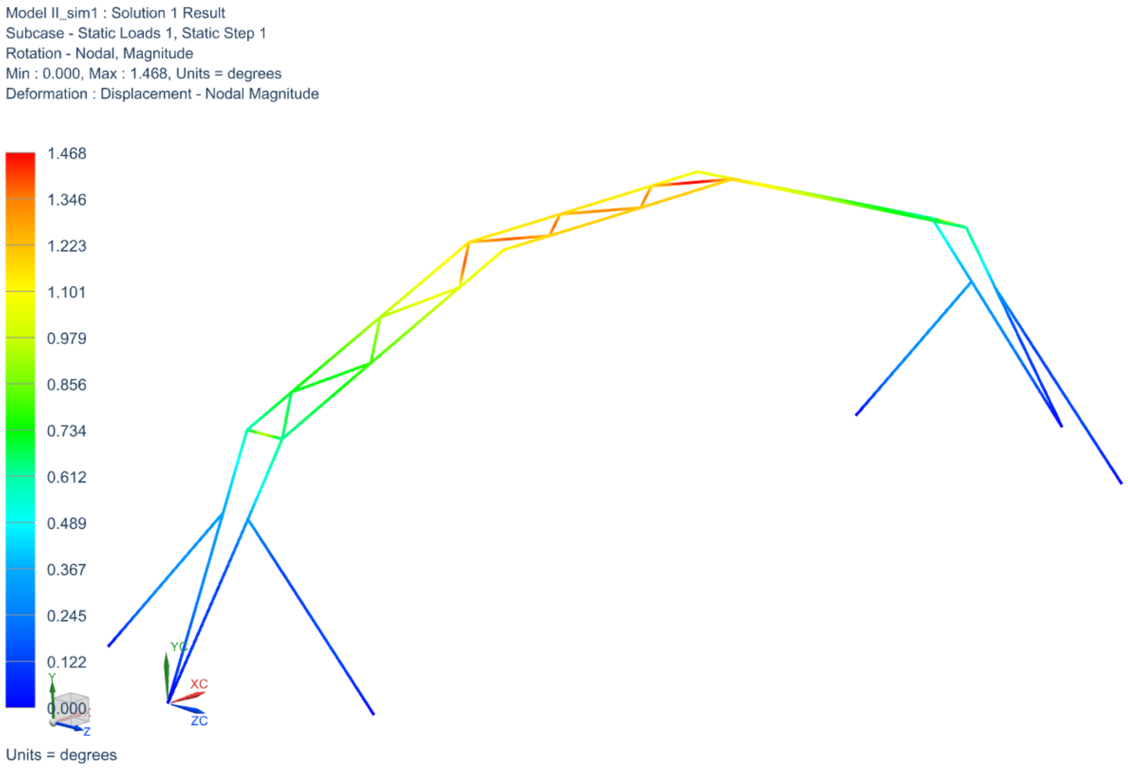


Figure 4-28: *Model II* – 20m: Torsion Results

The maximum results are summarized in the next table.

		Where
Maximum Vertical (y) Deflection	34 mm	Boom’s back main beam (central section)
Maximum Horizontal (z) Deflection	96 mm	Boom’s central section
Maximum Torsion	1.5º	Boom

Table 4-4: *Model II* – 20m results summary

The “arch” configuration of the *Model II* removes some torsional stiffness, comparing to a totally horizontal equivalent Boom. The goal of the proposal of this model was the increase of vertical stiffness, comparing to the *Lattix*’s concept model. This way, by making the Boom in three steps, the horizontal and torsional stiffness are reduced.

3) *Lattix’s*:

For the *Lattix’s* proposed model, it was used the proposed sections for the main Beams (in the Boom and Legs) with [340 x 210] mm.

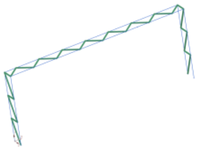
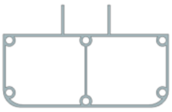
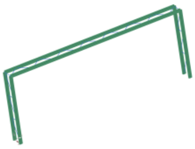
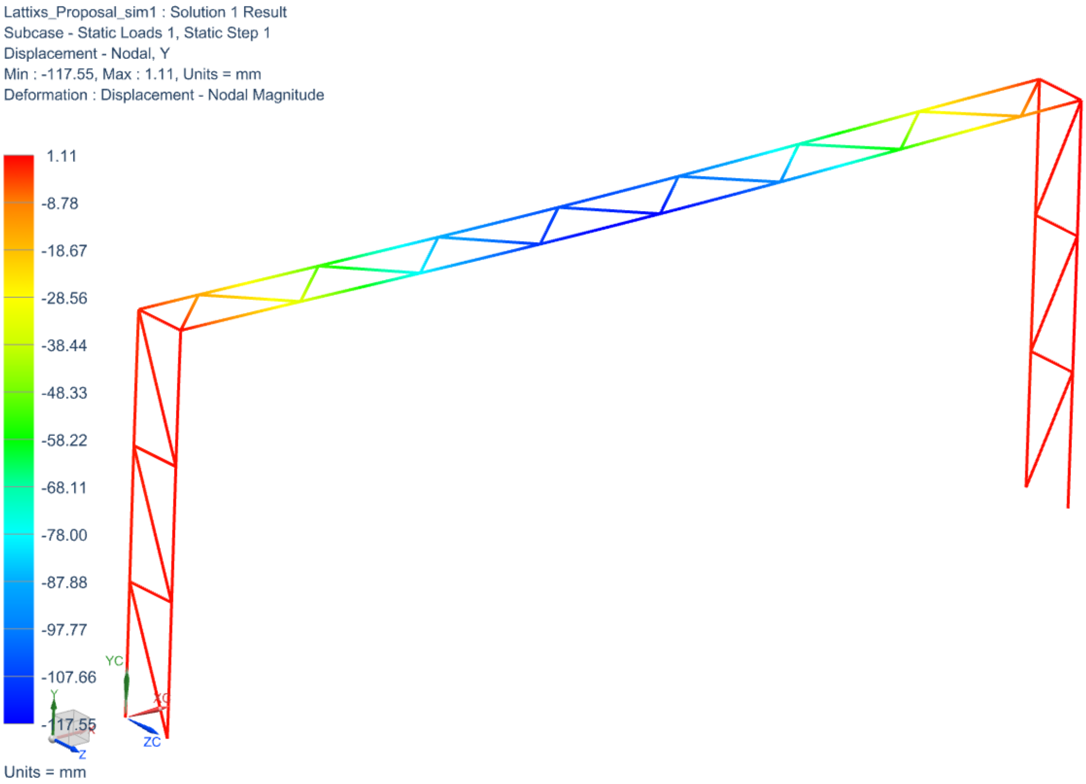
Beams	B	H	tb	th	Kg/m	
Diagonals	90 mm	90 mm	6 mm	6 mm	5.5	
Main Beams	[340 x 210] mm 				19	

Table 4-5: Sections used in the *Lattix's Model* – 20m

The main displacement results are presented below.



Lattixs_Proposal_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Y
Min : -117.55, Max : 1.11, Units = mm
Deformation : Displacement - Nodal Magnitude

Figure 4-29: *Lattix's Model* – 20m: Vertical Displacement Results

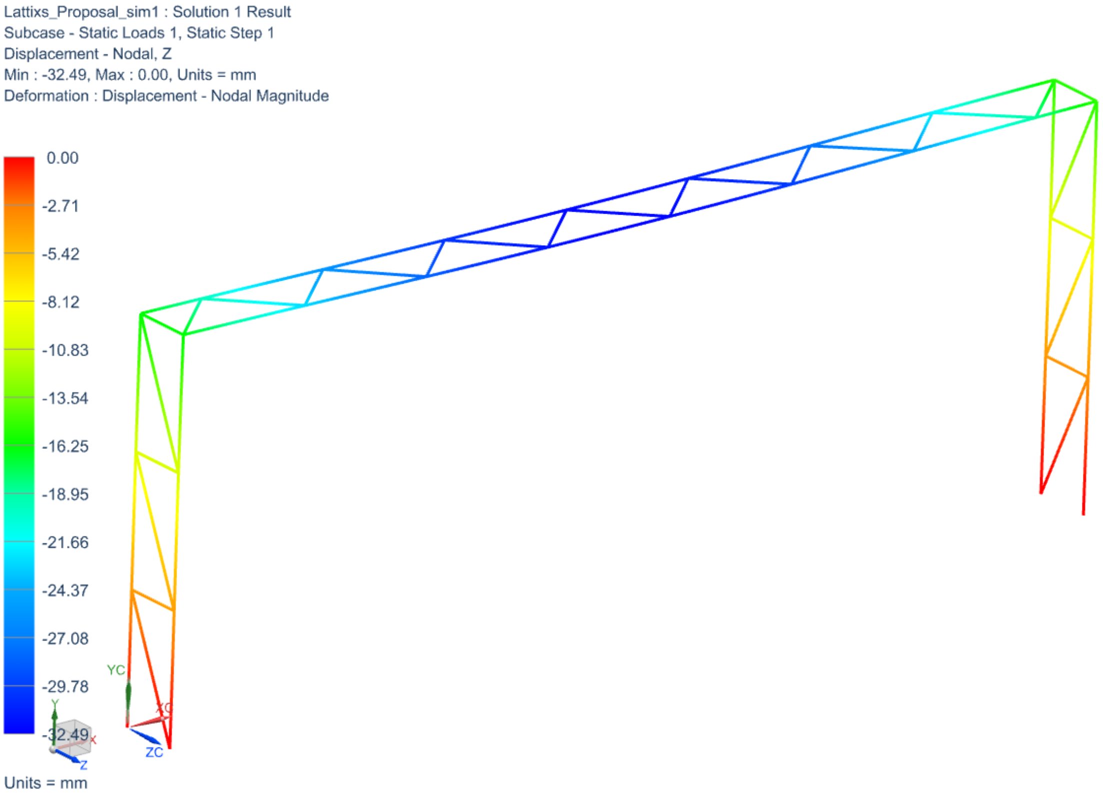


Figure 4-30: ***Lattix's Model*** **– 20m: Horizontal Displacement Results**

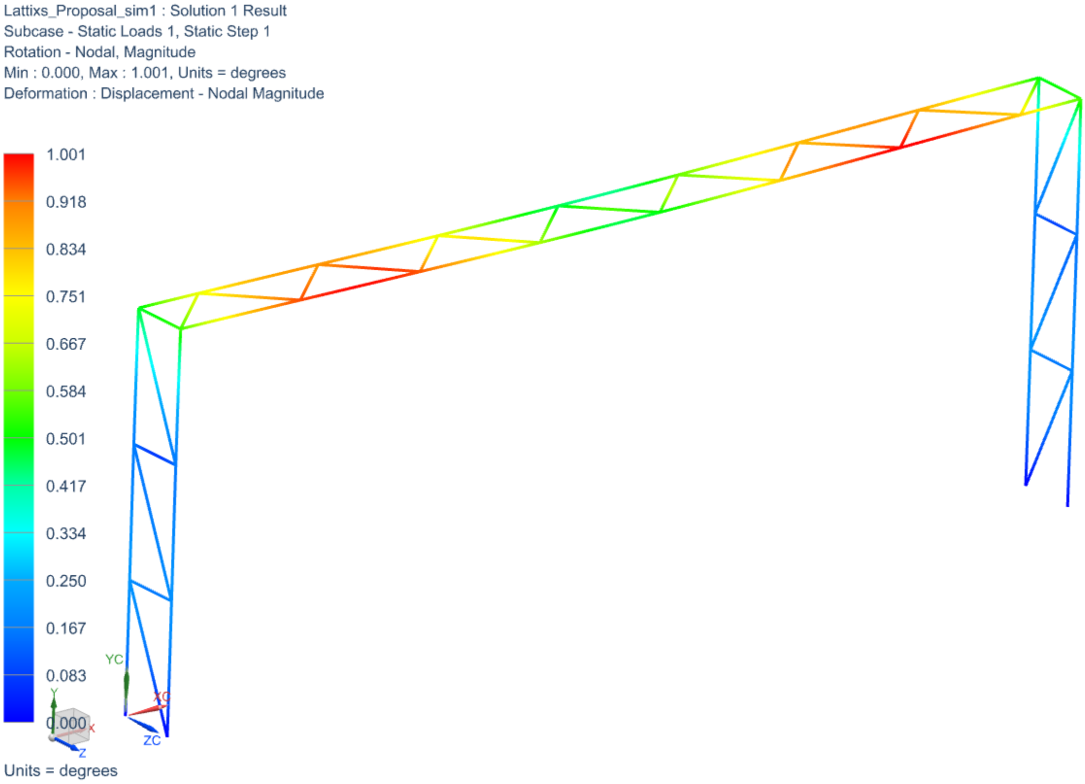


Figure 4-31: ***Lattix's Model*** **– 20m: Torsion Results**

The maximum results are summarized in the table below.

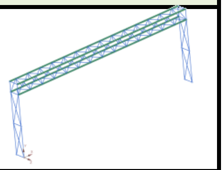
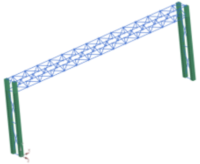
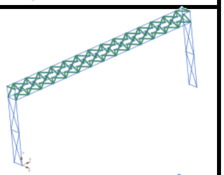
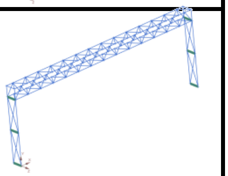
		Where
Maximum Vertical (y) Deflection	118 mm	Boom’s centre
Maximum Horizontal (z) Deflection	33 mm	Boom’s centre
Maximum Torsion	1º	Boom’s frontal beam

Table 4-6: *Lattix’s Model* – 20m results summary

Here we can observe that the 100mm of maximum deflection is exceeded in the vertical component. This would imply a small tuning of the sections until meet the requirements. But since this model (the structural configuration and its sections) was proposed by *Lattix*, and the difference to the limit value is just 18mm, it was decided to perform the cost comparison with these sections.

4) *LWG 1000*:

The sections used for modelling the *LWG 1000* are summarized in the table below.

Beams	B	H	tb	th	Kg/m	
Boom’s Main Beams	90 mm	90 mm	6 mm	6 mm	5.5	
Masts	305 mm	305 mm	4 mm	4 mm	13.1	
Diagonals	70 mm	70 mm	5 mm	5 mm	3.5	
Leg Plates	1000 mm	200 mm	t = 5 mm		-	

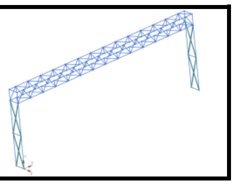
Stiffener Bars	80 mm	15 mm	(solid)	3.3	

Table 4-7: Sections used in the *LWG 1000* – 20m

The main displacement results are shown below.

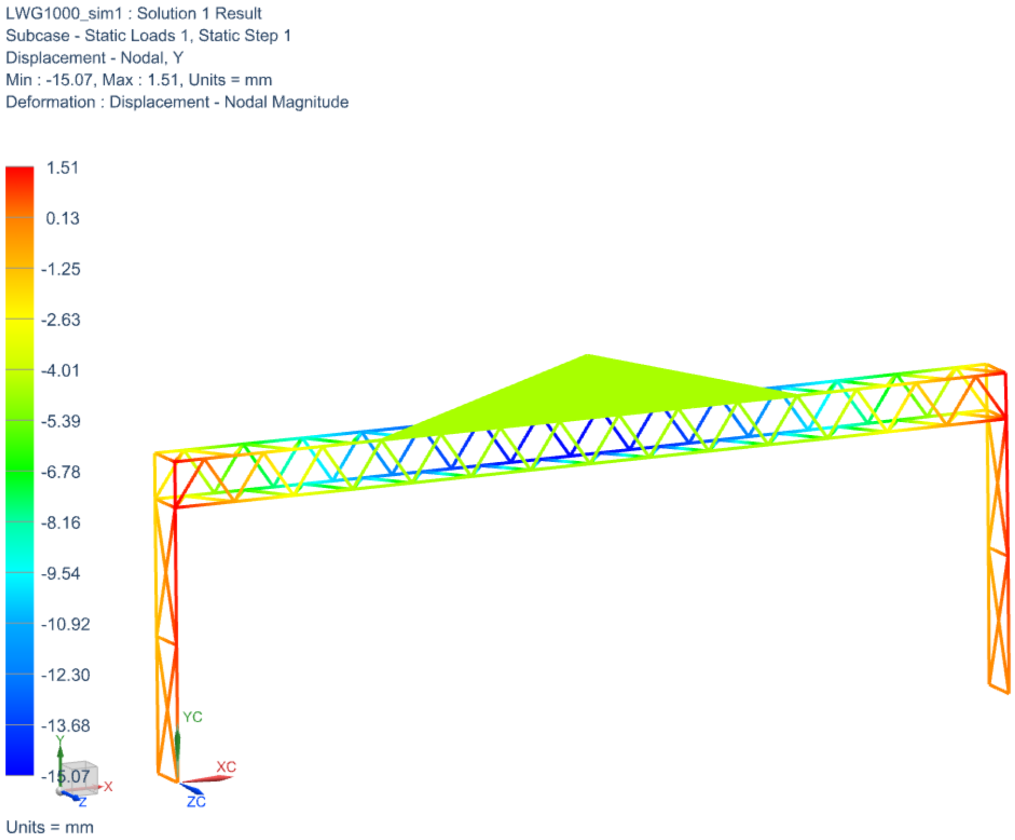


Figure 4-32: *LWG 1000* – 20m: Vertical Displacement Results

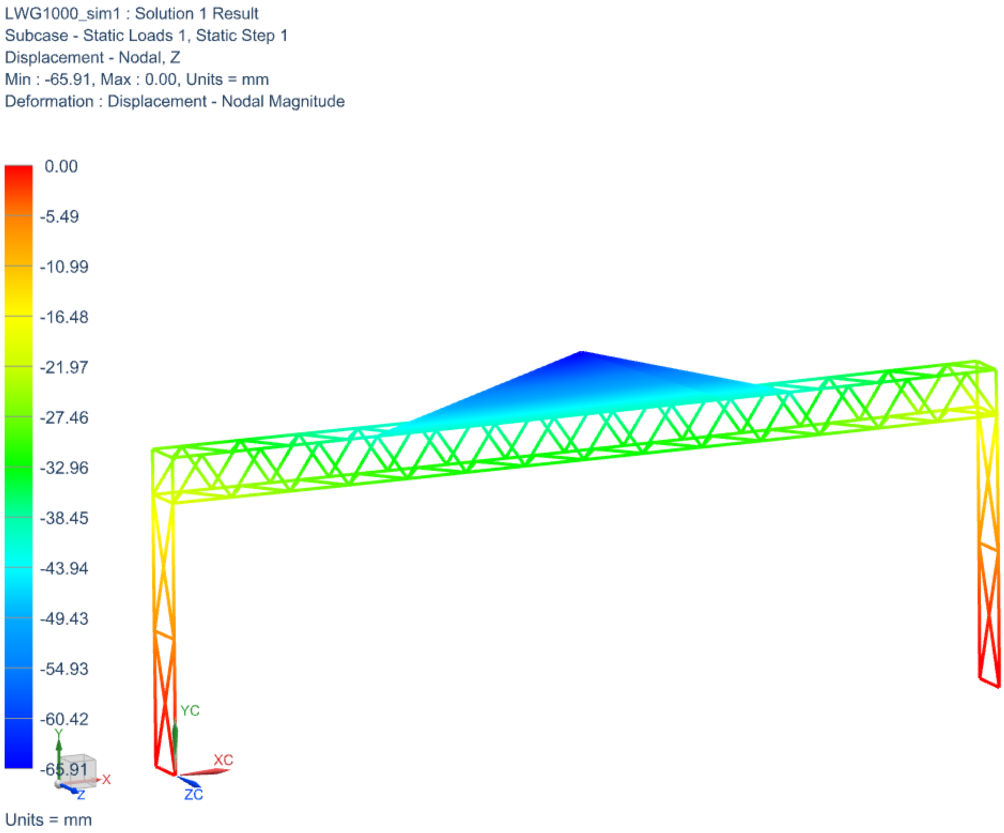


Figure 4-33: *LWG 1000* – 20m: Horizontal Displacement Results

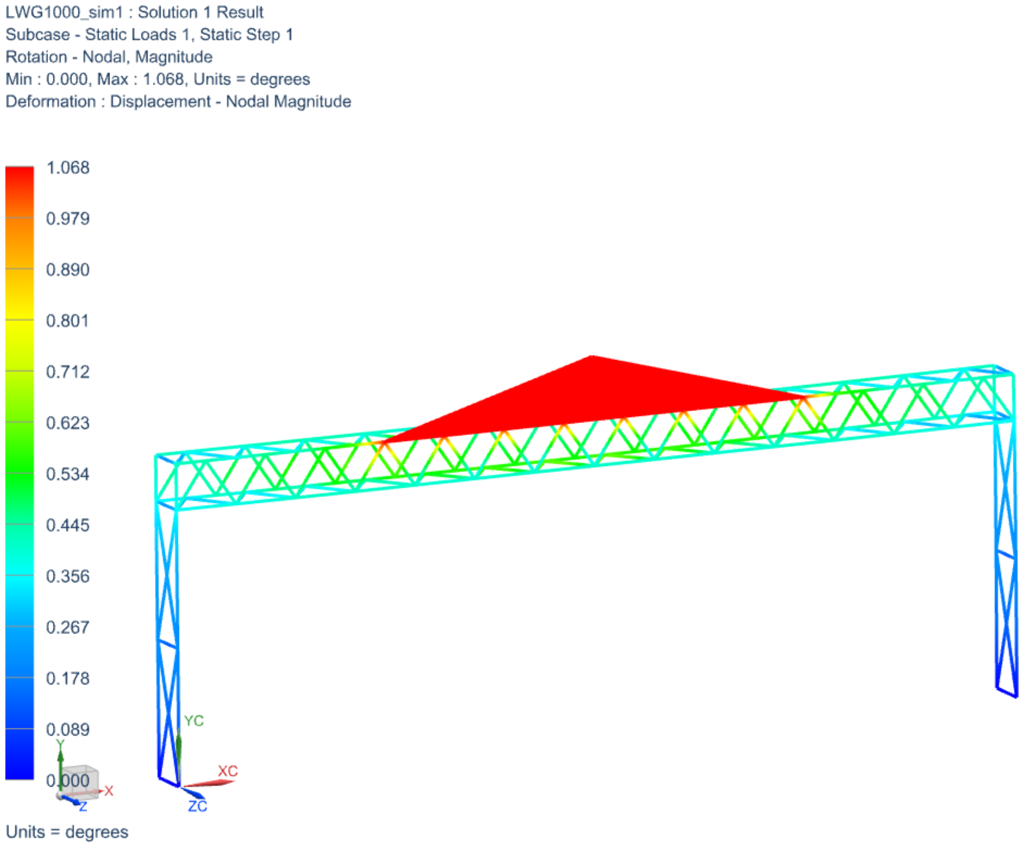


Figure 4-34: *LWG 1000* – 20m: Torsion Results

The main maximum results are shortened in the next table.

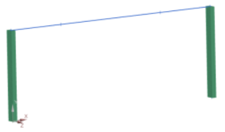
		Where
Maximum Vertical (y) Deflection	15 mm	Boom’s (back) centre
Maximum Horizontal (z) Deflection	41 mm	Boom’s (top) centre
Maximum Torsion	1.07º	Boom’s frontal beam

Table 4-8: ***LWG 1000*** **– 20m results summary**

It can be observed, by the low values of deflections that the square Boom section gives the highest values of stiffness. The fact of the *VMS* being placed on top of the Boom, some of the horizontal forces due to the wind will be transferred to the structure as torsional moments. And the highest value of horizontal displacement is on the point (on the spider mesh) that represents the centre of the *VMS*, but naturally, the maximum value considered for the results was the highest on the actual structure (in this case on the centre of the main top beams).

5) *Model W*:

For the *Model W*, it will be presented the box sections that represent the profiles welded to the aluminium sheets that originate the Main Frame. Is also presented the dimensions used for the walkaway (the walkaway was not modelled, but its weight and wind effects on the structure were considered). The dimensions of the walkaway’s members will be also important in the cost section. For simplifying the weight calculation, the walkaway panels were considered as single pieces.

Beams	**B**	**H**	**tb**	**th**	**Kg/m**	
Main Frame - Boom	850 mm	420 mm	6 mm	7 mm	43.1	
Main Frame - Legs	700 mm	350 mm	6 mm	7 mm	35.6	

Walkaway profiles (vertical and ceiling)	50 mm	30 mm	3 mm	3 mm	1.2	(Walkaway not modelled)
Protection lateral Sheets	20 m	2 m	t = 2 mm		-	
Ceiling Sheets	20 m	800 mm	t = 2 mm		-	

Table 4-9: Sections used in the *Model W* – 20m

The main displacement results are shown below.

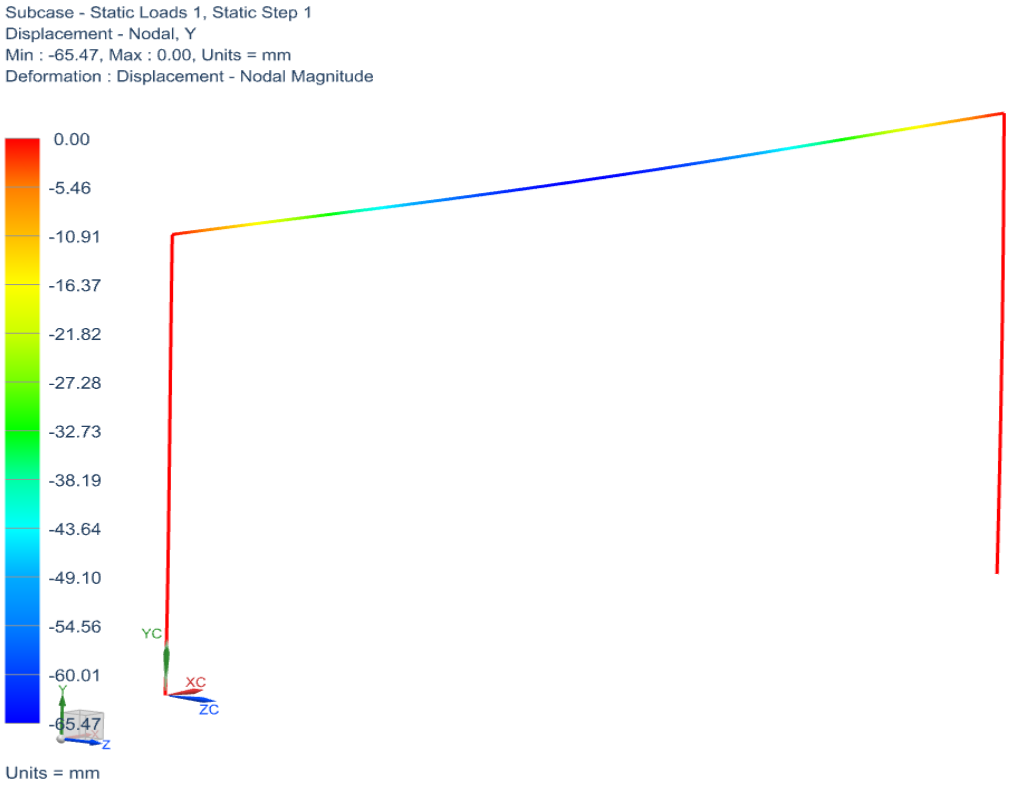


Figure 4-35: *Model W* – 20m: Vertical Displacement Results

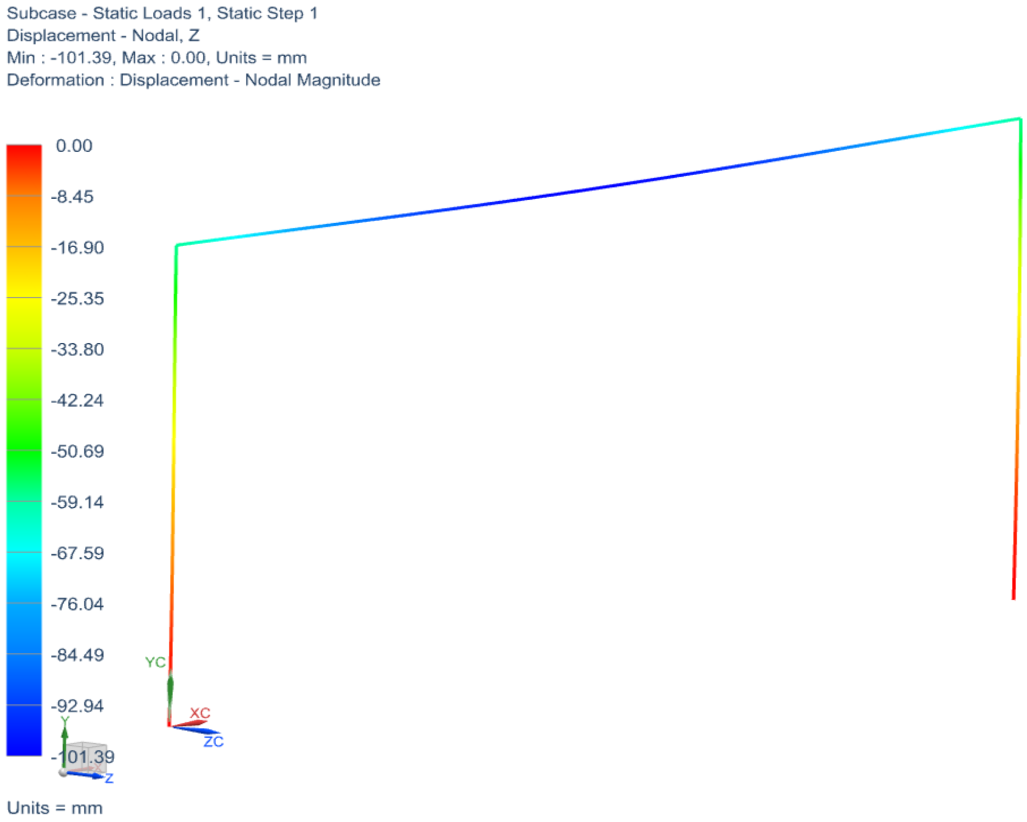


Figure 4-36: *Model W* – 20m: Horizontal Displacement Results

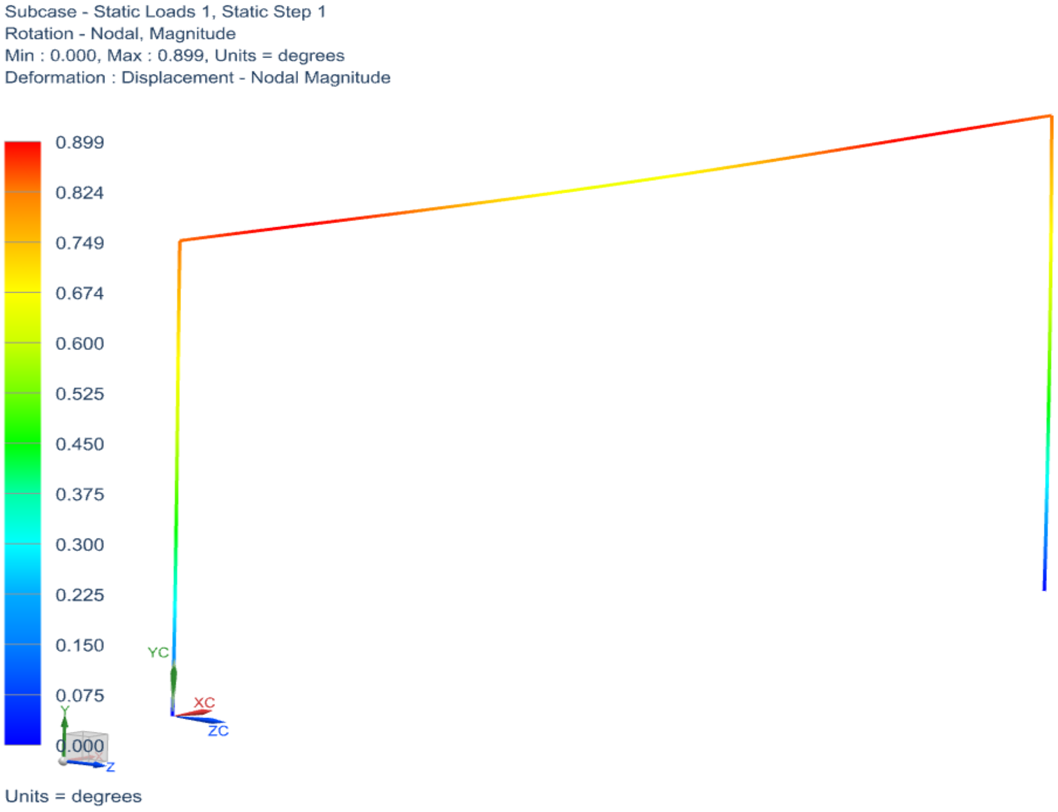


Figure 4-37: *Model W* – 20m: Torsion Results

The maximum results are presented in the next table.

		Where
Maximum Vertical (y) Deflection	65 mm	Boom’s centre
Maximum Horizontal (z) Deflection	101 mm	Boom’s centre
Maximum Torsion	0.9º	Boom

Table 4-10: *Model W* – 20m results summary

For this model, since the structure is a simple frame, the influence of the stiffness of the Legs is relatively high. With only the information that the sections of the Legs and Boom are different, it was considered the presented dimensions with the goal of meet 100mm of maximum displacement. The result exceeds in 1mm, hence the section’s tuning was considered enough for the purposes of this study.

6) *Model III*:

The next table presents the sections used in the *Model III*. The structure is decomposed in 4 main parts: The Frame (Top Beam plus the Side vertical Beams), the Bottom parallel Beams, the Diagonals and the Legs. Using box sections, it was given the same sections for all the beams (excluding the Diagonals) in order to prevent some Die costs, by resulting in just two dies.

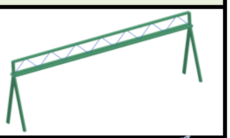
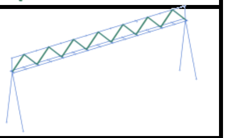
Beams	B	H	tb	th	Kg/m	
Main Beams + Legs	350 mm	150 mm	6 mm	6 mm	15.9	
Diagonals	90 mm	90 mm	6 mm	6 mm	5.5	

Table 4-11: Sections used in the *Model III* – 20m

The main displacement results are shown below.

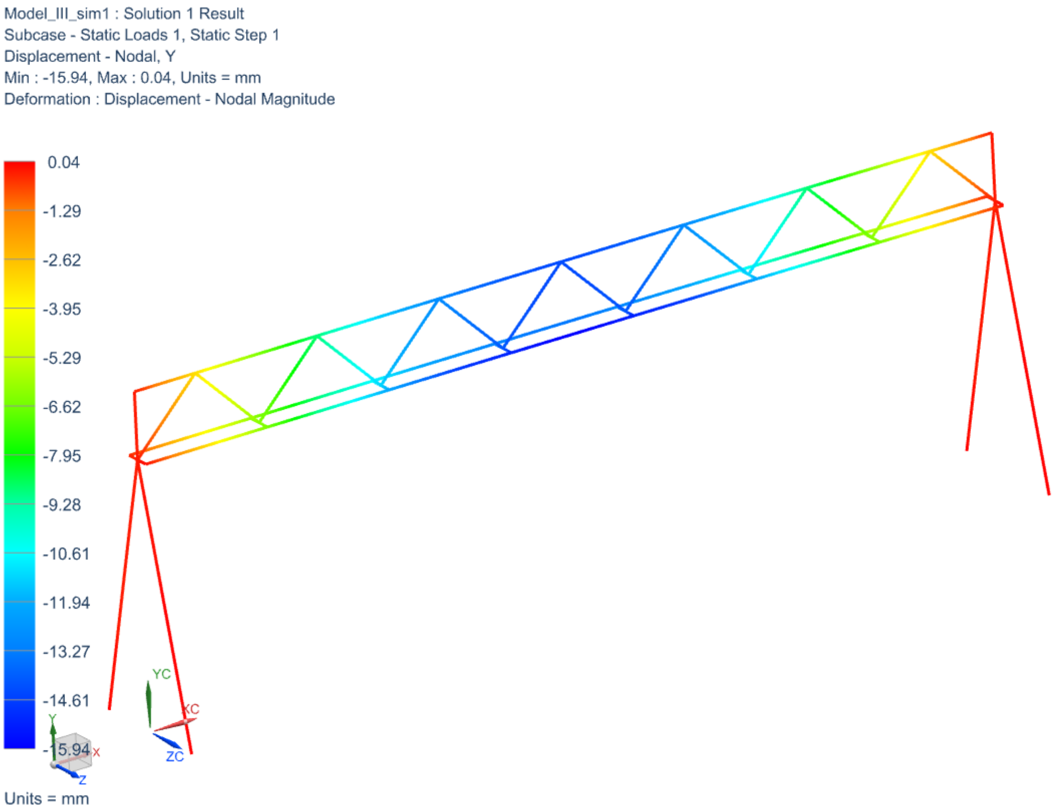


Figure 4-38: ***Model III*** **– 20m: Vertical Displacement Results**

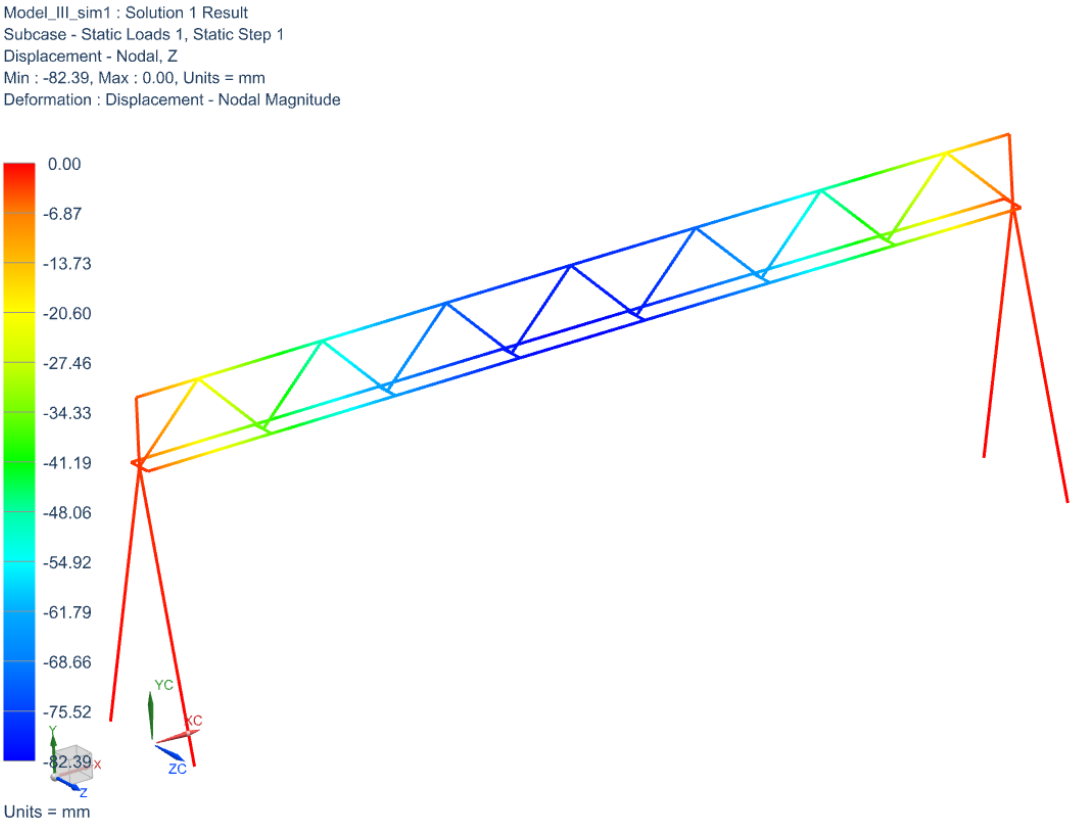


Figure 4-39: ***Model III*** **– 20m: Horizontal Displacement Results**

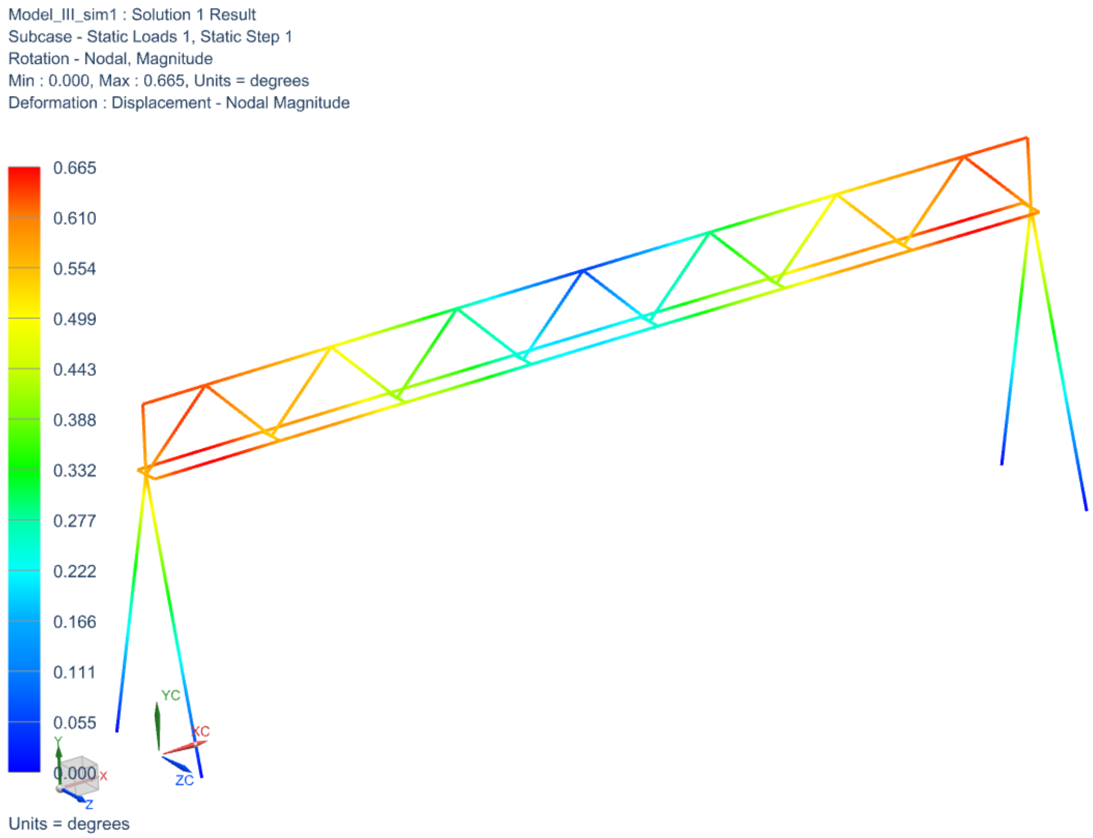


Figure 4-40: *Model III* – 20m: Torsion Results

Once more, the maximum results can be viewed in the table below.

		Where
Maximum Vertical (y) Deflection	16 mm	Boom's centre
Maximum Horizontal (z) Deflection	82 mm	Boom's centre
Maximum Torsion	0.7º	Boom

Table 4-12: *Model III* – 20m results summary

The dimensioning of this model resulted in a maximum deflection within the 100mm limit. Since the *VMS* is considered centred in the Bottom Beams, it is supported by the Boom's region with more horizontal stiffness.

7) *Model IV*:

The *Model IV*'s sections are presented in the table below. Contrarily to the *Model III*, it was used a higher number of different profiles in order to increase the ease of tuning and achieve the same range of deflections. This was important because, since the *VMS* is centred in the Top Main Beam, the Bottom Beams are subjected to high torsional moments, and the profile needs to be more “square” in order to increase the torsional stiffness. This way, with 4 different profiles is easier to achieve a more efficient material use even in the Die costs are slightly higher.

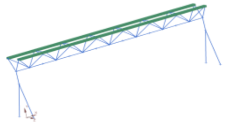
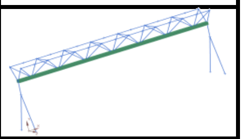
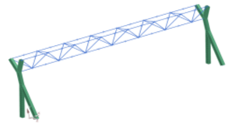
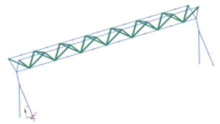
Beams	B	H	tb	th	Kg/m	
Main Top Beams	350 mm	200 mm	6 mm	6 mm	17.5	
Main Bottom Beam	350 mm	300 mm	7 mm	7 mm	24.1	
Legs	350 mm	250 mm	6 mm	6 mm	19.1	
Diagonals + Top Beams	90 mm	90 mm	6 mm	6 mm	5.5	

Table 4-13: Sections used in the *Model III* – 20m

The main displacement results are shown below.

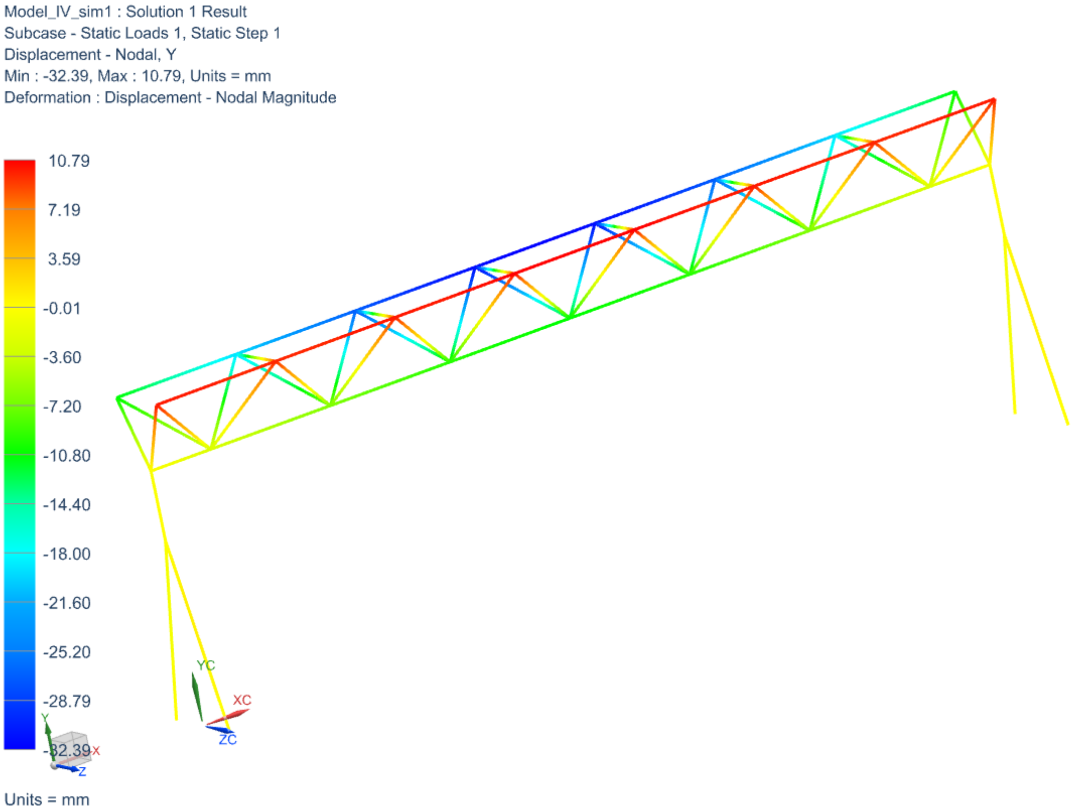


Figure 4-41: *Model IV* – 20m: Vertical Displacement Results

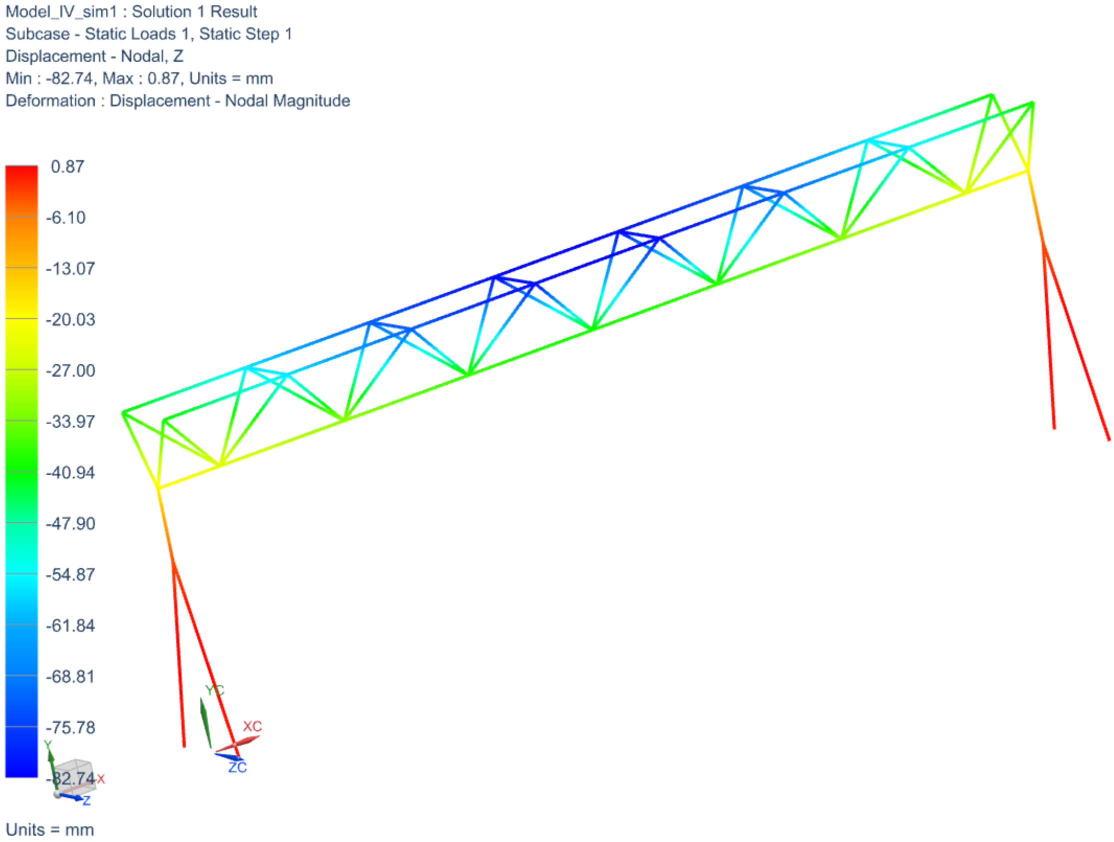


Figure 4-42: *Model IV* – 20m: Horizontal Displacement Results

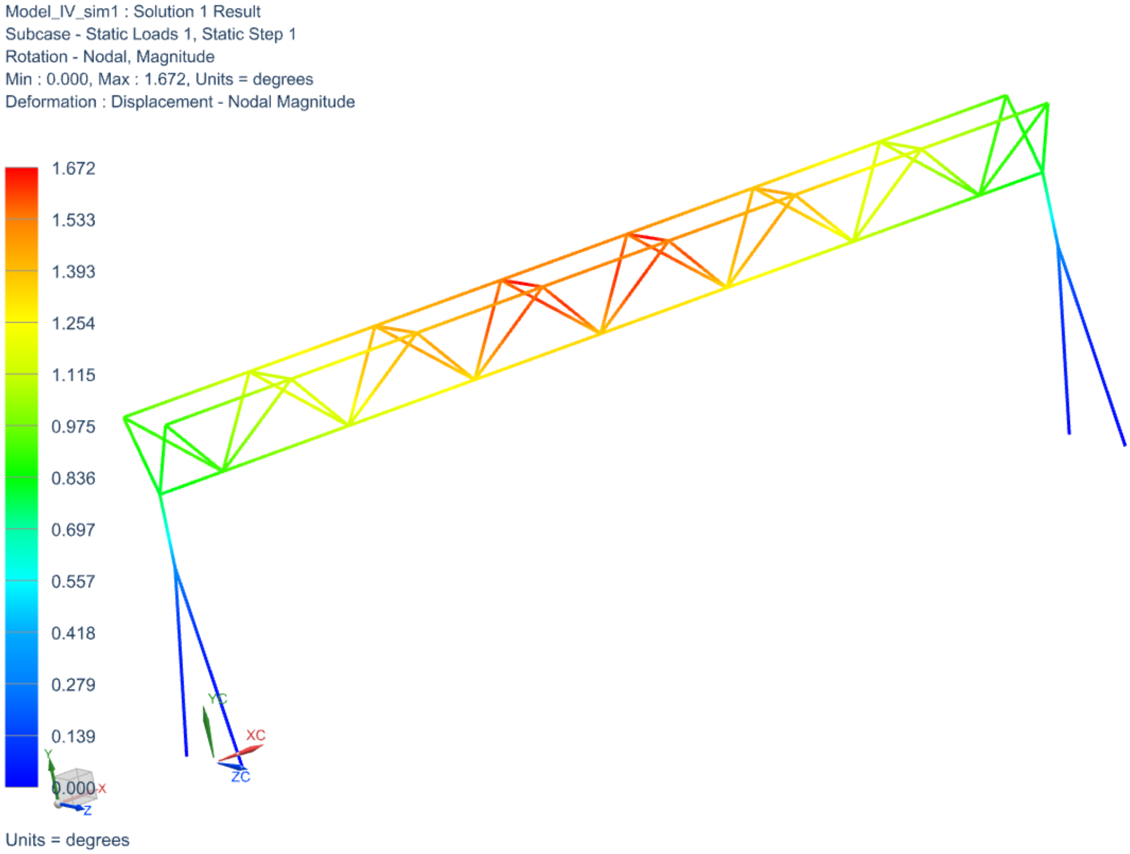


Figure 4-43: *Model IV* – 20m: Torsion Results

Lastly, the maximum results are presented in the next table.

		Where
Maximum Vertical (y) Deflection	32 mm	Main Top Beam (front)
Maximum Horizontal (z) Deflection	83 mm	Boom’s centre (top)
Maximum Torsion	1.7º	Boom’s centre

Table 4-14: *Model III* – 20m results summary

Analogously to the *Model I*, the *Model IV* due to the triangular Boom section and superior position of the *VMS* (centred on the Top Beams) is subjected to high torsional moments, which reflects in a high maximum rotational angle of the Boom.

At this point all the structures’ sections were dimensioned, in order to result in displacements in the same range. The next chapter will start by addressing a qualitative comparison between the author’s models (*I*, *II*, *III* and *IV*) with the one proposed by *Lattix* having as a reference the *LWG 1000* as well as the *Model W*, regarding mainly the use of material and the difference in assembly time and cost.

5. Evaluation of the Models

5.1 Cost Comparison

The goal of this comparison is to produce a method, which enables to implement a fair assessment between different structural arrangements. Therefore, due to the high number of uncertainties and assumptions the exact values of the results are not the focus, but the relation between them and the method used to implement the comparison.

Since the *LWG 1000* models have a 20m span configuration and most of the information provided is related to this span, it was decided firstly to make the comparison for the 20m case.

A qualitative comparison will be performed in order to estimate a relative cost and the strong and weak factors of each structural solution. Therefore, it is only relevant to consider the costs that differ with each structure´s configuration. It is no worthwhile to consider costs that are common, independently of the type or shape of the Gantry structure. This way, the total cost will be decomposed in Material, Parts (bolts, brackets, plates, etc), Assembly, Extrusion Dies and Production (Drill and Cut operations).

This comparison will be made recurring to a *Pugh* type matrix using qualitative values from assumed common costs that will be presented below, like labour, material costs, and so one. In this 20m span Gantries comparison it will be calculated the cost saving referring to the baseline model, which in this case is the *LWG 1000*.

The next table summarizes the assumed common costs and parameters used to originate some qualitative cost values between the studied models. Some real values were slightly altered due to confidentiality issues.

Number of Bolts per Connection:	1
Price per Bolt:	1.50 €
Number of connections made per hour:	10
Labour Cost per hour:	50 €/h
Cost per kg of material:	5 €/kg
Price per Normal Longitudinal Connector:	120 €
Price per Angle Longitudinal Connector:	150 €
Cost per Foundation:	3500 €

Main Beams Die Cost for ‘unit’ of complexity:	16000 €
Diagonals and simple profiles Die Cost:	1500 €
Production: Unitary Drill Cost:	3 €
Production: Unitary Cut Cost:	6 €
LWG’s Cost per bracket (Total = 448):	3 €

Table 5-1: Assumed parameters

The *Model W* is composed by a single frame and there is a large use of welding, in order to connect the Aluminium sheets to the extruded profiles originating the large sections. Therefore, it is needed to introduce some different parameters, in order to include the welding costs and prices of the different aluminium sheets. It is important to address that the cost of the *Model W* will be considered with the presence of a walkaway, because these Gantries with *VMS*s use a specific closed walkaway that influences its total cost (contrarily to a simple ladder). The table below summarizes the referred costs and other parameters.

Total Weld Cord Length:	280 m
Weld Cord Length in the Main Frame:	140 m
Welding productivity per hour:	9 m/h
Bolting productivity per hour:	10
Labour Cost (Welding) per hour:	100 €/h
Labour Cost (Bolting) per hour:	50 €
Cost per kg of Al. Sheet (Main Frame):	4 €/kg
Cost per kg of Al. Sheet (Perforated):	6 €/kg
Cost per kg of Al. Sheet (Ceiling):	4 €/kg
Cost per Die (Main Frame):	16000 €
Cost per Die (Vertical Profile):	1500 €
Cost per longitudinal Connection Plate:	800 €
Foundation cost:	3500 €
Bolts per bracket (walkaway):	2
Cost per Bolt:	1.50 €
Cost per Bracket (total = 56):	3 €
Aluminium sheet Cut Cost per unit length	3 €/m

Table 5-2: Assumed parameters for the *Model W*

The costs like extruded material cost per kg or the production costs are the same as the ones introduced in the first table, so they were not repeated.

Below, the tables with the comparison performed between the seven models are presented. The first table characterizes the structures in total weight, total number of beams, number of “virtual” nodes, and (bolted) connections. The weights resulted from the sections’ dimensioning presented in the previous chapter.

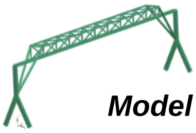
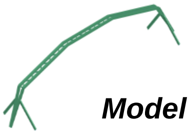
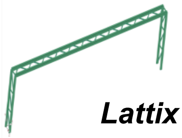
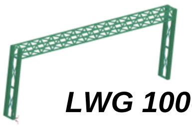
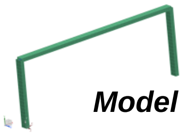
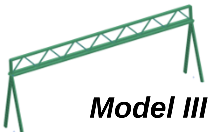
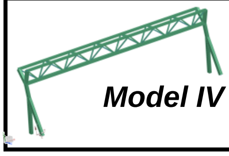
Model	Weight [kg]	∆ Weight [kg]	# Beams	# Nodes	# Connections
 ***Model I***	1506	379	56	23	98
 ***Model II***	1785	100	31	18	42
 ***Lattix’s***	1604	281	35	28	58
 ***LWG 1000***	1885	REF	144	84	280
 ***Model W***	2009	-124	50	28	28
 ***Model III***	1603	282	26	17	58
 ***Model IV***	2117	-232	50	27	82

Table 5-3: Structure Descriptions

If is the case, a negative cost saving will correspond to a cost increase.

Below the cost savings in material (aluminium for the beams), secondary elements (like bolts, connecting plates (end-plates) or foundations) and assembly are shown and compared to the reference (REF), the *LWG 1000*. For the Models that use brackets (for the main beams diagonals connections), the associated cost is added to the ‘Bolt Cost’ section. Naturally, this next table results are strongly depended on the number of connections (for the trussed models) and on the total welding cord length (for the simple framed model).

Model	**€ saving [€]**	**# Bolts**	**Bolts Cost [€]**		**Assembly Time [h]**	**Assembly Cost [€]**	
				savings			**savings**
Model I	**1896**	98	147	**1617**	9.80	490	**910**
Model II	**499**	42	63	**1701**	4.20	210	**1190**
Lattix’s	**1405**	58	87	**1677**	5.80	290	**1110**
LWG 1000	**REF**	280	1764	**REF**	28.00	1400	**REF**
Model W	**-622**	56	252	**1512**	36.71	3391	**-1991**
Model III	**1411**	58	87	**1677**	5.80	290	**1110**
Model IV	**-1160**	82	123	**1641**	8.20	410	**990**

Table 5-4: Savings in Material, Bolts and Assembly Costs

The next table considers the differences in number of connection plates and foundations.

Model	**# Long. Angle Connect.**	**Long. Angle Connect. Cost [€]**	**# Tot. Long. Connect. (normal + angle)**	**Total Long. Connect. Cost [€]**		**# Found.**	**Foundations Cost [€]**	
					savings			**savings**
Model I	6	900	9	1260	**-780**	4	9000	**0**
Model II	4	600	4	600	**-120**	6	10500	**-1500**
Lattix’s	0	0	2	240	**240**	4	9000	**0**
LWG 1000	0	0	4	480	**REF**	4	9000	**REF**
Model W	0	0	1	800	**-320**	2	6000	**3000**

Model III	0	0	3	360	**120**	4	9000	**0**
Model IV	0	0	3	360	**120**	4	9000	**0**

Table 5-5: Savings in Connection Plates and Foundations

It was considered a distinction between angle end-plates and the normal ones. This can be justified because the first ones are slightly more complex (and expensive) to produce. This way, the cost model allows differentiating the cost inputs for both cases. Concerning the cost of the End-Plates (either considering in angle or the normal ones) this parameter should be developed with more care. The implemented cost model is considering only the number of End-Plates and a fixed cost per plate. In reality, this may differ, because for example, four End-Plates for the *LWG 1000*'s Boom (with four relatively small main beams) could cost the same or less than the one for *Model W* (with a large Boom section), which is much larger the first ones. So, another degree of freedom, beside quantity and angle, should be the sections' size to be connected. But due to the lack of information regarding this subject it was decided to not consider this.

Relatively to the Foundations' costs, it was considered that for each side (each set of legs) the first foundations to be built has the associated total cost presented in the table with all the assumed values. Then, the next foundation has half of the previous cost and so on. So, if we have 6 foundations (2 sets of 3 foundations, one set at each side), the cost will be given by: 2 x (1x3000€ + 1x1500€ + 1x750€). This is done because most of the cost corresponds to logistics and, for the second foundation on (in each side), all the equipment was already moved into place and is ready to use.

The next table presents the total number of beam-extruded profiles existing in each structure and a qualitative comparison in terms of the required complexity of the main beams. For each level of complexity was given an associated cost, present in the table with the cost inputs. The savings in the extrusion tooling, namely in the number and complexity of dies, are also considered and compared to the baseline model. The estimations were done considering that, of the total number of different profiles, only one will have the associated level of complexity (corresponding to the main Boom's beams that connect to the diagonals). Thus, the remaining ones correspond to the diagonal or simpler profiles, with a smaller associated die cost. The total Die Costs were divided by five, assuming that each die can manufacture the beams equivalent to produce five Gantries.

Model	# Different Profiles	Main Sections Complexity	Die Costs [€]	
				savings
Model I	3	↑↑	4930	**-1470**
Model II	3	↑	3460	**0**
Lattix's	2	↑	3200	**260**
LWG 1000	3	↑(Masts)	3460	**REF**
Model W	3	↑	6140	**-2680**
Model III	2	↑	3200	**260**
Model IV	4	↑↑	10550	**-7090**

Table 5-6: Savings in Die Costs

As the previous table shows, it was considered that the main beam of the *Model I* and *Model IV* have a profile 1.5 times more complex (not the double as the symbolisms may suggest), and consequently 1.5 times more costly.

The table below will present the costs related to the operations after the extrusion, namely drilling and cutting. These costs are associated to the number of bolts and to the total number of beams. It is also relevant to mention that these operations are considered in the extruded profiles.

Model	Production: Drill Costs [€]		Production: Cut Costs [€]	
		savings		**savings**
Model I	588	**1092**	336	**528**
Model II	252	**1428**	186	**678**
Lattix's	348	**1332**	210	**654**
LWG 1000	1680	**REF**	864	**REF**
Model W	336	**1344**	690	**174**
Model III	348	**1332**	156	**708**
Model IV	492	**1188**	300	**564**

Table 5-7: Savings in Die Costs

Since the *Model W* uses aluminium sheets, for its 'Cut Costs' calculation, it was included the longitudinal cutting cost related to the aluminium sheet cutting.

The following table reveals the sum of the savings in all the considered costs for all the models.

Model	**Total Cost [€]**	
		savings
Model I	24 280	3 793 **(13.5%)**
Model II	24 196	3 876 **(13.8%)**
Lattix's	21 395	6 678 **(23.8%)**
LWG 1000	28 073	**REF**
Model W	27 132	941 **(3.4%)**
Model III	21 455	6 618 **(23.6%)**
Model IV	31 820	- 3 747 **(-13.3%)**

Table 5-8: Total Cost

Here we can identify the models that appear to be worthy in terms of cost. We can observe that the two existing models (the baseline *LWG 1000* and *Model W*) have a very similar cost. Then, the ones with the best results (on the order of a 24% reduction) are the *Lattix's* and the *Model III*, that have in common a planar Boom (one laid out horizontally and the other vertically). Both *Model I* and *Model II* show an improvement of almost 14%. This reveals the potential of the *Model II*, which has two more foundations than most of the models that use four, having an added cost in this topic. Lastly, the *Model IV* is the only that revels a cost increase. This can be explained by the high weight and high number of different dies required.

By performing a cost breakdown, the percentages of the total cost spent in material (aluminium for the extrusion), parts (bolts, connection plates, brackets and foundations), extrusion dies and production operations can be identified. The following table presents the referred percentages for each model.

Model	Material	Parts	Assembly	Dies	Production
Model I	31%	42.9%	2%	20.3%	3.8%
Model II	36.9%	46.1%	0.9%	14.3%	1.8%
Lattix's	37.5%	43.6%	1.4%	15%	2.6%
LWG 1000	33.6%	40.1%	5%	12.3%	9.1%
Model W	35.1%	26 %	12.5%	22.6%	3.8%
Model III	37.4%	44%	1.4%	14.9%	2.3%
Model IV	33.3%	29.8%	1.3%	33.2%	2.5%

Table 5-9: Total Cost breakdown

It can be observed that in most of the cases, in a descendent way, the biggest cost shares are: Purchased Parts (Bolts Nuts and Brackets, End-Plates and Foundations), then Material (the cost associate with the aluminium extrusion process), then the Dies Cost, then the Production Costs (associated with drilling and cutting after the extrusions) and finally the Assembly Costs.

As a reminder, the assembly costs are considered the connection of the trussed elements of each Boom module or the welding of the main modules. All the Installation Costs were neglected, because it was considered that since the installation on site is the assembly of Leg modules with the Boom modules, the difference between each type of structural arrangement would not be significant (because the total number of modules would be the same in most of the cases).

To conclude this section, it is important to stress that the exact cost saving percentages are not the focus of this study. This was a cost breakdown that enables to compare different type of structural configurations, based on a different amount of inputs, where a lot of them were assumed due to the lack of information. A method was followed, in order to a cost breakdown be performed. For the 20m span size, the models' sections were dimensioned until reach the same range of displacements (except for the *LWG 1000* and *Lattix's* proposed model, where the structures were mostly given from the start) to reach roughly the same level of material use, in order to get the weights of each model. Then, making the structure breakdown in terms of number of beams and connections, number and type of end-plates, foundations, dies, etc. each structure was characterised. And by this, all the type of costs considered could be calculated and compared.

5.2 Benefit Assessment

This chapter will be used to perform another comparison to the seven models already introduced. But this evaluation will be focused on the fulfilment of all the needs and requirements imposed by the customers and also by the company (in this case *Lattix*) and not only the Costs, which its minimization is one of many requirements.

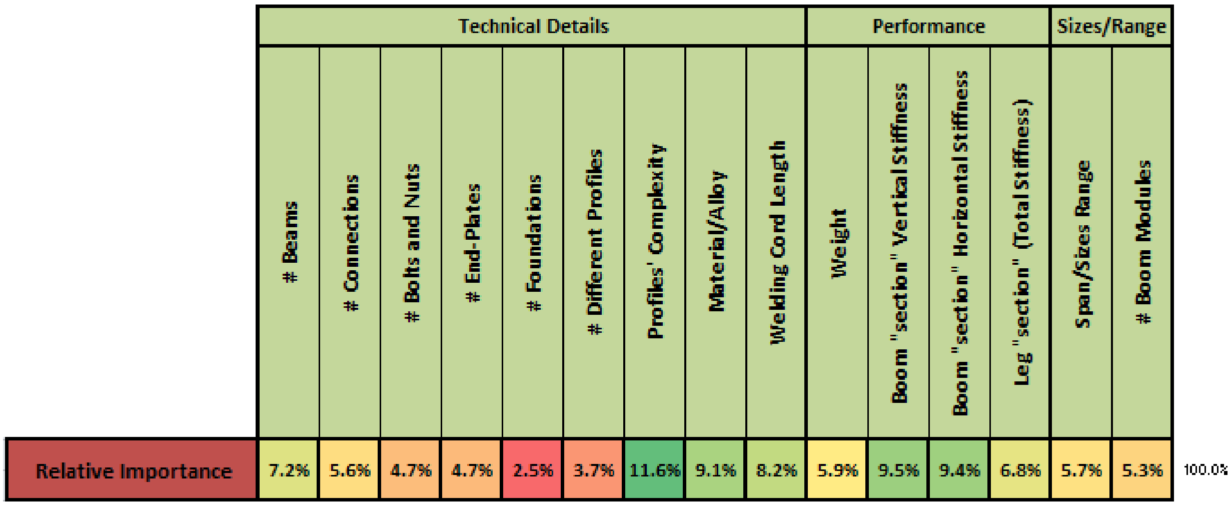
This way, each structure will be decomposed into its technical descriptors where each has a relative importance. The method used to get the importance ratings for each parameter to be evaluated was addressed in the chapter 4.1.4 in the *House of Quality*.

The method used to perform this evaluation was a more conventional *Pugh Matrix* type with the *LWG 1000* model as a baseline. The evaluation was performed using ratios over the baseline values. This way, instead of using “+1’s” or “-1’s”, meaning just “better” or “worse”, it was given a fairer evaluation between all the compared models. The used matrix will be presented ahead and explained in more detail.

5.2.1 Technical Descriptors

The technical descriptors were already enumerated in the chapter 4.1.4. This section will present the quantification of each one for all the models, which will enable to make ratios with the baseline model and perform a comparison.

Firstly, from the *House of Quality* we can take the relative weights for each parameter, which will enable do give more importance to the technical descriptors that are associated with the fulfilment of more and more important needs and requirements.

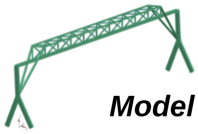
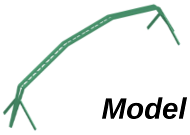
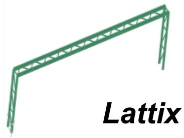
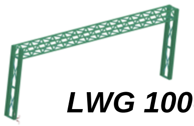
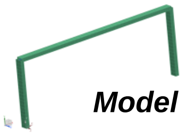


	Technical Details									Performance				Sizes/Range		
	# Beams	# Connections	# Bolts and Nuts	# End-Plates	# Foundations	# Different Profiles	Profiles' Complexity	Material/Alloy	Welding Cord Length	Weight	Boom "section" Vertical Stiffness	Boom "section" Horizontal Stiffness	Leg "section" (Total Stiffness)	Span/Sizes Range	# Boom Modules	
Relative Importance	7.2%	5.6%	4.7%	4.7%	2.5%	3.7%	11.6%	9.1%	8.2%	5.9%	9.5%	9.4%	6.8%	5.7%	5.3%	100.0%

Figure 5-1: Technical Descriptors and their relative importance

This section will repeat many values already used for the Cost Breakdown performed in the last chapter.

The first table contains the values that will allow to rate the following technical descriptors: ‘Weight’, ‘# Beams’, ‘# Bolted Connections’ and ‘# Bolts and Nuts’.

Model	**Weight [kg]**	**# Beams**	**# Connections (bolted)**	**# Bolts and Nuts**
 ***Model I***	1506	56	98	98
 ***Model II***	1785	31	42	42
 ***Lattix’s***	1604	35	58	58
 ***LWG 1000***	1885	144	280	280
 ***Model W***	2009	50	28	56

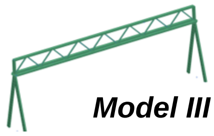
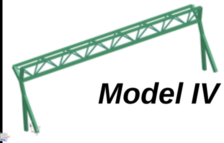
 ***Model III***	1603	26	58	58
 ***Model IV***	2117	50	82	82

Table 5-10: Technical Descriptors 1

This method did not include the number of brackets as a technical parameter. This was done because only two models use brackets: *Model W*, in the walkaway, and *LWG 1000*, to connect the diagonals to the main beams. The first model uses as quantity so small (56 in the considered walkaway, correspondent to 168€) that it can be neglected, and also because its structure, the main frame, does not use any. So in practice, only the *LWG 1000* uses brackets (448 in total, correspondent to 1344€, a much more considerable value). Since only the baseline model uses a relevant quantity of brackets, this would be the same as for example the baseline is rated with "1" and all the other models with "10". So the relative results between the models to be compared would be the same. Therefore, it was decided not to consider '# Brackets' as an additional technical descriptor. But if one of the models used in the comparison had a relevant use of brackets in its structure, this parameter should be implemented in the method as a parameter to be minimized since represents additional costs in purchased parts and a more complex assembly.

The next table will describe the following technical descriptors: '# Foundations', '# End-Plates', '# Different Profiles' and 'Main profiles' Complexity'.

Model	**# Foundations**	**# End-Plates** **(normal + angle)**	**# Different Profiles**	**Main Sections Complexity**
Model I	4	9	3	↑↑ (1.5)
Model II	6	4	3	↑ (1)
Lattix's	4	2	2	↑ (1)
LWG 1000	4	4	3	↑ (Masts) (1)
Model W	2	1	3	↑ (1)

Model III	4	3	2	↑ (1)
Model IV	4	3	4	↑↑ (1.5)

Table 5-11: Technical Descriptors 2

Regarding the technical descriptor ‘Material/Alloy’, the rate of this parameter in all the models was considered the same. This is because all the models are aluminium structures, where the extruded profiles are produced from the same alloy series (6xxx). For the case of the *Signature’s* model, which uses aluminium laminated sheets that are welded to the extruded profiles, the sheets are from 5xxx series alloys. Therefore, this parameter was considered to be irrelevant to compare, since there’s no contrast as for example a structure in steel vs aluminium or vs concrete.

Concerning the ‘Welding Cord Length’, this parameter offers a challenge to the method being used in this evaluation. Only *Model W* uses welding, which means that the total welding cord length for the remaining models is zero. Since we are using ratios over the baseline, when comparing *Model W* with the *LWG 1000* we would obtain zero dividing by a number (in this case 140m only for the structure or 280m considering also the walkaway). This would originate an infinite number, which makes no sense to consider. The models that don’t use welding would also originate an indeterminate or a not-a-number by dividing zero by zero. Therefore, a different approach to rate the ‘Welding Cord Length’ parameter was done. Each model was rated giving parameters from 0 to 10 (10 was the highest ratio found in the implement matrix, so the maximum rate value was levelled by that), where “0” means “poor”, namely a large welding cord length (reminding that its direction of improvement is minimizing it) and “10” means “great”, namely no welding used. This way all the models were rated with “10” in this parameter excluding the *Model W*, which obviously was rated with “0”. This, though, would be exactly the same as, manually just put all the models with a “1” as the baseline, and *Model W* with a “0”.

The technical parameter ‘Span/Sizes Range’ is related to the ability of the design to ideally cover a great variety of spans and heights. The limiting factor of the trussed models is the fact that the number of diagonals must be integer. So from the start the *Model W* revels to be able to cover the bigger range due to its frame configuration. The models with framed Legs have the same ability to cover a wider range of heights, where the trussed Leg systems have the problem of the integer number of diagonals (which is the case of the *Lattix’s* model). This way, concerning the

Boom and Leg's type of structure (Frame or Truss) and the number of Boom sections (where a bigger number of sections enable a bigger freedom of size adjustments) the models were also rated from 0 to 10 regarding the ability to cover a wider span of sizes.

Regarding the parameter 'number of Boom Modules', it has the goal of be minimized, in order to enable to save installation time and consequently the cost during this phase. Since the case studies is the 20m span, all the models are considered to have two Boom modules, except the *Model II* that has three, due to its stepped Boom. Contrarily to the last two presented technical descriptors this one is evaluated recurring to direct ratios.

Model	**Welding Cord Length Rating Poor [0 to 10] Great**	**Span/Sizes Range Rating Poor [0 to 10] Great**	**# Boom Modules**
Model I	10	4	2
Model II	10	5	3
Lattix's	10	1	2
LWG 1000	10	3	2
Model W	0	9	2
Model III	10	3	2
Model IV	10	3	2

Table 5-12: Technical Descriptors 3

The remaining technical descriptors are the 'Boom Section Vertical and Horizontal Stiffness' and the 'Leg Section Total Stiffness'. It can be observed that the Boom stiffness in both directions are one of the most important parameters (with 9.5% and 9.4% of relative importance), where the Leg stiffness has a value of 6.8%. This difference makes sense, since the Boom's displacements are the structural requirements more difficult to comply. Therefore, it was chosen to diverge the method to rate these different parameters.

For the 'Leg Section Stiffness', which correspond to the stiffness of each leg assembly (with one or more masts), it was implemented a system of two ratings for each model that are multiplied to get the total rating. Each model was rated regarding the Leg's structure relative stiffness (regarding the structural arrangement) and of the 'Main Beam' (regarding the section of the main beams). Each parameter was rated from 1 (poor) to 3 (good), in order to the maximum result (3 x 3) be "9", which, as mentioned before, is close to the maximum ratio value in the *Pugh Matrix*. If the maximum ratio had a different value, the rating system for the technical descriptors that cannot be described by ratios would have to be adjusted. We should not rate a parameter from 1 to 10 if all the others have ratios from 1 to 2, for example. But when the *Pugh Matrix* will be presented it would be easier to understand the range of the values.

The table below reveals the rate system implemented to characterize the Leg's total stiffness. Once more, this was used because, the importance of this parameter is not the highest and the type of leg can be easily adjusted from model to model.

Model	**Leg Total Stiffness Rating**		
	Structure (A) Poor [1 to 3] Great	**Main Beam (B)** Poor [1 to 3] Great	**Rate (A x B)**
Model I	2	1	**2**
Model II	3	2	**6**
Lattix's	2	2	**4**
LWG 1000	2	2	**2**
Model W	1	2	**2**
Model III	1	2	**2**
Model IV	1	3	**3**

Table 5-13: Technical Descriptors 4

Concerning the vertical and horizontal stiffness of each model's Boom, a different method to enable the use of efficiency ratios was applied. This was done because of the key importance of both these parameters. Since the method is quite extensive, it is presented in a separate chapter.

5.2.2 Boom Section Stiffness Evaluation

This chapter is dedicated to explain the method used for rating the vertical and horizontal stiffness of the Boom from each model. These two parameters, alongside with ‘Profile’s Complexity’ are the most important technical descriptor for the general fulfilment of the requirements.

Firstly, the method used to make all Boom’s stiffness comparison will be described.

Method

The goal of this exercise is to compare the stiffness of each Boom configuration. The method consist in testing sample sections from each model with the goal of reach an efficiency rate for the structural performance, regarding a similar material use. In order to do that with a fair comparison between all the models, a systematic approach that converts all the Boom’s models into the same level of material use must be done. For example, we should not compare the *LWG 1000* Boom’s section (a quadratic truss system with [1 x 1] m section) with *Model W’s* Boom (A simple beam with [850 x 420] mm). The first would result in higher moment of inertias and consequently higher stiffness, but if the second model allows the displacements requirements to be achieved, why should a customer want to have bigger Boom sections?

This way, it was implemented a “packaging” strategy. The goal was to fit all the Boom configurations into the same dimensional boundary condition. This would allow to rate the stiffness of each the configuration for the same geometrical constrains. Regarding the packaging choice, the dimensions were chosen by the most limitative model, which is the *Model W*. The *LWG 1000* has a quadratic Boom section and the *Models I* and *IV* a triangular section, which means the distance between the main beams can be adjusted in the two degrees of freedom (vertical and horizontal) by the length and arrangement of the Diagonal beams. On the other hand, since the *Lattix’s*, *Model II* and *III* have a planar Boom, it can only be dimensioned in one direction. Lastly, the *Model W* uses a single profile layout, so, there is no distance offsets between main profiles, like in the other models. The figure below, without any relation of scale, summarises the previous explanation, where the blue lines represent the Diagonals that define the offset distance between the main profiles (in red).

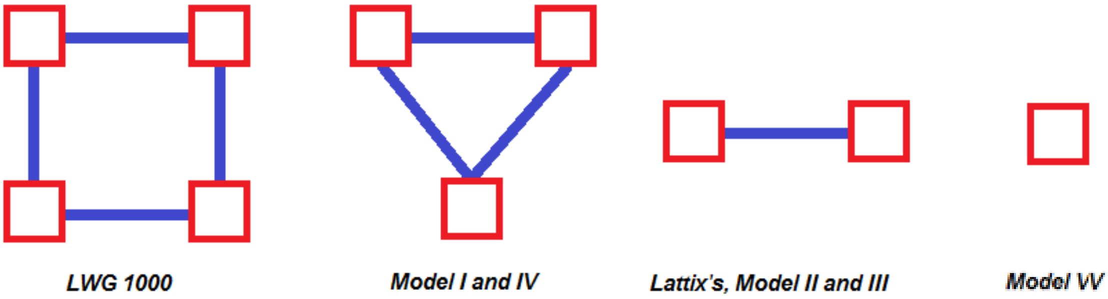


Figure 5-2: Boom sections' type of arrangements: quadratic vs triangular vs planar vs single profile

One of the directions of the planar section dimensioning is ruled by the profile sections, which is limited to the maximum extrudable dimensions ([420 x 230] mm). The same happens with *Model W*, where one direction is ruled by the same maximum extrudable section, and the other, but the width of the aluminium sheets (See Figure 4-15).

This way, as mentioned before, the most restricted Boom in terms of spatial dimensioning is *Model W*'s, so its Boom dimensions ([850 x 420] mm) were used as a boundary condition to fit all the other models' Booms. In the figure below it can be viewed the adjustment of all boom types in the same "box" boundary.

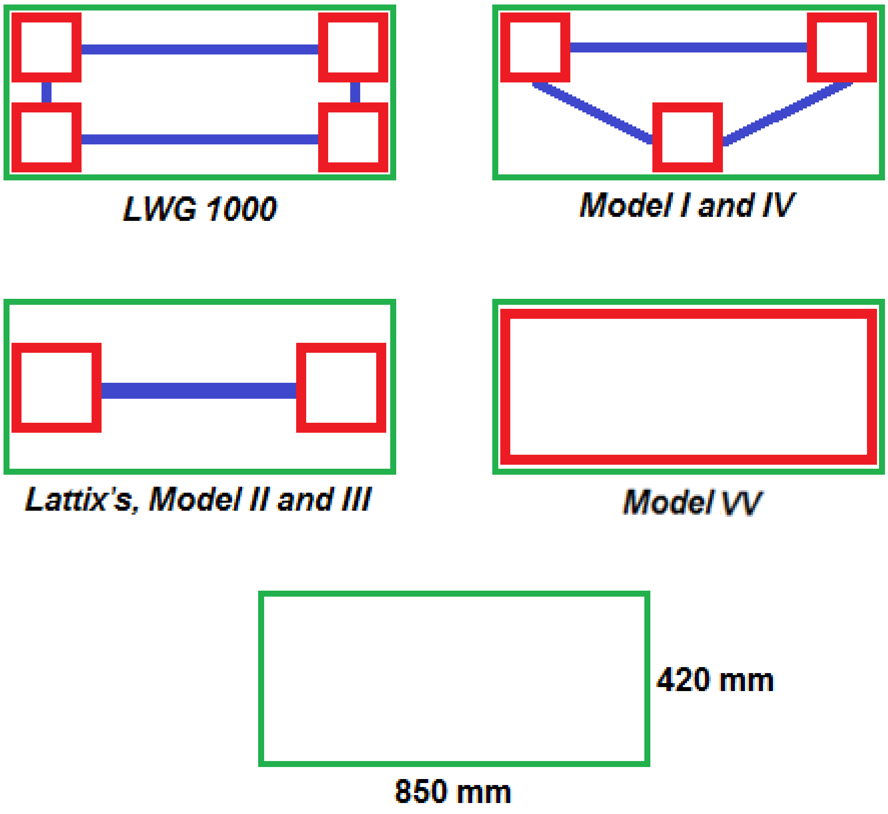


Figure 5-3: Boom sections "packed" inside boundaries

At this stage, all models were redesign to comply with the Boom boundary conditions. The goal is to get Boom section samples from each model. Therefore, after limiting the external dimensions, it is time to dimension the sections for each model. The approach, here, was to reach a 1ton Boom for each model (naturally, with the Boom modelled to comply with the packaging boundary). With all the Gantry models with a 1ton Boom, which enables the same material use for determining the structural performance in a fair way, it was cut samples with roughly 5m long. Because of the number of Diagonal beams (which is an integer number) some samples have slightly more than 5m and other slightly less.

With all the samples modelled it was performed an analysis with the same load case for each Boom sample. The detail of the load case applied, constrains, and the displacement results reading will be addressed in the next sections.

The Test

The chosen test to evaluate the stiffness of the seven Boom samples was to evaluate the deflections at each boom modules' end, when it is fixed at one end (as a cantilever beam) and is applied a moment at the opposite one. The used value for the vertical and horizontal loads was 10000 Nm. The figure below shows in simple schematics the test configuration.

Figure 5-4: Test schematics: Cantilever with a Moment applied

It will be performed two tests: one, with an applied moment to induce vertical displacements and other to produce horizontal ones. Following the same analyses type as before, it was used 1D beam elements to the models' Boom module samples.

Why constrain all DOFs?

All the Boom samples were constrained at one end, at the main beams, in all the degrees of freedom. If it was used pinned constraints (allowing rotating in the respective direction) the planar Boom models (*Lattix's*, *Model II* and *III*) and also *Model W* would consist in statically indeterminate systems, because they would not have a constriction from the support to one rotational direction (or in the case of *Model W* to any rotational direction).

The next figure represents in orange the fixing points for the *Lattix's* boom module sample, as an example. Notice again that besides the *software* represents the real used sections, it is using 1D Beam elements, that's why it has two punctual constraints (one for each main section).

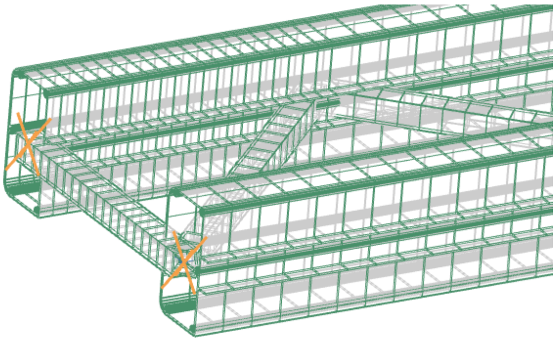


Figure 5-5: Constraints for *Lattix's* Boom module sample (represented in orange)

Why a Moment?

This section will address the decision between the application of a Concentrated Load (P) or a Moment (M) at the Cantilever's free end, for the purpose of the test. Firstly, it is relevant to remember briefly how the deflections can be calculated analytically.

From the differential equation that governs the beam's elastic line we have the following, (Beer, Johnston & DeWolf, 2006):

$$\frac{d^2\delta}{dx^2} = \frac{M(x)}{EI} \quad (5.1)$$

where, **δ** is the deflection , **x** is the distance from the cantilever's free end (in this case), **M(x)** is the moment at the point x and **EI** is the beam's stiffness. The figure below exemplifies the deflection of a cantilever with a concentrated load applied, where the orange line represents the elastic line.

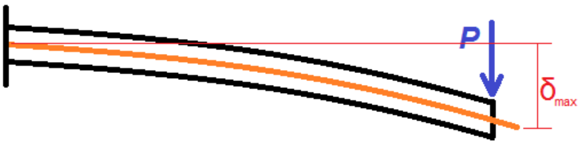


Figure 5-6: Elastic line in a cantilever example

By the integration of the previous equation along x, the angle of the deflection can be determined, where $\frac{d\delta}{dx} = \theta(x)$ and C_1 is the integration constant.

$$EI\,\theta(x) = \int_0^x M(x)\,dx + C_1 \quad (5.2)$$

Consequently, by the second integration the deflection **δ** can be also determined.

$$\mathrm{EI}\ \delta = \int_0^x \left[\int_0^x \mathrm{M(x)}\ \mathrm{dx} + \mathrm{C_1}\right] \mathrm{dx} + \ \mathrm{C_2} \quad (5.3)$$

The integrations constants $C_1$and C_2 can be found by the boundary conditions at the fixed end (where in this case is known that $\delta = \theta = 0$).

So, both the integration constants and the deflection depend on the integration of the Moment along the beam's length. Therefore, it is relevant to present the moment diagrams for the two compared loads.

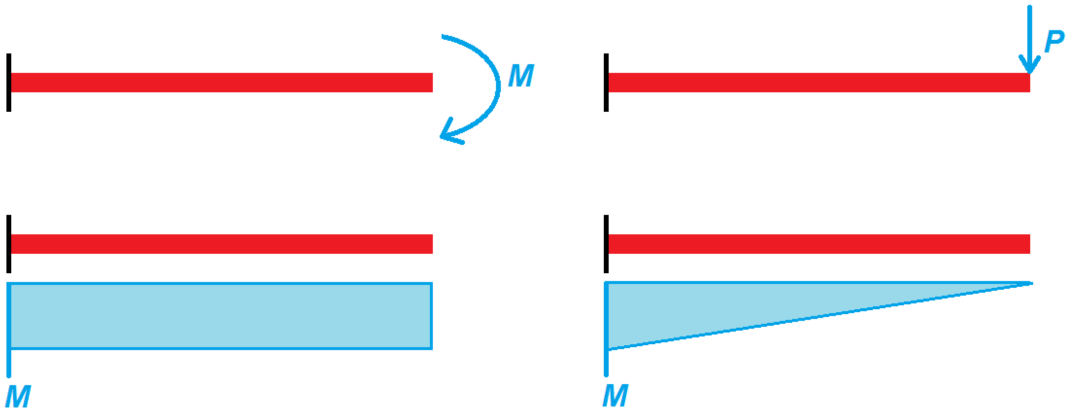
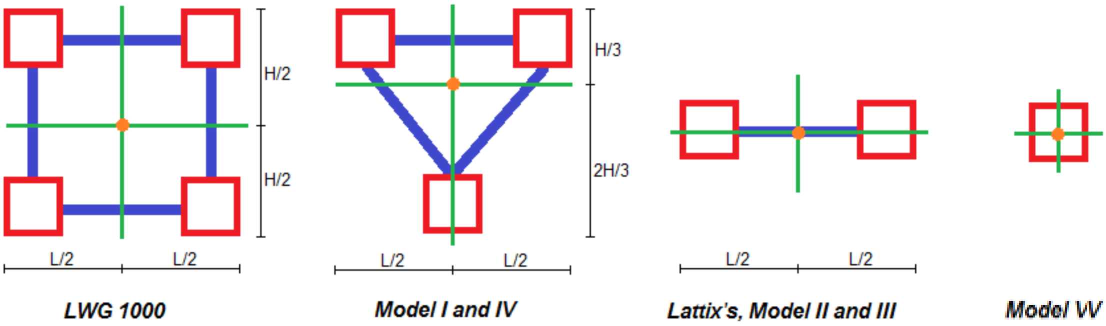


Figure 5-7: Moment Diagrams: Moment applied (M) vs Concentrated Load applied (P)

The application of the Moment will not produce any shear along the beam. And contrarily, the application of the Concentrated Load will expose the beam to a constant shear stress. In practice, the supports in a cantilever are not ideal, namely it does not fully constrain all the degrees of freedom. This would imply an initial rotation, which at the free end would induce a considerable error in the deflection caused by the load applied. This effect would be amplified when a Concentrated Load is applied, instead of a Moment, due to the presence of shear stress in the supports. In theory, this is negligible, since the supports are ideal and the *software* locks perfectly all their degrees of freedom. Nevertheless, it was decided to use a Moment, having in mind the translation to the real word, even thou the results in this test would be the same.

How to apply the Moment?

In order to have the same effect from the same load case on each different Boom section, the Moment was applied in the centre line of each Boom sample. The next figure represents the centreline (with the orange point) for each type of Boom configuration, and its location.



LWG 1000 **Model I and IV** **Lattix's, Model II and III** **Model W**

Figure 5-8: Boom sections' Centre Lines

To do this, a structure at the free end connecting the main beams (the end nodes) was modelled to a point coincident to the section's centre line. These auxiliary structures had all the same offset from the module's end (of 210 mm). In order not to influence the stiffness of the Boom, it was given a virtual material very stiff and with zero density and a solid square profile ([100 x 100] mm). Naturally, *Model W* has the only Boom structure that does not need this implementation, because the Boom has the end node coincident to the centre line (since is formed just by one beam). Below some figures with the described structure are presented, which enable a punctual (one beam is a 1D element) application of the Moment, for three different Boom sections.

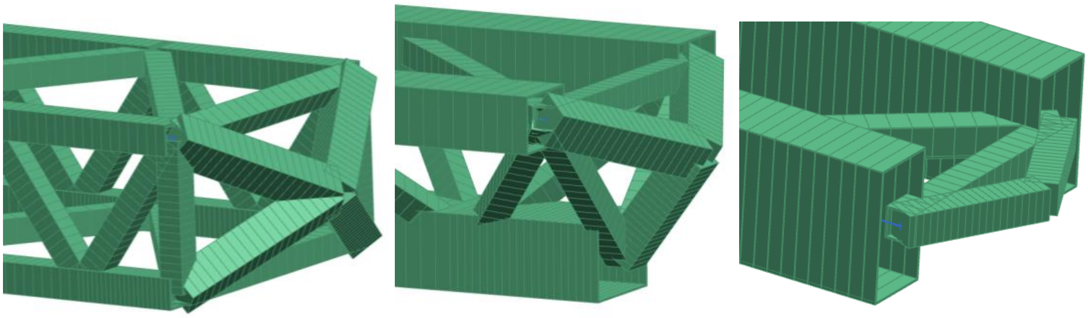


Figure 5-9: Supports for the Moment application for the three Boom configurations

How to get the maximum deflections?

This section will cover how the results are taken from the *FEA*, to be later used to get the stiffness values. Both vertical and horizontal deflection values were taken in the main beams' end nodes (where the support structure for the Moment application is attached), where the deflection at the support is not relevant.

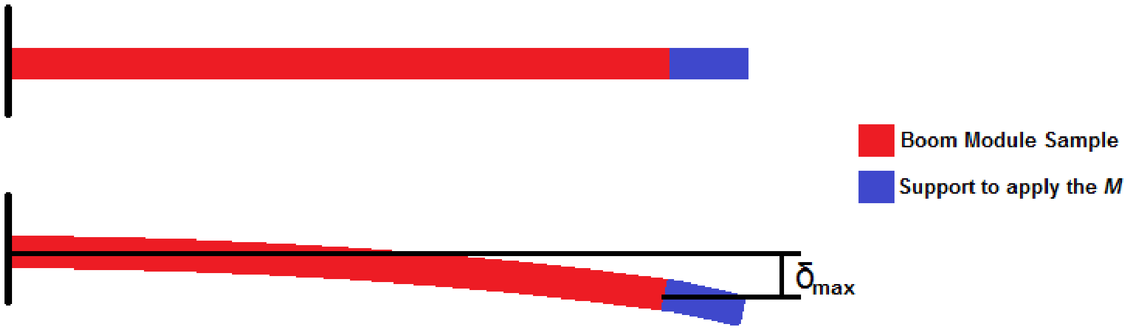


Figure 5-10: Deflection neglecting the support

Then the average deflection value was used. This was considered an adequate method because this way, the influence of the deflections at each end is pondered over the centre line. This means that in the quadratic and planar Booms, each end node have the same influence to the average value because of the Boom's symmetry, but for the triangular Booms, the two top nodes have more "weight" to the average deflection due to their relative position over the centre line.

How to get the stiffness (EI)?

From the resolution of the equation (5.3) for a cantilever (with a length ***L***) with a Moment applied at the free end, the maximum deflection can be described by the following.

$$\delta = \frac{M\,L^2}{2EI} \quad (5.4)$$

So, the stiffness can be known by the rearrangement of the previous expression.

$$EI = \frac{M\,L^2}{2\delta} \quad (5.5)$$

How to scale the results?

As mentioned before, each model's Boom sample has a determined length around the 5m target (from 4.9m to 5.5m), due to the different Diagonal's geometries. This way, for the result's accuracy and to obtain a fair comparison, it is relevant to scale the stiffness values.

The scaling of the stiffness values for each model was done recurring to a ration with the baseline model (*LWG 1000* (ref)), as the following expressions suggest.

$$\frac{\mathrm{EI}}{\mathrm{EI}_{\mathrm{ref}}} = \frac{\frac{\mathrm{M\,L}^2}{2\delta}}{\frac{\mathrm{M\,L}_{\mathrm{ref}}^2}{2\delta_{\mathrm{ref}}}} \quad \Leftrightarrow \quad \frac{\mathrm{EI}}{\mathrm{EI}_{\mathrm{ref}}} = \frac{\delta_{\mathrm{ref}}}{\delta}\frac{\mathrm{L}^2}{\mathrm{L}_{\mathrm{ref}}^2} \quad \Leftrightarrow \quad \mathrm{EI} = \frac{\delta_{\mathrm{ref}}}{\delta}\frac{\mathrm{L}^2}{\mathrm{L}_{\mathrm{ref}}^2}\,\mathrm{EI}_{\mathrm{ref}} \qquad (5.6)$$

This way, with both deflections known (the model to be scaled ($\boldsymbol{\delta}$) and the reference's ($\boldsymbol{\delta_{\mathrm{ref}}}$)) as well as the reference model's EI, each model can be scaled by putting the lengths ratio unitary $\left(\frac{\mathrm{L}^2}{\mathrm{L}_{\mathrm{ref}}^2} = 1\right)$.

The next tables summarise the vertical and horizontal deflection results and the stiffness calculation for each model. But before, it is relevant to remind the model's common coordinate referential to better understand the direction of application of the Moments, exemplified in the next figure.

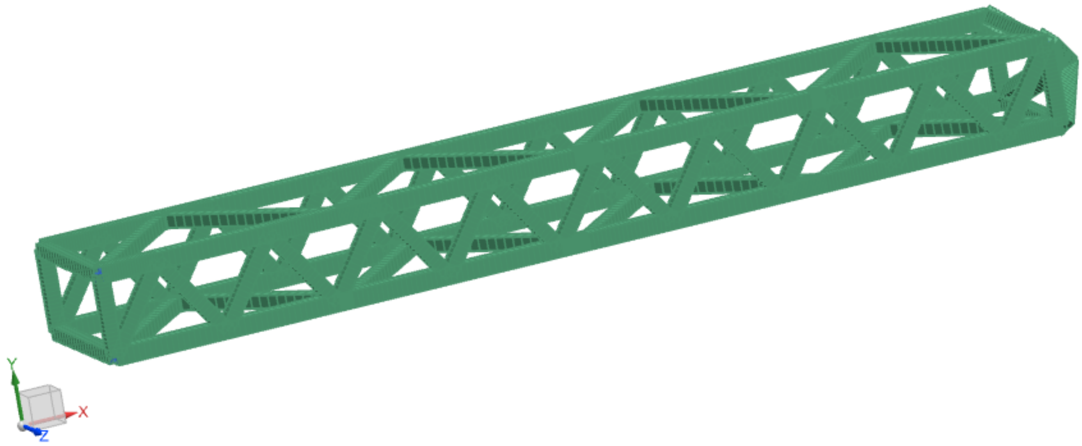


Figure 5-11: Boom Module Sample's Coordinate Referential

Model	Boom Module's Length [m]	M [Nm]	Vertical Stiffness (M_{-z})		
			δ_y [mm]	EI [kNm^2]	Scaled EI [kNm^2]
Model I	5.040	10000	3.316	38 298	**37 662**
Model II	5.571	10000	6.016	25 795	**20 761**
Lattix's	5.454	10000	7.969	18 664	**15 673**
LWG 1000	4.998	10000	5.176	24 129	**24 129**
Model W	4.998	10000	3.034	41 167	**41 167**
Model III	5.100	10000	0.706	184 129	**176 837**
Model IV	5.040	10000	3.690	34 417	**33 845**

Table 5-14: Boom Module Sample's Vertical Stiffness

Model	**Horizontal Stiffness (M_y)**		
	δ_z [mm]	**EI [kNm^2]**	**Scaled EI [kNm^2]**
Model I	1.344	94 479	**92 911**
Model II	0.752	206 494	**166 201**
Lattix's	0.681	218 400	**183 407**
LWG 1000	1.284	97 312	**97 312**
Model W	0.969	128 896	**128 896**
Model III	6.192	21 004	**20 172**
Model IV	1.246	101 957	**100 265**

Table 5-15: Boom Module Sample's Horizontal Stiffness

These are the values that will originate the ratios to use in the *Pugh Matrix* and they define the technical descriptors 'Boom Vertical Stiffness' and 'Boom Horizontal Stiffness'.

5.2.3 *Pugh Matrix* and Value Assessment

With all the technical descriptors quantified or rated in the previous two sub-chapters, it is time to introduce the implemented *Pugh Matrix*.

Technical Descriptor	**Weight**	**Baseline** (***LWG 1000***)	***Model I***	***Model II***	***Lattix's***	***Model III***	***Model IV***	***Model W***
# Beams	7.2%	1	2.571	4.645	4.114	5.538	2.880	2.880
# Connections	5.6%	1	2.857	6.667	4.828	4.828	3.415	10
# Bolts and Nuts	4.7%	1	2.857	6.667	4.828	4.828	3.415	5
# End-Plates	4.7%	1	0.444	1	2	1.333	1.333	4
# Foundations	2.5%	1	1	0.667	1	1	1	2
# Different Profiles	3.7%	1	1	1	1.500	1.500	0.750	1
Profile's Complexity	11.6%	1	0.667	1	1	1	0.667	1
Material/Alloy	9.1%	1	1	1	1	1	1	1
Welding Cord Length	8.2%	1	1	1	1	1	1	0

Weight	5.9%	1	1.252	1.056	1.175	1.176	0.890	0.938
Boom Vertical Stiff.	9.5%	1	1.561	0.860	0.650	7.329	1.403	1.706
Boom Horizontal Stiff.	9.4%	1	0.955	1.708	1.885	0.207	1.030	1.325
Leg Total Stiff.	6.8%	1	0.500	2	1	0.500	0.500	0.750
Span/Sizes Range	5.7%	1	1.333	1.667	0.3	1	1	3
Boom Modules	5.3%	1	1	0.667	1	1	1	1
Total (Benefit)	**100%**	**1**	**1.288**	**1.948**	**1.706**	**2.259**	**1.352**	**2.101**

Table 5-16: *Pugh Matrix* - Models' potential to fulfil all the requirements

Now it is necessary to organize the model's performance in a Value rating. The Value is defined by the Benefit over the Cost $\left(\text{Value} = \frac{\text{Benefit}}{\text{Cost}}\right)$, where the Benefit is the *Pugh Matrix*'s rates, representing the ability to fulfil all the customer's and the company's requirements, and the Cost is defined by the relative costs presented in the cost breakdown.

In order to do this, it is necessary to convert the relative costs in ratios, as the next table suggests. Notice that a cost saving relative to the reference model (*LWG 1000*) is represented by a ratio below "1". The table summarizes also the Benefit ratios and the resulting Value for each model.

Model	**Cost**		**Benefit**	**Value**
		ratio		
Model I	24 280 €	0.865	1.288	**1.489**
Model II	24 196 €	0.862	1.948	**2.260**
Lattix's	21 395 €	0.762	1.706	**2.239**
LWG 1000	28 073 €	1	1	**1**
Model W	27 132 €	0.966	2.101	**2.175**
Model III	21 455 €	0.762	2.259	**2.965**
Model IV	31 820 €	1.133	1.352	**1.193**

Table 5-17: Models' Cost, Benefit and Value in ratios

Below a graphic, which displays the relative position between the models in terms of Cost and Benefit, is presented. Naturally the graph area where the highest

Value is achieved is in the most inferior right zone (corresponding to highest Benefits with the lowest Costs).

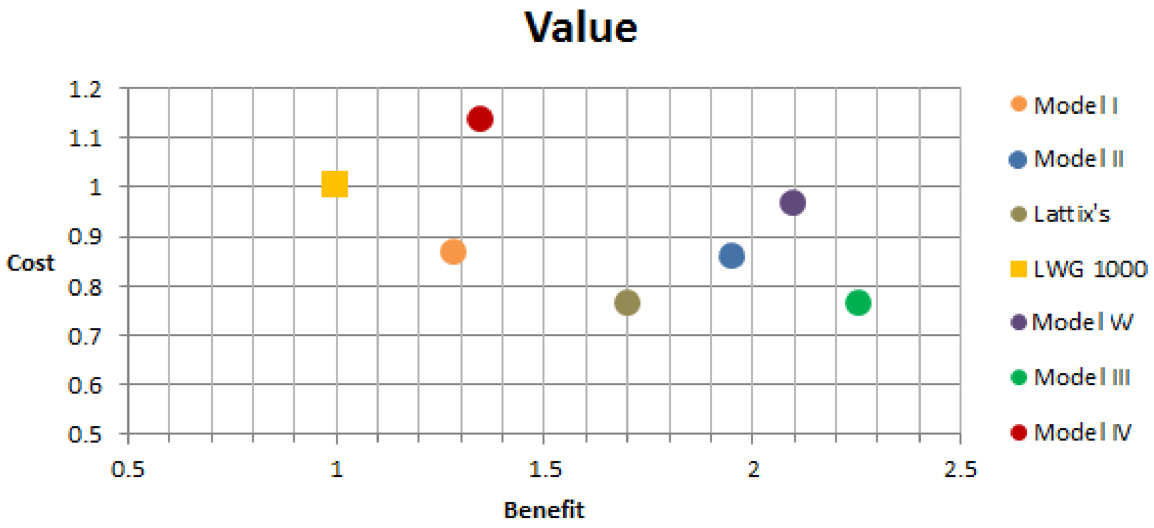


Figure 5-12: Model's Benefit vs Cost

Now, a ranking of the Cost, Benefit and Value results is presented for each model.

Model	Cost Rank	Benefit Rank	Value Rank
Model I	3rd	6th	**5th**
Model II	3rd	3rd	**2nd**
Lattix's	1st	4th	**3rd**
LWG 1000	5th	7th	**7th**
Model W	5th	2nd	**4th**
Model III	1st	1st	**1st**
Model IV	7th	5th	**6th**

Table 5-18: Models' Cost, Benefit and Value ranks

The decision factor may vary a lot dependent on the customer or on a specific driver from the company. Now, by not distinguishing between customer and the company (or in other words, external and internal requirements), there are many different drivers to rule customer's decision. A customer may be mostly driven by the cost, or the product's appearance (which is a subjective requirement), by the standardization of the product, or the unique characterization or customization, the light-weightiness, etc. This means that the "importance rates" of the requirements in the *House of Quality* change from customer to customer. And depending on the client or situation, the decision may be taken considering just one or a few parameters.

Since this is a generic exercise, it was decided to include all the requirements to find a Benefit relation and a relative cost breakdown to find a Cost relation. With this, it was found a Value rate for each model.

5.3 30m Span Assessment

This chapter will assess the performance of each Gantry model's structural configuration for a 30m span. This study is important because with the span increase some models may reveal some weaknesses as for example the lower values for the Boom's vertical stiffness.

Due to the big amount of information it will be only presented the results, since the method to get them was exactly the same, but starting with the modelling of every model to a 30m span configuration. The models' sections were once again dimensioned until reach Boom's displacements in the order of 140/150mm (S/200).

5.3.1 30m Span: Value Assessment

Below, the tables with the new results will be presented. From the new Cost Breakdown it is presented the final total cost and the correspondent saving percentage, as well as its values in a ratio. Then, from the new *Pugh Matrix*, the values of Benefit are taken and consequently the new Value ratios.

Model	**Cost**		**Benefit**	**Value**
		ratio		
Model I	29 589€ (12.8%)	0.872	1.306	**1.498**
Model II	29 416€ (13.3%)	0.867	1.856	**2.141**

Lattix's	29 355€ (13.5%)	0.865	1.773	**2.049**
LWG 1000	33 931€ (Ref)	1	1	**1**
Model W	38 794€ (-14.3%)	1.143	2.032	**1.777**
Model III	27 489€ (19%)	0.810	2.283	**2.818**
Model IV	35 386€ (-4.3%)	1.043	1.378	**1.321**

Table 5-19: 30m Span Models' Cost, Benefit and Value in ratios

There new results give origin to a slightly different arrangement of the graphic "*Benefit vs Cost*" for each model.

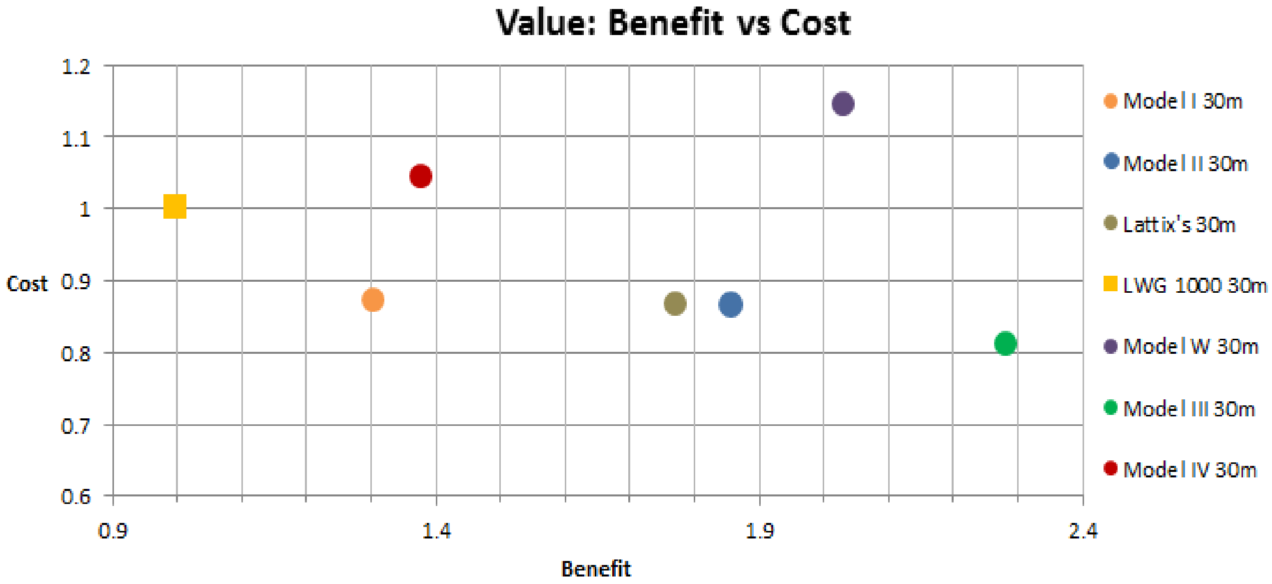


Figure 5-13: 30m Span Model's Benefit vs Cost

Lastly, are presented the new ranks for the three categories.

Model	Cost Rank	Benefit Rank	Value Rank
Model I	2nd	6th	**5th**
Model II	2nd	3rd	**2nd**
Lattix's	2nd	4th	**3rd**

LWG 1000	5th	7th	**7th**
Model W	7th	2nd	**4th**
Model III	1st	1st	**1st**
Model IV	6th	5th	**6th**

Table 5-20: 30m Span Models' Cost, Benefit and Value ranks

Notice that for the cost ranks, all the models with costs with less than a one thousand monetary units (in this case, euros) difference, were given the same rank, namely a tie.

The next graph represents for each model the 20m and 30m versions. It can be assessed the change in cost and benefit associated to the use change in span from each structural configuration.

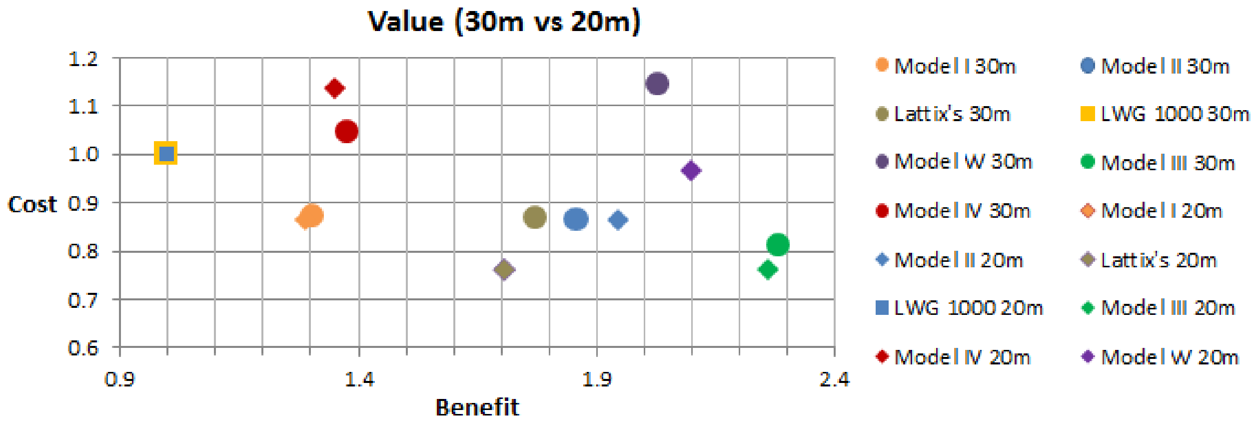


Figure 5-14: 30m vs 20m Span Model's Benefit vs Cost

The next section will assess the use of a central Leg set for the models with a 30m span configuration.

5.3.2 30m Span with central Leg set: Value Assessment

This section will consider the use of a third Leg set for each model. Regarding that one of the external requirements is “avoid a 3rd Leg”, it is considered relevant this study, because by adding a third Leg, the Boom’s stiffness can be reduced. Therefore, the size of the sections and the total weight can be reduced.

The used method, once again, was the same as in the two previous cases. This way, only the results will be presented. Nevertheless, there are some aspects that are pertinent to address before the results.

Regarding the modelling of the baseline model *LWG 1000*, when adding the central Leg, the stiffness of each Leg Mast could be reduced. Since *Lattix* uses normalized masts, the designed 3 Leg version uses a D4420 Mast instead of a D4425 (where the information regarding the bending stiffness and weight was taken from *Lattix*’s product catalogue).

Other aspect important is referred to both *Model II* and *Model III*. These two models have Legs in angle. Due to the central position of the Legs, the resultant force form *VMS* loads is directly supported by the compression of the “back” Leg. This means that it could have been design a gantry with sections that are stiff enough but, in reality, under certain compressive forces some elements may suffer bucking. In short, the geometry of these two models’ Legs combined with the direct application of the resultant forces from the *VMS* will result in high compressive forces in the Leg’s masts. Therefore, a buckling verification was performed.

The next figures exemplify for the *Model II*, the application of the *VMS*’ wind force and self-weight and the almost direct load flux through the back Leg.

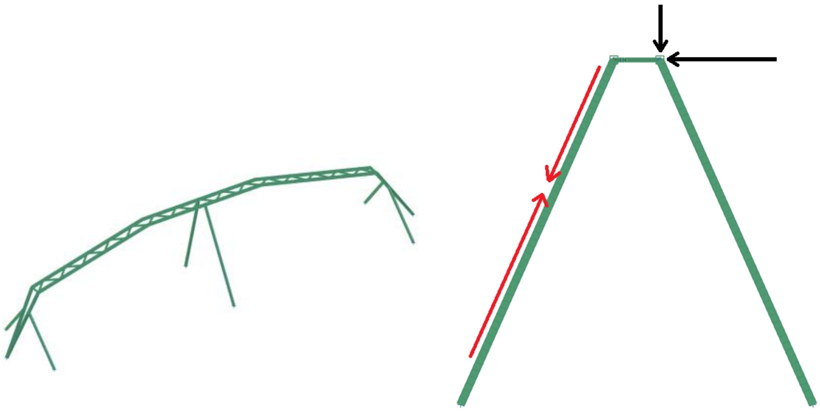


Figure 5-15: ***Model II*****: Compressive resulted forces in the back Leg**

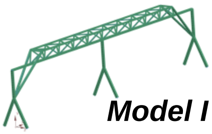
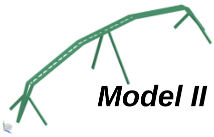
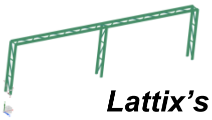
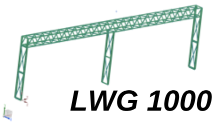
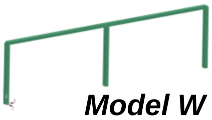
Neglecting the buckling possibility, it would be easy to reduce very significantly all the sections in these two models, since the back mast from the central Leg system supports most of the *VMS*' loads. Therefore, it was considered a simple buckling verification in order to restrict the reductions of the Leg's profiles.

Considering that the mast was subjected to a perfectly align load equivalent to the horizontal *VMS* load from the wind (F_{wind_VMS} = 29.7 kN) and that it was fixed at one end and free at the other (which represents the most severe case for the critical load calculation with a **K** factor of 2 in the denominator) the following expression was used to perform the verifications for both models.

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad (5.7)$$

Where $\mathbf{P_{cr}}$ is the critical axial load, **EI** is the bending stiffness, **K** is the mast's length factor (K = 2 for this consideration) and **L** is the mast's length. The goal was that the value of P_{cr} was superior to the F_{wind_VMS}, in order to the Leg's section be validated.

Below, are presented the final results of the current assessment.

Model	Cost		Benefit	Value
		ratio		
 ***Model I***	32 441€ (10.7%)	0.893	1.311	**1.468**
 ***Model II***	26 990€ (25.7%)	0.743	1.897	**2.553**
 ***Lattix's***	25 272€ (30.4%)	0.696	1.723	**2.475**
 ***LWG 1000***	36 315€ (Ref)	1	1	**1**
 ***Model W***	36 667€ (-1%)	1.010	2.075	**2.055**

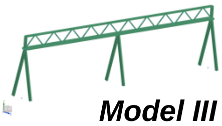
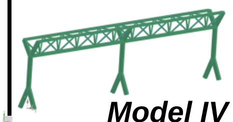
 ***Model III***	23 976€ (34%)	0.660	2.405	**3.643**
 ***Model IV***	36 550€ (-0.6%)	1.006	1.370	**1.361**

Table 5-21: 30m Span with 3rd Leg Models' Cost, Benefit and Value in ratios

Below it is once more presented the graph "*Benefit vs Cost*" with the new results compared to the 30m span ones.

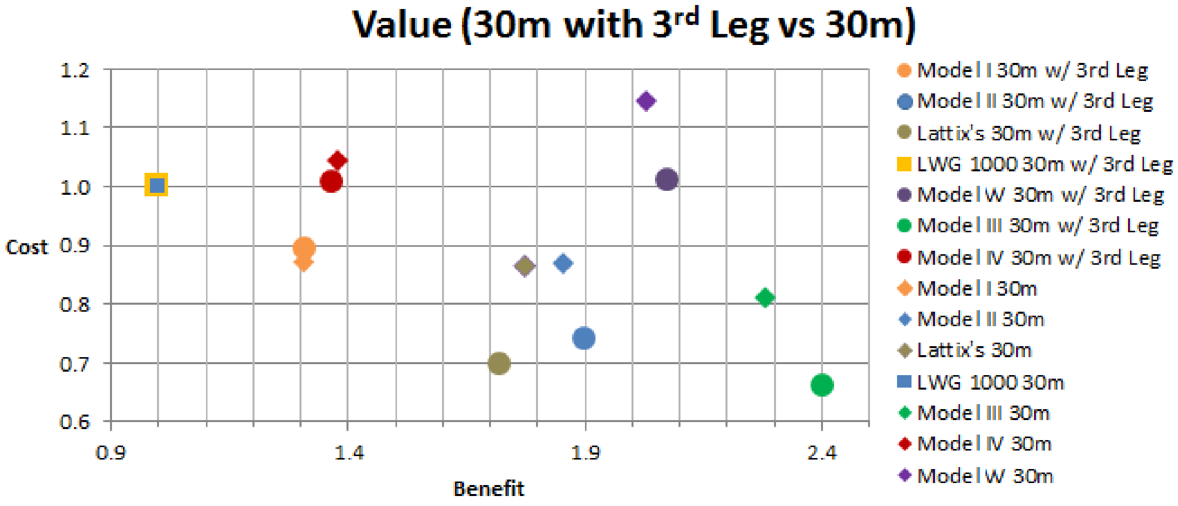


Figure 5-16: 30m with 3rd Leg vs 30m Span Model's Benefit vs Cost

The results of the three cases show that *Model III* had the best associated benefit, lower cost, and hence the highest value.

In this work, two important values were combined: the cost and the benefit (where the latter one results from all the requirements' fulfilment). Consequently, for further work the *Model III* was selected to be developed in more detail.

6. Development of the Concept

This chapter addresses the development of the model that was previously selected. The method and the logic reasoning used to design the structure will be presented.

The detailed design was applied to the *Model III* due to its high potential to fulfil the requirements while keeping the costs down. The design was applied to the 30m span configuration with a 3rd Leg, due to its best previous results.

6.1 Detailed Design

This entire section will cover the detailed design of the selected Gantry structural configuration. It will focus mainly on the profiles' design and in the connection between the different parts. Regarding the connections, the approach for its design was the avoidance of welding, and to enable a direct fit between the attached elements, with the minimization of the use of extra parts. For the design of the required extra parts (mainly brackets), their production aspects were taken into account. A design that relies on extrusions as the main production method was suggested. Following operations after extrusion are just cutting and drilling. In order to avoid high costs in secondary parts, they can either be produced "in-house" or outsourced.

6.1.1 Profiles' Design

One of the reasons that enable *Model III* to keep a lower cost relative to the other models is the fact of using just two profiles: one simple section for the Diagonal Beams and one common for the Main Beams and Legs. The dimensioning of the sections in the previous chapter has this in consideration so the common section could be applied with the same dimensions, thus extruding the Main Beams and Legs from the same die.

For the cross-section of the Diagonal Beams, a square profile section of [90 x 90] mm and a wall-thickness of 6 mm was used.

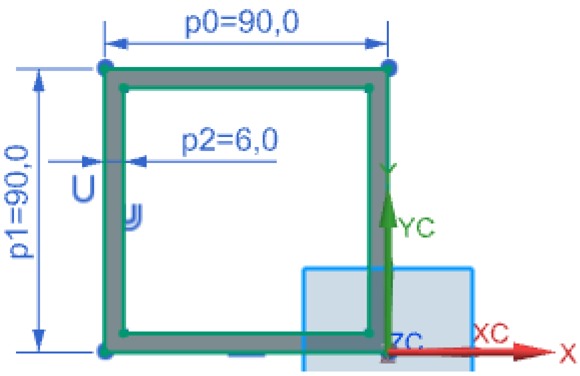


Figure 6-1: Diagonal Beam's Profile and its basic dimensions

Area:	2016 mm^2
$I_{zz} = I_{yy}$:	2 383 000 mm^4

Table 6-1: Diagonal Beam's section Area and Principal Moments of Inertia

The Diagonal Beams must have a 45º cut at each end, to make them fit in angled position in a lattice structure.

For the remaining members, a more complex section had to be designed. The focus on the design was to get a profile that enables the fitting to the Diagonal Beams both for the Bottom Beams and for the Top Beams.

The figure below reminds the configuration of *Model III*'s Boom, with two Bottom Beams side by side and one central Top Beam, connected by vertical Diagonal Beams.

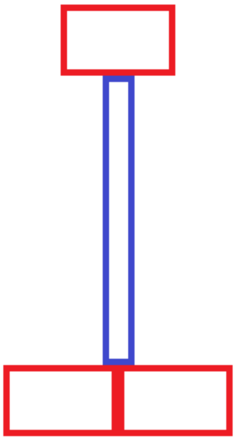


Figure 6-2: *Model III*'s Boom configuration

The profile was designed with flanges enabling the housing of the Diagonal Beams both for Top and Bottom Beams, and also to enable the lateral coupling of the Bottom Beams. The generated profile is presented in the figure below, together with correspondent values of area and moments of inertia.

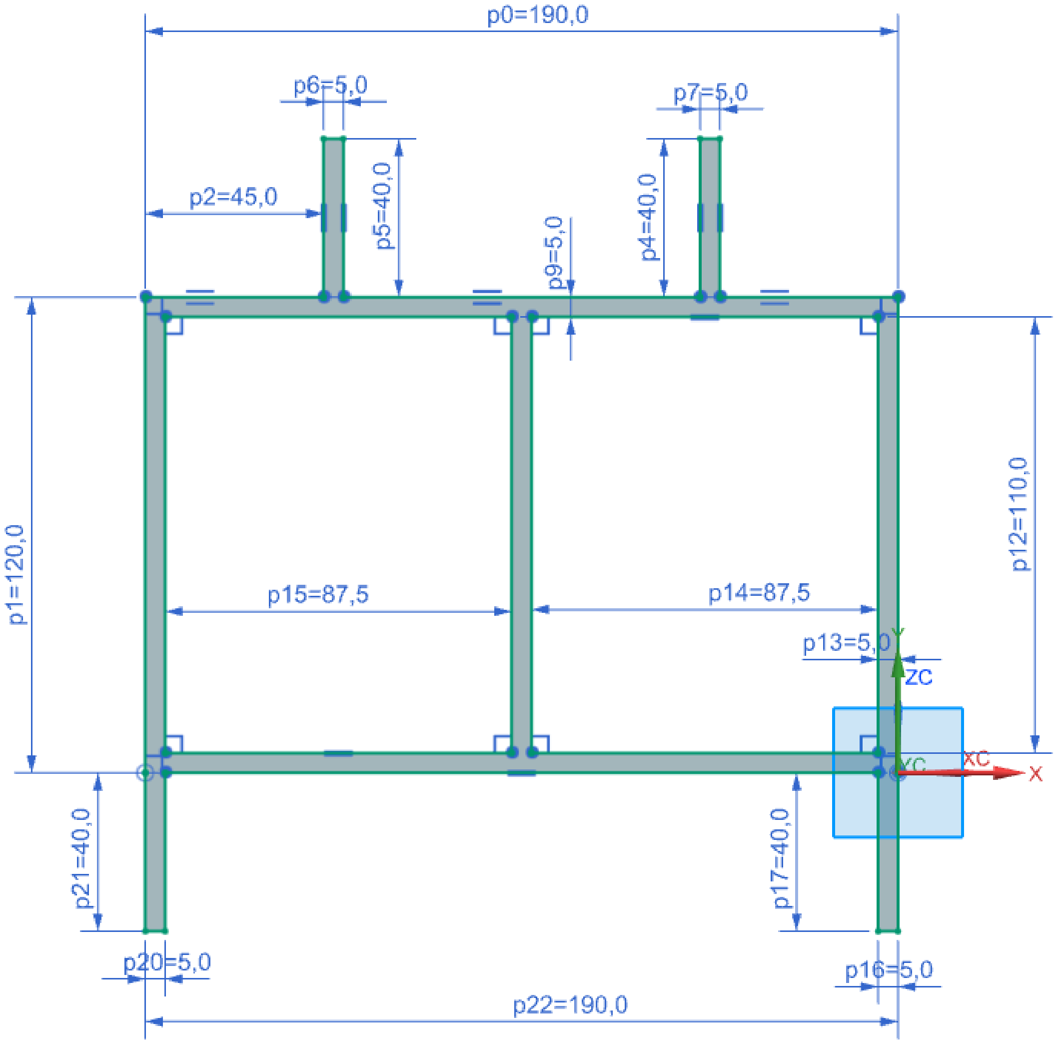


Figure 6-3: Main Profile and its basic dimensions

Area:	4350 mm^2
$I_{zz(\text{horizontal axis})}$:	19 458 000 mm^4
$I_{yy(\text{vertical axis})}$:	13 176 000 mm^4

Table 6-2: Main section's Area and Principal Moments of Inertia

The flanges enable the direct bolting with the Diagonal Beams and also the direct bolting of both the Bottom Beams. The inner wall, besides giving more stiffness to the profile more, increases its resistance to buckling. Below, it can be seen the section schematics of the Boom and the importance of the location of the flanges. (The figure is turned in the horizontal to save space).

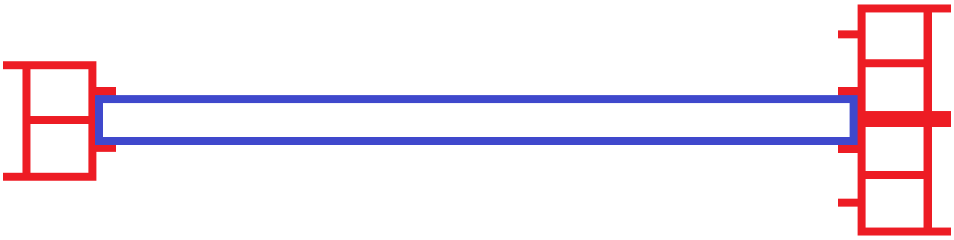


Figure 6-4: ***Model III*****'s Boom Section: Main Profile**

Regarding the manufacture of the main profile, it offers a good extrudability, since it does not have thin chambers that can cause a rapid wear of the die, or a slow and uneven cooling by being symmetric in one axis and almost in the other.

Concerning the bolting between the Diagonals and the main profile's flanges, each connection is made by one single bolt, because there is no access to the inner side of the Diagonal's profile.

Now that the two profiles are designed, in a way that enable the direct connection between the Diagonals and the Main Beams, it is time to develop the remaining connections, starting with the ones between the horizontal Boom modules. Nevertheless, a brief mention to the stacking of the profiles and to the profile's water drainage is presented before addressing the connections' design.

6.1.2 Profiles' Stacking

One important characteristic of the profiles is their stacking, an easy factor to neglect in the design stages. The profiles should be stacked without any supports (or at least complex ones) and putted one on top of the others without occur any damage. This topic is related to the profile's design itself, so, here, the ideal way to stack the profiles before the assemblage or transportation will be presented.

Since the Diagonal Beams have a square cross-section without external details, they can be stacked one on top of the others in parallel rows and columns. The major attention will be given to the stacking of the main profiles.

The main profiles should be stacked laterally, with the side walls aligned with the floor. Then, from below to the top, each consecutive column should be raised one profile at a time, put laterally besides the neighbour row member and then mated until the flanges touch. The following figures demonstrate the main profile's stacking.

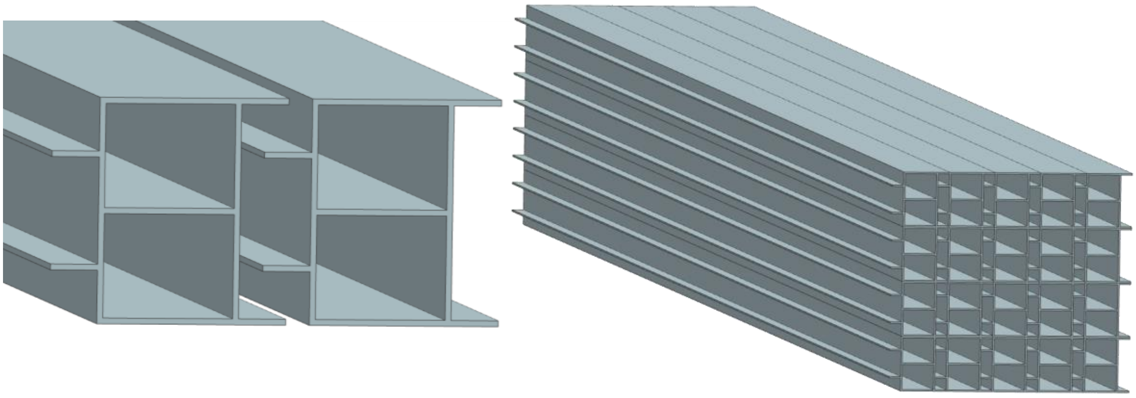


Figure 6-5: Main Profile’s Stacking

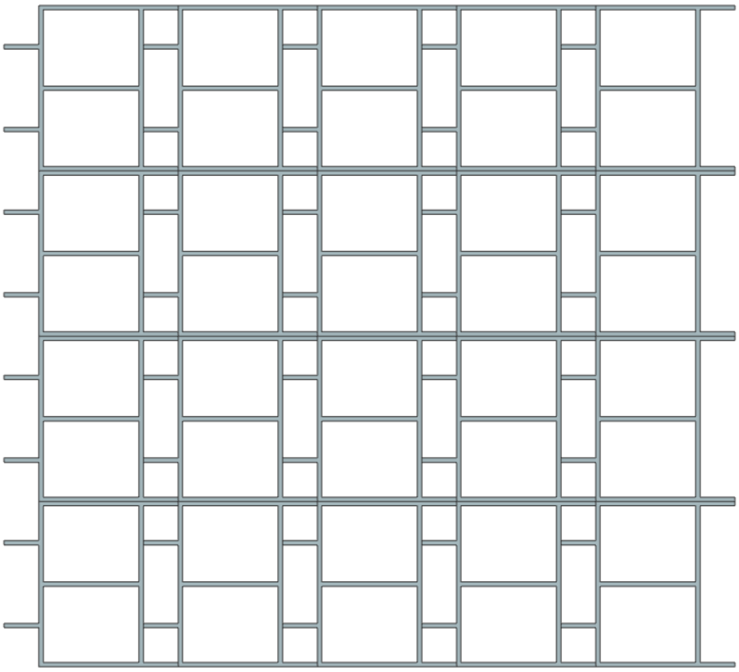


Figure 6-6: Main Profile’s Stacking: Section front view

The design of the main profile enables a compact stacking, where the flanges are protected from carrying the weight from the beams above.

6.1.3 Profiles’ Water Drainage

Another characteristic that should be taken into account is the possibility of the profiles to drain water. The retention of water can lead to the corrosion both from the profiles, brackets and the bolts and nuts used in the joint sections.

The water can enter inside the profiles by the top access holes in the main profiles (in the Bottom Central Booms, made to place the bolts connecting the central

Leg in place, which will be explained ahead), or through the side winds by the open sides at each Boom's end. Thus, is recommended that all Boom's main profiles have a drainage device.

The Diagonals have the extremities closed by the main profiles, so this issue is not a concern.

To enable the water drainage, small holes in each profile's chamber are proposed in the bottom face of each Boom's main beam. The location of the holes, besides depending of the Beam type (Top or Bottom Beam, which decide the face to apply the holes) would depend on the position of the beam. The central ones (for the 30m span cases) should have them in both sides, near the horizontal joint sections. Whereas the side ones, would have only one set in the inner side, near the horizontal joint section.

In this matter, the presence or not of the central Leg set is relevant. Without the central Leg, the central Beams would have such curvature that the maximum deflection would be located at their centre. Therefore, the water would be accumulated in that position. So, if we regard a 30m span model without a central Leg (for a 3 module Boom) the central beams should have drainage holes in the beams' centre.

6.1.4 Boom – Boom: Horizontal Connection

This section is referred to the horizontal connection between two Main Beams in order to connect two consecutive Boom modules, which are used both for Top and Bottom Beams.

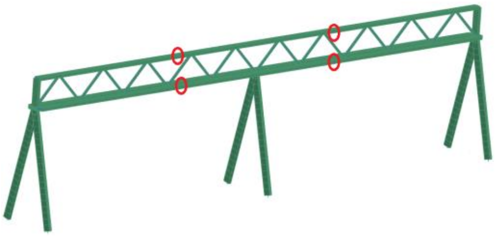


Figure 6-7: Location of Boom–Boom Horizontal Connections (marked in red)

The approach used to connect consecutive profiles is the use of interior mounted brackets with an outer flange to enable external bolting. This bracket type is applied to each side of each profile's chamber by the use of bolts, resulting in the effect of having a welded end-plate. The following figure shows the application of the Connecting Brackets for the longitudinal connection of two sets of Bottom Beams.

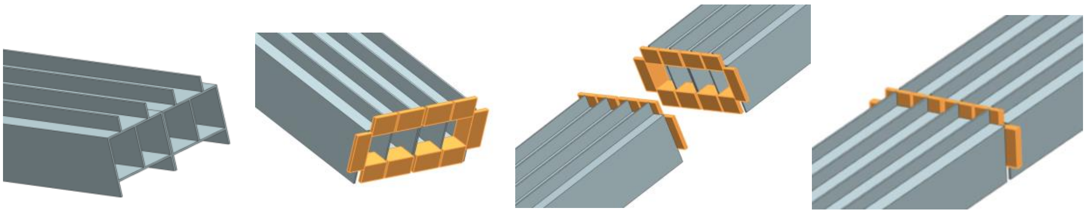


Figure 6-8: Bottom Beam's Longitudinal Connection – Connecting Brackets

This connection requires three bracket sizes, all with the same profile. The goal behind the design of the brackets is to enable a simple production, avoiding all processes beside drilling or cutting. Weather the brackets are manufactured "in house" or are purchased from a supplier they can be extruded from the same die and cut in three different lengths.

The suggested material for the brackets is a 5xxx or 6xxx Series Aluminium Alloy. They provide corrosion resistance, and good stiffness values. By avoiding steel, the contact between the brackets and the interior of the profiles is immune from any possible steel-aluminium galvanic corrosion.

Since some brackets are common in the connection of other members they will be named to ease their identification. But firstly, the common profile is presented below, from a *screen* taken from the *software NX*.

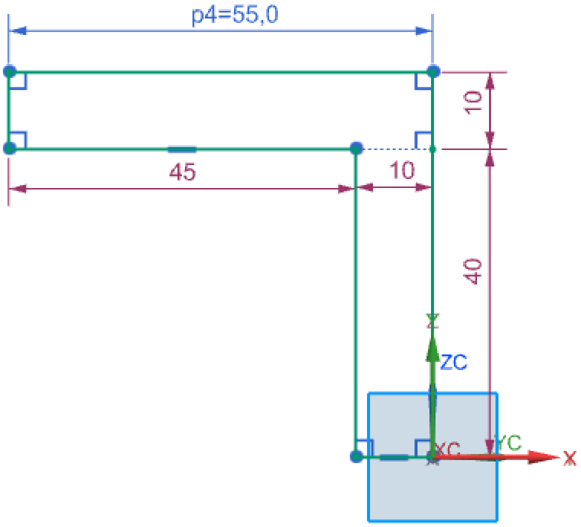


Figure 6-9: Bottom Beam's Longitudinal Connection – Connecting Brackets' profile

These dimensions are suggested, but if a bolt dimensioning was performed, some changes to the brackets' profile may be necessary.

The bigger flange corresponds to the outer flange and has 5 mm more than the inner flange to count with the thickness of the main profiles, where the bracket is mounted on.

For the horizontal connections of the main profiles three lengths are needed. For the vertical walls there are two brackets with 110 mm (Bracket 1.1). For the horizontal walls that don't have a Bracket 1.1 on an attached vertical wall, there are 87 mm brackets (Bracket 1.2), which is only the case of the Bottom Beams (having just one Bracket 1.1 for each profile). For the horizontal walls that also have a Bracket 1.1, there are 77 mm brackets (Bracket 1.2.1).

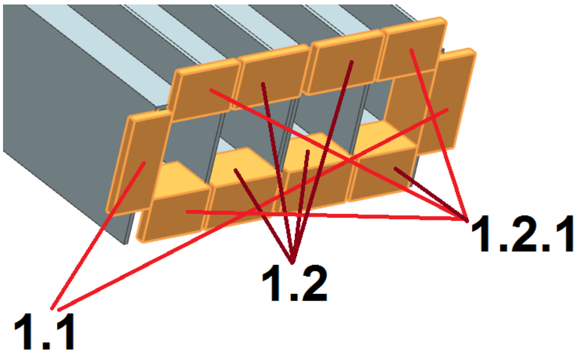


Figure 6-10: Bottom Beam's Longitudinal Connection – Brackets identification

Naturally, to connect the Top Beams (since is a singular profile) the Brackets 1.2 are not used.

The use of this type of brackets, allied to the design of the flanges of the main sections, enable to hide the connection joint, making the global design more appealing to the road users.

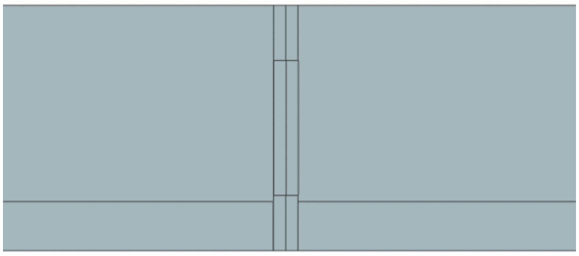


Figure 6-11: Front view of a Horizontal Joint – Hidden brackets

6.1.5 Vertical Profile – Top Beam: 90º Connection

The current section refers to the 90 degree connections between the two Vertical Profiles with the Top Beam.

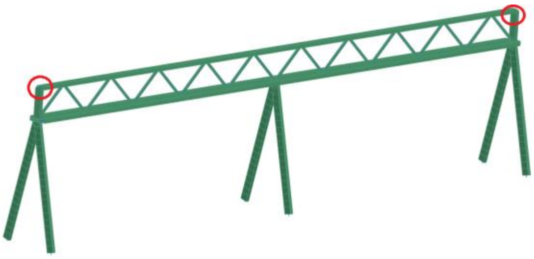


Figure 6-12: Location of Vertical Profile–Top Beam 90º Connections (marked in red)

To enhance the 90º coupling between the Vertical Frame and the Top Beam, both beams were cut in 45º angle. This connection was performed with the use of two Brackets 1.1 but cut in 45º (called Bracket 2.1 for one side and Bracket 2.1.1 for the other). Then, the linkage is reinforced by external brackets, one on top (Bracket 3.1) and two beneath (Brackets 3.2). The figures below help to visualize the described connection.

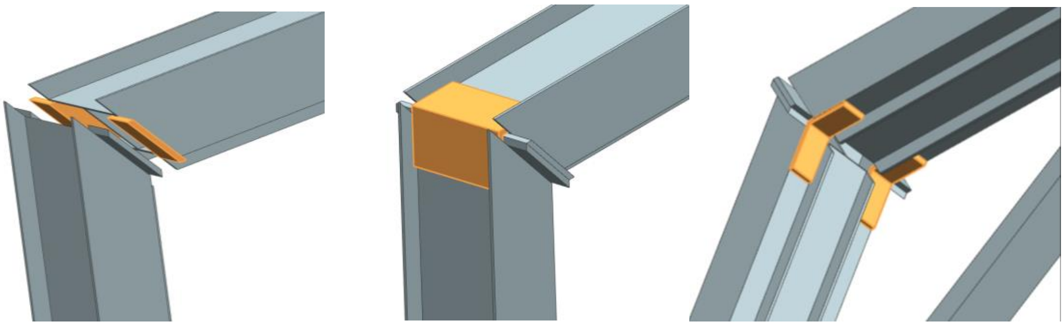


Figure 6-13: Vertical Profile–Top Beam 90º Connections – Brackets 2.1 and 2.1.1, 3.1 and 3.1.1's

Notice that the brackets 3.1.1 have the presented configuration (two on the outer surfaces, instead of one in the inner surface (as well as the bracket on top, 3.1) because the interior surface is where the Diagonal Beams fit. The figure below demonstrates the importance of this decision, as is the case of the opposite side connection, where a Diagonal is fixed between the two Brackets 3.1.1.

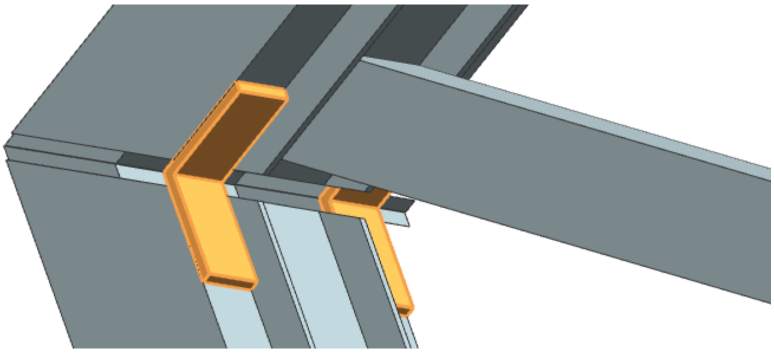


Figure 6-14: Diagonal's position between the Brackets 3.1.1

6.1.6 Vertical Profile – Bottom Beams: 90º Connection

This section addresses the inferior connection of each Vertical Profile, namely the 90 degree connections between them with the Bottom Beams.

Figure 6-15: Location of Vertical Profile–Bottom Beams 90º Connections (marked in red)

To perform this joining, it was used the same method as for connecting two horizontal Top Beams, but with less two brackets. This way, it was used two Brackets 1.1 for the Vertical Profile's sides and two Brackets 1.2.1 for the back side.

A demand of the Main Profiles' sections is that, in order to create a flat surface so the Vertical Profile can rest on top of the Bottom Beams, a cut must be performed in one flange of the Bottom Beam at each side of the Gantry. The figure below shows the referred cut of 200 mm (the Vertical Profile's height).

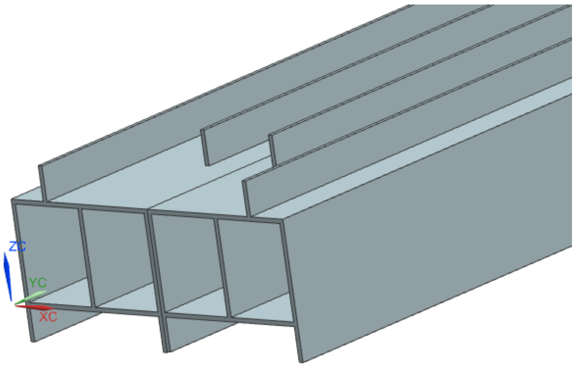


Figure 6-16: Flange cut of 200 mm in each Bottom Beam to house the Vertical Profile

The Brackets 1.2.1 are applied just to one side, because of the interference with the Diagonal Beams on the other.

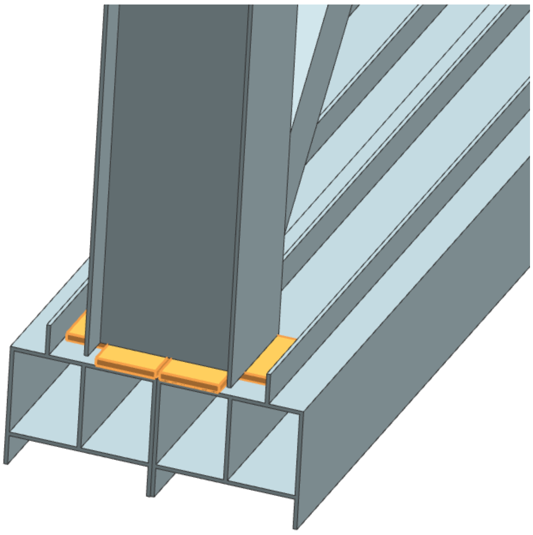


Figure 6-17: Vertical Profile–Bottom Beams 90º Connections – Brackets 1.1 and 1.2.1

5.1.7 Leg – Leg 28º Connection

Each Leg is spread apart from the centre of the Gantry by 1.5m making each one an angle of 76º with the vertical direction, thus 28º between each other. The used Leg height (from the ground to the bottom of the Boom) was 6m, thus the Legs have a length of 6.185m and consequently the angles are the ones described.

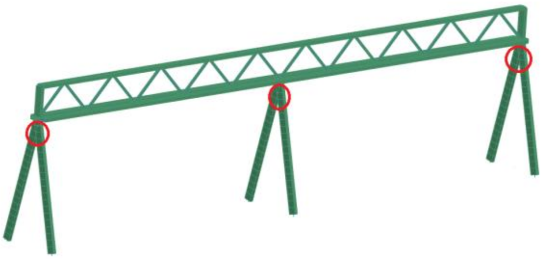


Figure 6-18: Location of Leg–Leg 28º Connections (marked in red)

The connector that enables to join each pair of Legs is the same connector that joins them to the Boom's Bottom Beams. Therefore, this Bracket will be explained in the next section, where the latter connection will be described.

In order to make both Legs fit in each other and to fix them both in the ground (Foundations) and in the Boom with an angle, some cutting operations after the extrusion are required. Firstly, both ends need to be cut with a 14º angle to create the flat surfaces. Then, a vertical cut is required that cuts one chamber of each Leg's profile, in order to enable the contact with each other. After that, a cut in the flange is needed to later apply a lateral bracket. Lastly, two grooves at each Leg are cut, on the surface that will be in contact with the bracket. The grooves will enable the fitting of the Legs with the bracket already with the bolts in position, due to the lack of access. The cutting sequence can be better understood with the following figure.

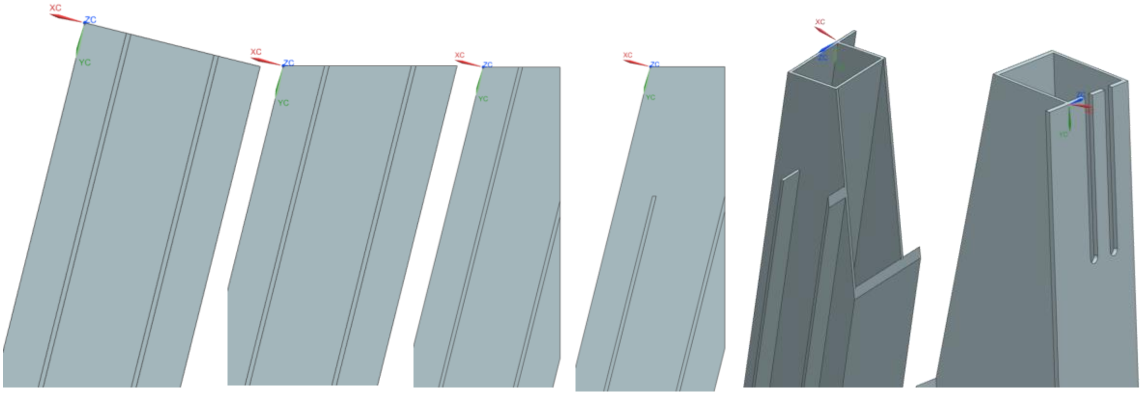


Figure 6-19: Leg's cut sequence after the extrusion

After the cut sequence the Legs are ready to be positioned in place in order to be fixed by the brackets, which will be described in the next section.

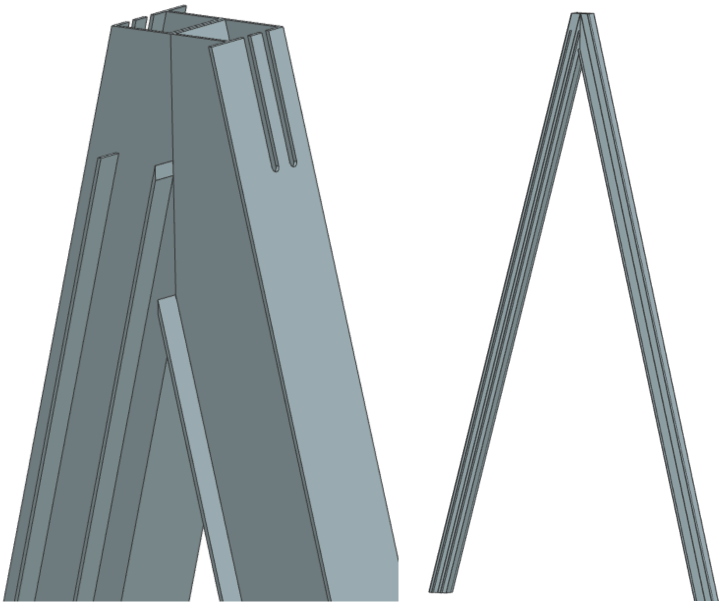


Figure 6-20: Legs in position to be fixed

6.1.8 Legs – Bottom Beams Vertical Connection

This section describes the connection between each set of Legs with the Bottom Beams, which consists in the joint of the Leg sets with the Boom.

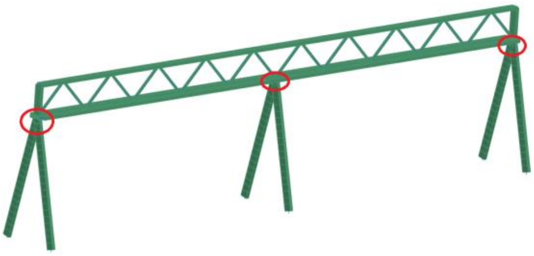


Figure 6-21: Location of Legs–Bottom Beams Vertical Connections (marked in red)

This operation requires simplicity in assembling, because it is done during the installation on site, where the Legs are fixed to the ground and the Boom is suspended by a crane and then connected to the Legs.

The main device that fixes the set of Legs to the Bottom Beam is the same that fixes the Legs to each other. This is a bracket (called Leg Bracket) produced by a singular extrusion that uses the side wall to join both Legs, and the top walls to join the Leg set to the Boom.

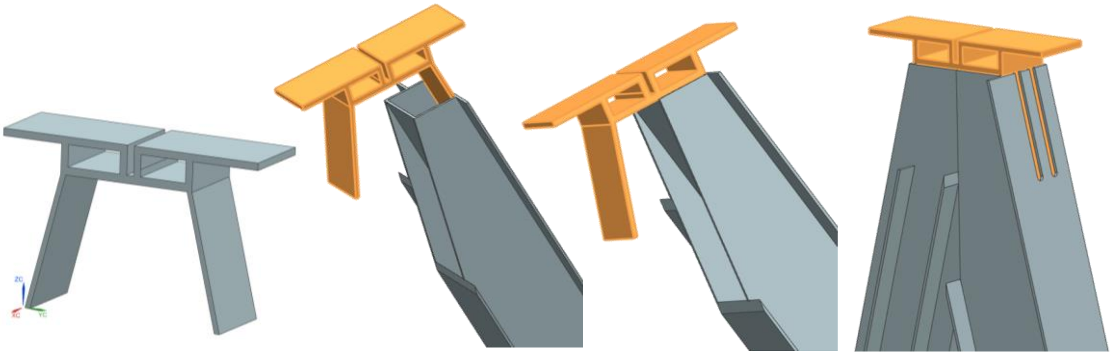


Figure 6-22: Leg Bracket: Connection of both Legs

The connection sequence for joining the Legs consists of putting the bolts in position in the Leg Bracket (two rows, thus two grooves in the Legs) in the side where the Leg will be fixed on. Then, the other Leg is slid into position (after placing the correspondent bolts in the Bracket) and the bolts are fastened in the remaining side wall of the bracket. Since the bolting points in this connection do not have access to both sides, it is proposed the use of *Huckbolts* (presented in the section 2.5). So the “fastening” of the bolts consists on the pressing of the collar placed in the bolts already putted in place in the Leg Bracket, where the heads have no access after the fitting of both Legs.

The superior part of the Leg Bracket has the role of contacting with the inferior surface of the Bottom Beams. Therefore, the centre flanges that join both Bottom Beams have to be taken into account. So, a central groove had to be included in the design of the Leg Bracket's superior part. Below, the Leg set is presented in place with the Leg Bracket highlighted, for a side Leg set and also for a central Leg set (the 3rd Leg).

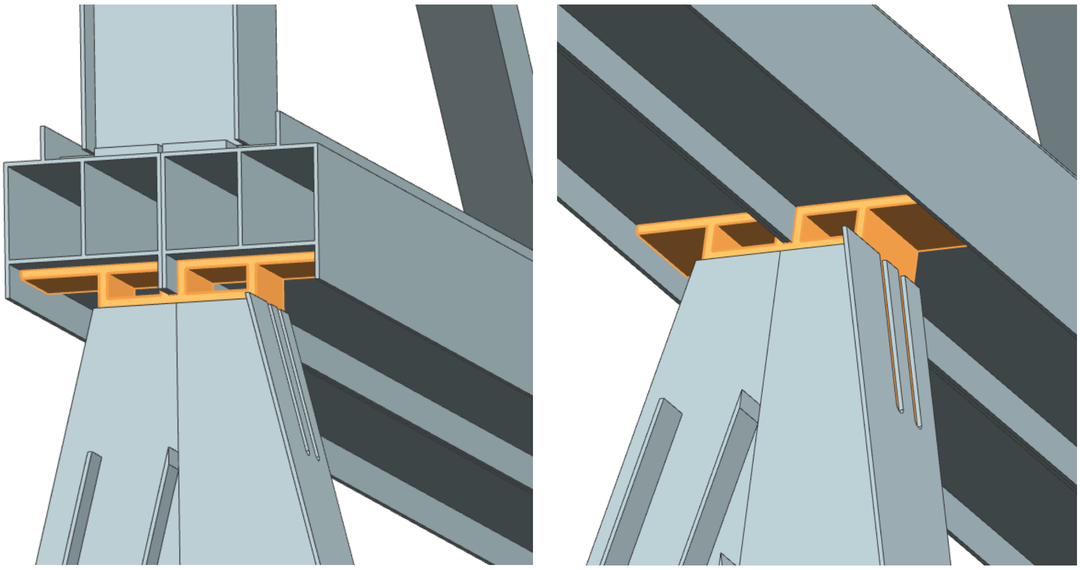


Figure 6-23: Leg Bracket: Connection of a Leg set to the Bottom Beams

Since the central Leg set has no access inside the Main Bottom's profiles, it requires the drilling of coincident holes on the superior wall, with a bigger diameter than the bolts. This allows putting the bolts in position in the inferior wall (with the heads inside the profile), giving access to the bolt's head and to an insertion device. Here the use of *Huckbolts* is recommended, due to the lack of space to introduce a fastening tool inside the profile by the access holes in the top walls.

In order to stiffen the present connection, another bracket was designed. This bracket has two main goals: to give a better fixation between both Legs and increase the area of contact between the Leg set and the Bottom Beams. This bracket has two variations, due to the position of the Legs. The Legs facing the extremities to the Gantry have only 40 mm of possible contact with the inferior surface of the Bottom Beam. Therefore, here is applied a bracket called Leg Outer Side Bracket. On the interior side of the side Leg sets and on both sides of the central Leg set are used the

Leg Inner Side Brackets, which have a more contact area with the Bottom Beam (enabling the use of more bolts, having a stiffer joint). Below, the referred brackets can been seen in highlighted.

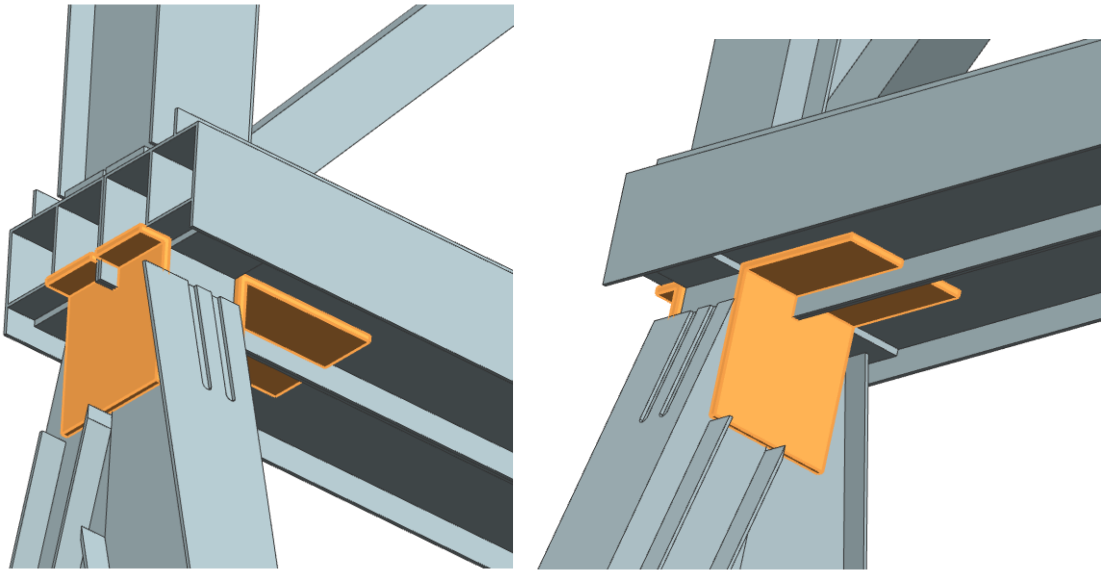


Figure 6-24: Leg Inner and Outer Side Brackets: Connection of a side Leg set to the Bottom Beams

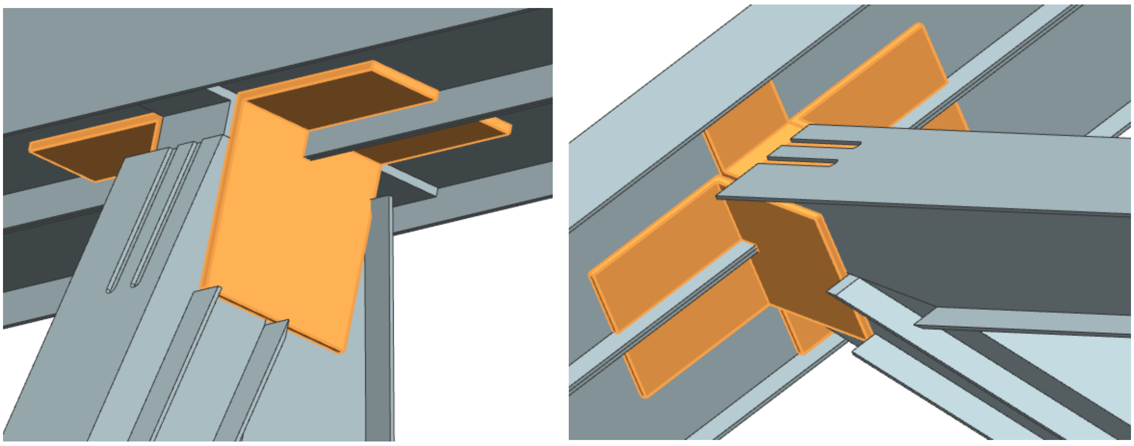


Figure 6-25: Leg Inner Side Brackets: Connection of a central Leg set to the Bottom Beams

The application of the Inner Side Brackets for the central Leg set also requires the drilling of access holes in the top wall of the adjacent Bottom Beams, in order to put the bolts in place as it was explained previously.

6.1.9 Leg – Foundation 14º Connection

Lastly, the connection that fixes the Gantry to the soil: the joint between the Legs and the Foundations is addressed.

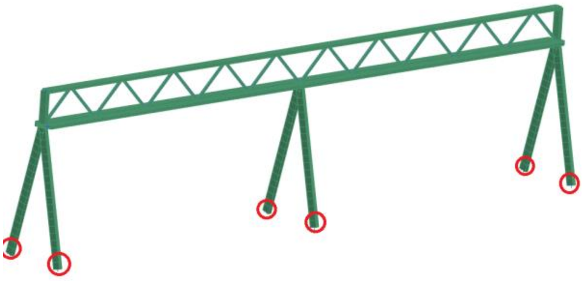


Figure 6-26: Location of Leg–Foundation Connections (marked in red)

This connection is made with the use of brackets of the same type as the ones presented before, for example for the longitudinal Boom joints. Each Leg has six attached brackets, but due to their angle (of 14º) there is the need of four bracket types. Firstly, for the top walls, there is needed a 14º profile bracket and a 104º one: Bracket 4.1 and Bracket 4.1.1, respectively. The figure below presents both brackets' profiles.

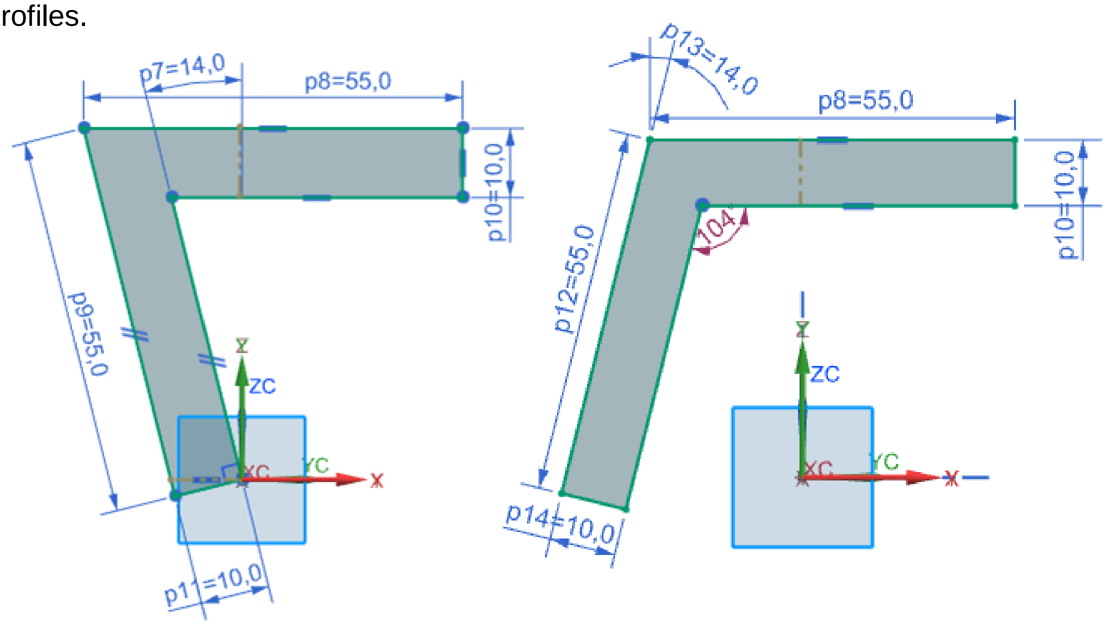


Figure 6-27: Bracket 4.1 and Bracket 4.1.1's profiles, respectively

Then, for the interior of the Leg's interior profile's side walls, there is the need of two bracket types, with the 90º profile (as presented previously) and 77 mm length. One with the sides cut with a positive 14º angle (Bracket 4.2) and the other with a negative angle (Bracket 4.2.1), in order to fit both wall from each profile's side. Below is the Leg with all the brackets illustrated in place and also a figure with the denominations of each bracket type.

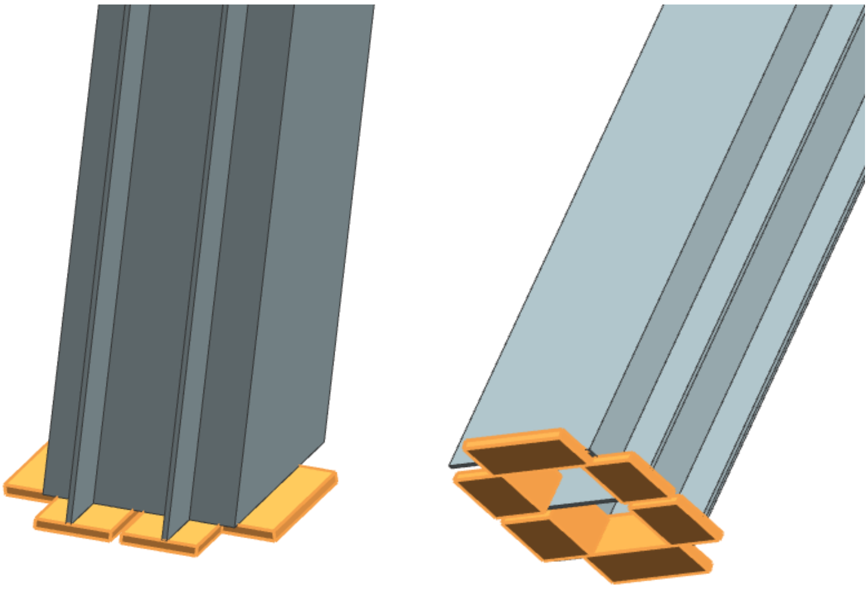


Figure 6-28: Leg’s base with all the brackets fitted

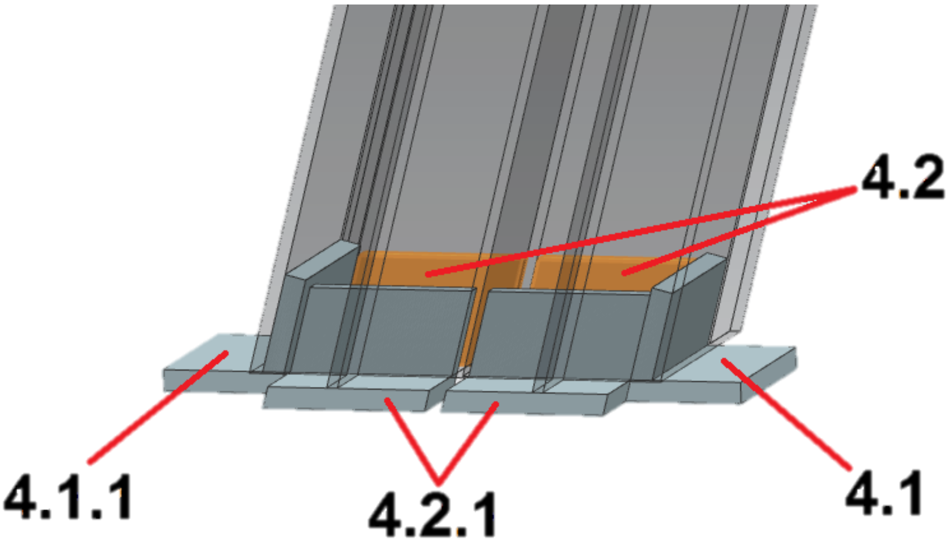


Figure 6-29: Leg’s base brackets denominations

After the Leg being fitted with the related brackets, it is placed on a Baseplate. The Baseplate, made from the same alloy as the brackets, will provide the joint between each Leg with the correspondent Foundation. Therefore, the superior face of the Baseplate will contact, through bolting, with the brackets mentioned previously in this section, and the inferior surface, with the top of the Foundation, with studs. The baseplate has a [475 x 400] mm surface area (and a thickness of 10 mm), which gives a 100 mm distance from each bracket's edge face to the correspondent Baseplate's face.

The Foundations are not going to be addressed in detail, since they are independent of the Gantry model and are not a structural member. Below the present connection with the baseplate in place is presented.

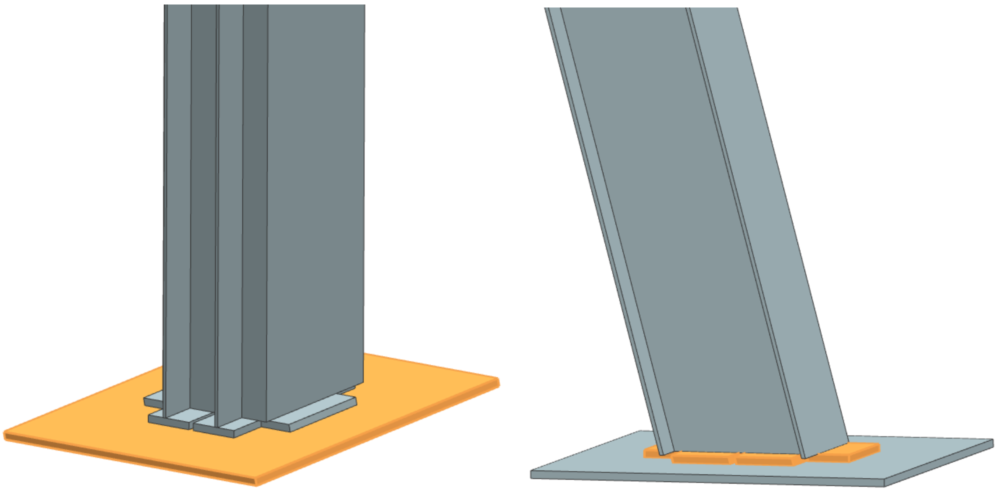


Figure 6-30: Leg's base with the brackets and Baseplate fitted

It is relevant to mention that due to the low tolerances needed between the brackets and the profile, the base of the Legs enable the drainage of water, if eventually water enters from the top.

The bolted connections were not dimensioned, since it would be out of this work's scope. Therefore, the brackets' dimensions suggested, such as thickness and contact areas, may be adjusted to comply with the number and required bolt sizes.

6.2 Structure Breakdown

6.2.1 List of Parts

This section summarizes all the different parts that the designed *Model III* Gantry contains, as well as the different stages of production that are required for each. But firstly, to give a better understanding of the parts' position in the global structure, it is going to be presented a figure containing a frontal, lateral and a perspective view of the assembled Gantry.

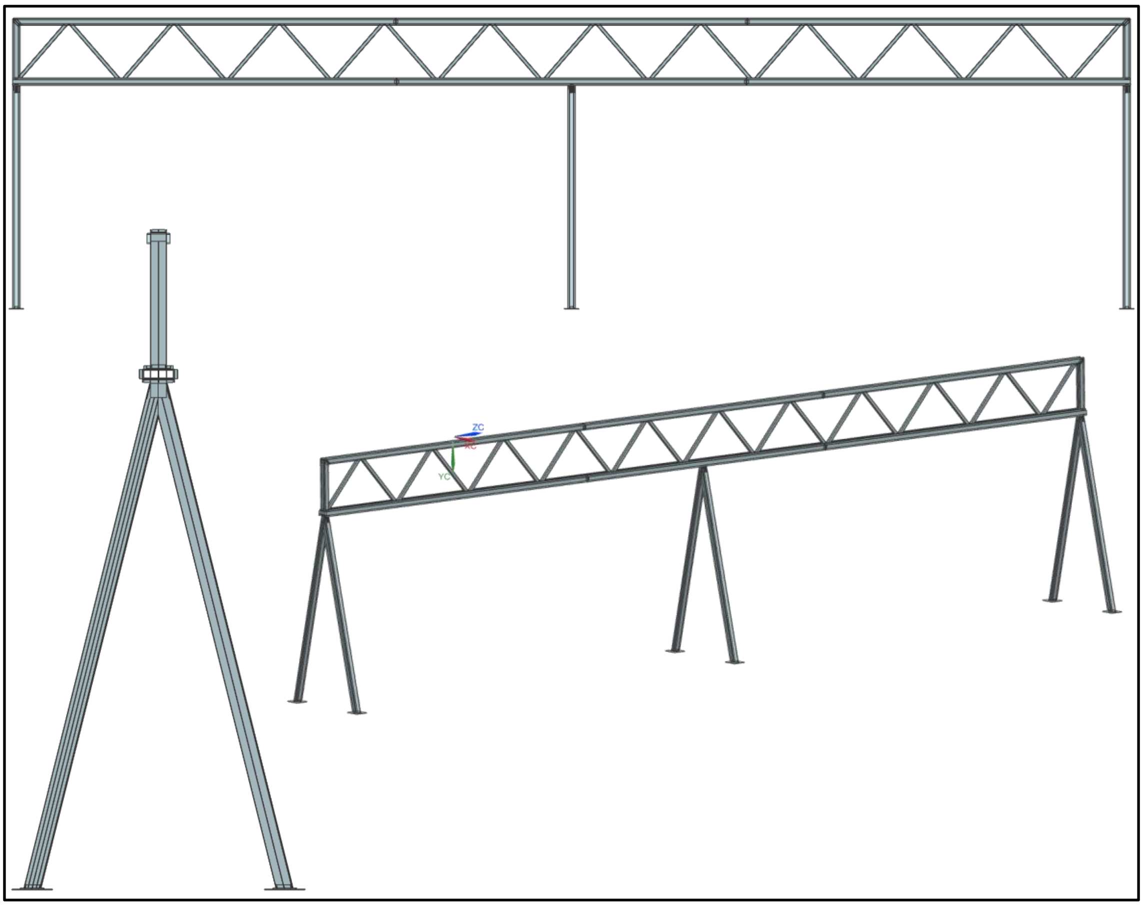
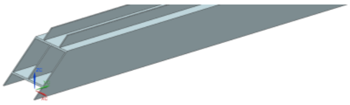
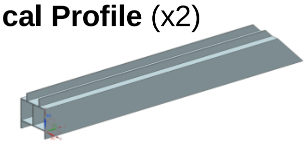
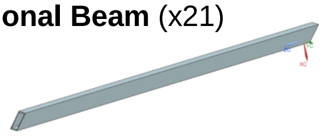
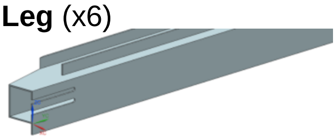
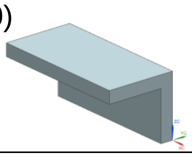
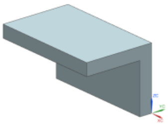
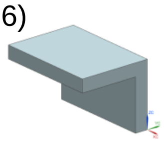
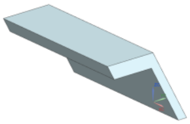
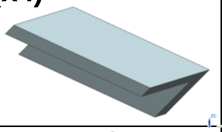
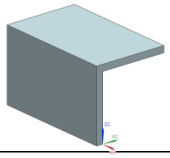


Figure 6-31: ***Model III*** **Gantry frontal, side and perspective views**

The following table is divided in two major groups: the structural parts, produced "in-house" and the secondary parts like brackets and plates (considered as purchased parts, although they can be also produced "in-house").

Profile	**Member/Part Name** (x Qty.)	**Operations**
P_1	**Bottom Beam Central** (x2) 	Extrusion **+** 90º Cuts **+** Diag.'s Holes **+** Bracket Holes (Longitudinal and Legs) **+** Access Holes **+** Rain Holes (bottom face)
P_1	**Bottom Beam Left** (x2) 	Extrusion **+** 90º Cuts **+** Diag.'s Holes **+** Bracket Holes (Long. and Legs) **+** Flange Holes **+** Rain Holes (bottom face) **+** Right Flange Cut

P_1	**Bottom Beam Right** (x2) 	Extrusion **+** 90º Cuts **+** Diag.'s Holes **+** Bracket Holes (Long. and Legs) **+** Flange Holes **+** Rain Holes (bottom face) **+** Left Flange Cut
P_1	**Top Beam Central** (x1) 	Extrusion **+** 90º Cuts **+** Diag.'s Holes **+** Bracket Holes (Longitudinal) **+** Rain Holes (top face)
P_1	**Top Beam Sides** (x2) 	Extrusion **+** 45º and 90º Cut **+** Diag.'s Holes **+** Bracket Holes (Long. And 45º) **+** Rain Holes (top face)
P_1	**Vertical Profile** (x2) 	Extrusion **+** 45º and 90º Cut **+** Bracket Holes (90º and 45º)
P_2	**Diagonal Beam** (x21) 	Extrusion **+** 45º Cuts **+** Diagonal's Holes
P_1	**Leg** (x6) 	Extrusion **+** 14º Cuts **+** 90º (vertical) Cut **+** Flange Cut **+** Grooves Cut **+** Bracket Holes (Leg's and Baseplate)
P_1^*	**Bracket 1.1** (x20) 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_1^*	**Bracket 1.2** (x16) 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_1^*	**Bracket 1.2.1** (x36) 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_1^*	**Bracket 2.1 (x4)** 	Extrusion **+** 45º Cuts **+** Bracket Holes
P_1^*	**Bracket 2.1.1 (x4)** 	Extrusion **+** -45º Cuts **+** Bracket Holes
P_2^*	**Bracket 3.1 (x2)** 	Extrusion **+** 90º Cuts **+** Bracket Holes

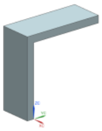
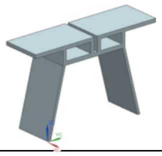
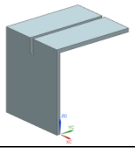
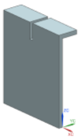
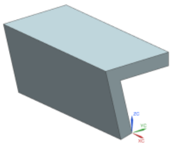
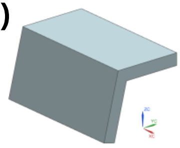
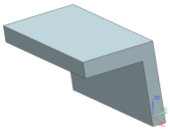
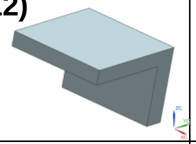
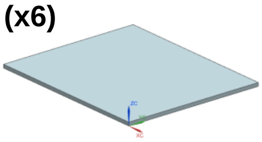
P_2^{*}	**Bracket 3.1.1 (x4)** 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_3^{*}	**Bracket Leg (x3)** 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_4^{*}	**Bracket Leg Inner Side (x4)** 	Extrusion **+** 90º Cuts **+** Groove Cut **+** Bracket Holes
P_4^{*}	**Bracket Leg Outer Side (x2)** 	Extrusion **+** 90º Cuts **+** Flange Cut **+** Groove Cut **+** Bracket Holes
P_5^{*}	**Bracket 4.1 (x6)** 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_6^{*}	**Bracket 4.1.1 (x6)** 	Extrusion **+** 90º Cuts **+** Bracket Holes
P_1^{*}	**Bracket 4.2 (x12)** 	Extrusion **+** 14º Cuts **+** Bracket Holes
P_1^{*}	**Bracket 4.2.1 (x12)** 	Extrusion **+-** 14º Cuts **+** Bracket Holes
P_1^{**}	**Baseplate (x6)** 	Cut from sheet **+** Baseplate Holes

Table 6-3: List of Parts

* Extrusion profiles for the brackets (possibility of being produced by an external supplier).

** Piece not manufactured from an extrusion, but from a laminated sheet.

In order to enable a simple and direct contact between the different parts, in some cases, some extra production operations need to be added (like cutting or drilling). This arise a cost issue, which should be considered (having more profiles to enhance the connections or just two that require more operations?). But, in all the cost studies done in the previous chapters, the breakdown showed that the production costs (operations after the extrusion) were corresponded to the smallest share. The adding of production operations cannot be avoided since the design considers only two extrusion dies, which claim a significant portion in the cost breakdown. By having just two profiles, the fitting between all the parts will not be direct, thus extra production operations are needed.

6.2.2 Design Strategy

This section addresses the design strategy for the proposed Gantry system. The design strategy divides the total amount of the Gantry assembly's parts into four categories, where each contemplates a major type of part. The referred categories are: strategic parts, core parts, purchased parts, and lastly consumables.

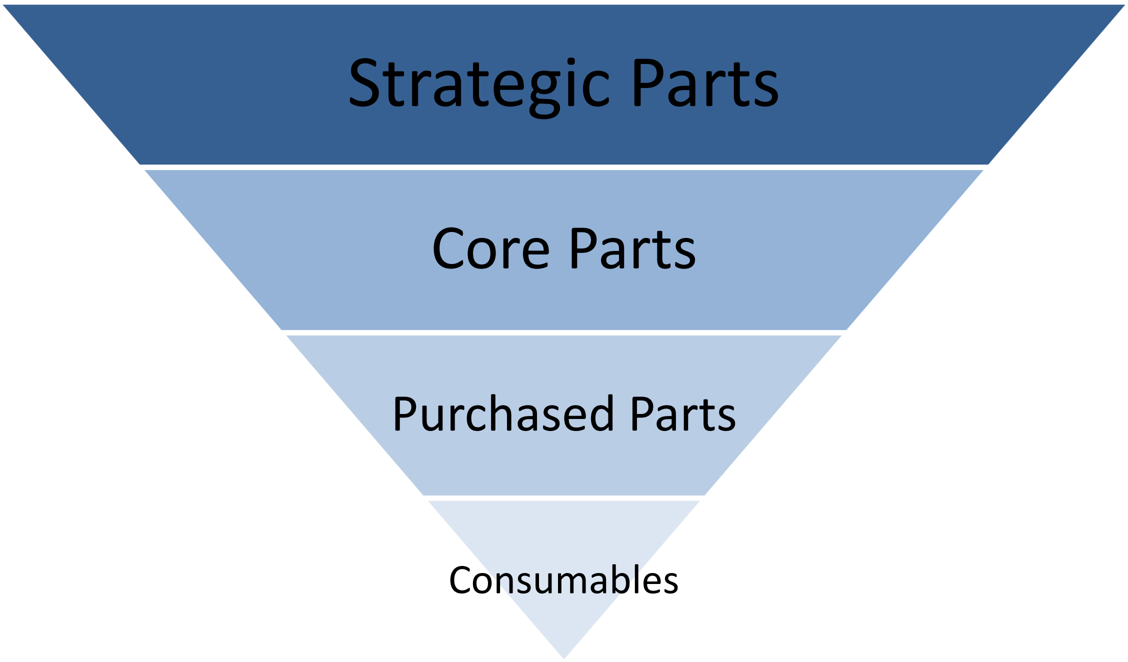


Figure 6-32: Design Strategy Pyramid

Strategic parts are related to products or variations of the main product, in this case a Gantry, from the baseline model or business model. In this context, it is considered that this field corresponds to special orders, where a high degree of customization is required and where the client is willing to pay the extra cost related to the specific product variation.

The core parts correspond to the extruded beam elements that consist of the structural parts. The list of parts that belong to this category is the one in the green section on the Table 6-3, in the previous section. They are considered as core parts in the way that the gantry's size and structural performance depend directly from their profile dimensions. The main profile beams also have the purpose of allow a diverse combination of fitted accessories, due to the potential of the outer flanges to perform direct joints. This way, they have also a core role in the customer's customization and simplification of assemblage regarding the Gantry's accessories.

The purchased parts are related to the feasibility of the Gantry solution. These parts are outsourced to suppliers. In this case, they correspond to the ones that enable the connection between all the Gantry's core parts. In the Table 6-3, the purchased parts (excluding the accessories) are listed in the second half in light orange. Notice that, as mention before, the brackets were considered as outsourced parts. Although, since they are produced recurring to extrusions, the company can produce them in the same plant as the beams.

The consumables resemble to all the bolts, nuts and washers that are required for all the joints. These parts were not listed in the present work because the bolted joints were not dimensioned. All the logistics and materials required to perform the packaging of all the parts or the sub-assemblies are also considered consumables.

6.2.2 Sub-Assemblies and Transportation

A Gantry is not totally assembled on site, where is going to be installed. It arrives in modules, which are assembled there. The traffic only needs to be interrupted for the Boom's fixation to the Legs, which are already attached to the Foundations. So, it is important to understand which the main sub-assemblies are, if they can be transported as one and when and how they should be connected.

***Sub-Assembly 1*: Left Boom Module**

This Sub-Assembly corresponds do the left module of the total Boom assembly. For the designed 30m span configuration it contains seven Diagonal Beams.

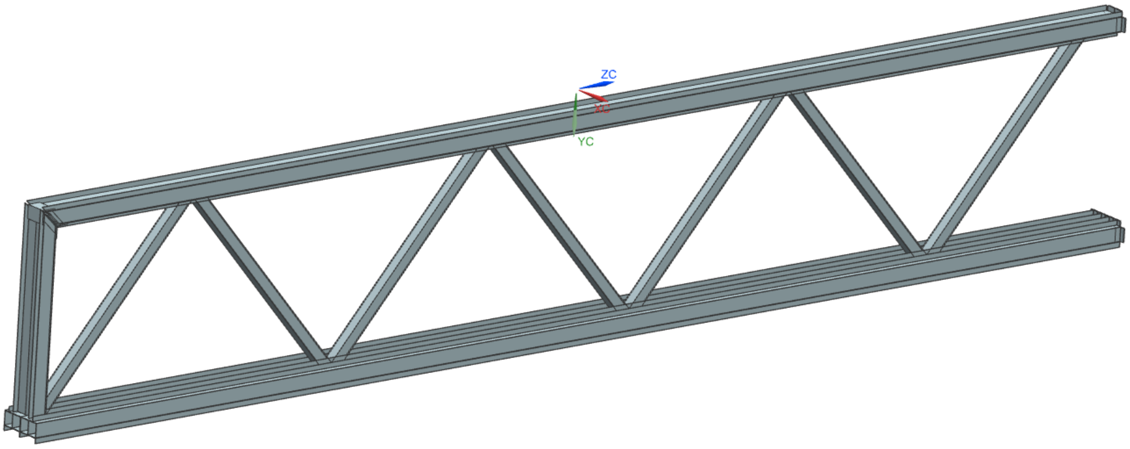
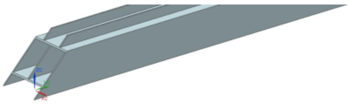
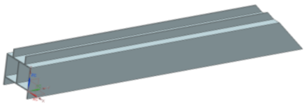
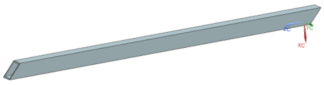
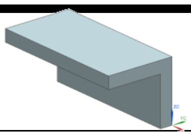
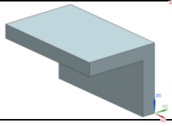
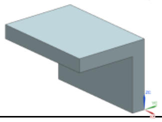


Figure 6-33: ***Sub-Assembly 1*****: Left Boom Module**

Below, is presented the list of parts that this Sub-Assembly contains and their correspondent quantity.

Part Name	Image	Quantity
Bottom Beam Left		1
Bottom Beam Right		1
Top Beam Sides		1
Vertical Profile		1
Diagonal Beam		7
Bracket 1.1		6
Bracket 1.2		4
Bracket 1.2.1		10

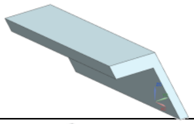
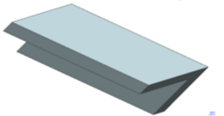
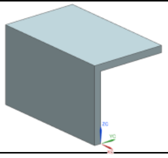
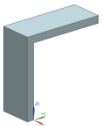
Bracket 2.1		2
Bracket 2.1.1		2
Bracket 3.1		1
Bracket 3.1.1		2

Table 6-4: List of Parts of *Sub-Assembly 1*

This Sub-Assembly can be transported to the installation site as one piece, as well as the other Boom assemblages. This subject will be resumed after the third Boom's Sub-Assembly is presented.

Sub-Assembly 2: Central Boom Module

This Sub-Assembly is the central module of the Boom. It has five Diagonal Beams as the next figure displays.

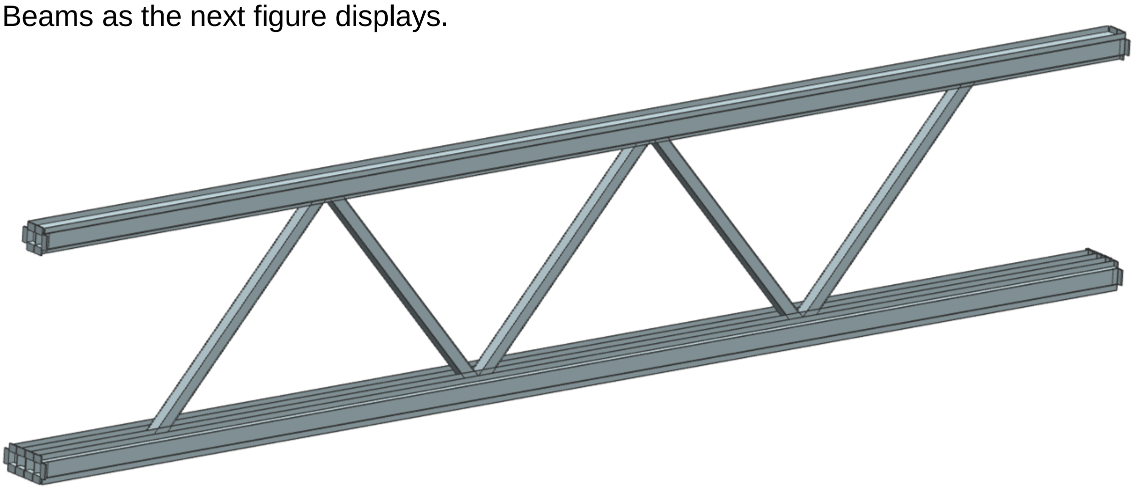


Figure 6-34: *Sub-Assembly 2*: Central Boom Module

The table with the parts that the *Sub-Assembly 2* gathers is presented below.

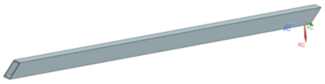
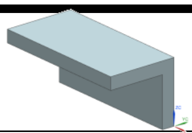
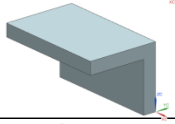
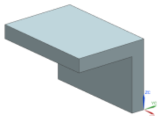
Part Name	Image	Quantity
Bottom Beam Central		2
Top Beam Central		1
Diagonal Beam		5
Bracket 1.1		8
Bracket 1.2		8
Bracket 1.2.1		16

Table 6-5: List of Parts of *Sub-Assembly 2*

Sub-Assembly 3: Right Boom Module

This Sub-Assembly is the right module of the Boom and it has seven Diagonal Beams. A figure representing it and the table with its parts are presented below.

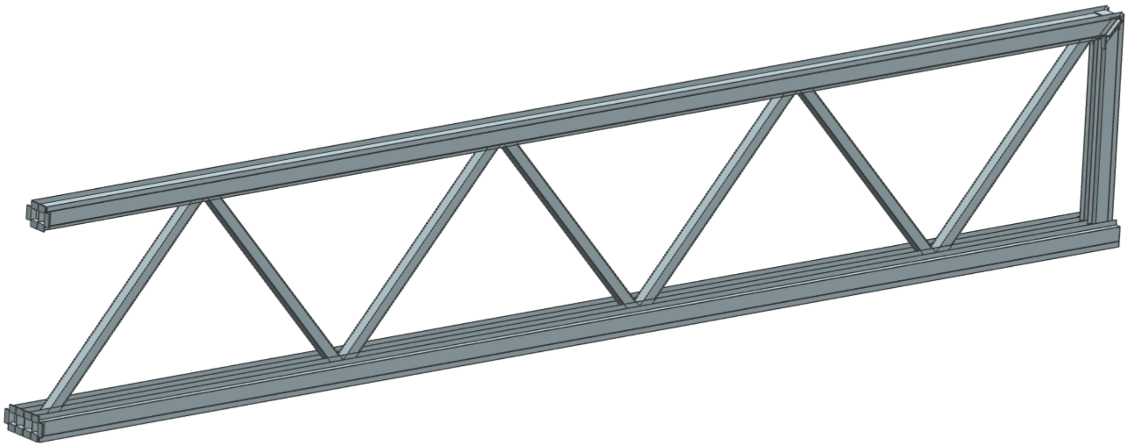


Figure 6-35: *Sub-Assembly 3*: Right Boom Module

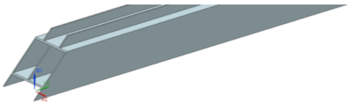
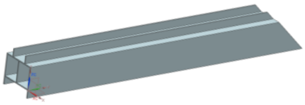
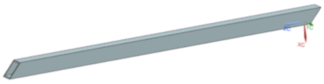
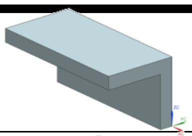
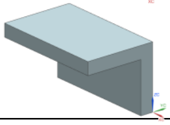
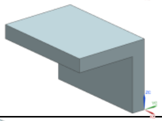
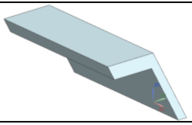
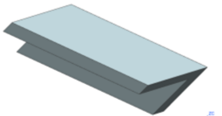
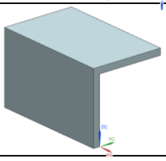
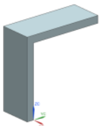
Part Name	Image	Quantity
Bottom Beam Left		1
Bottom Beam Right		1
Top Beam Sides		1
Vertical Profile		1
Diagonal Beam		7
Bracket 1.1		6
Bracket 1.2		4
Bracket 1.2.1		10
Bracket 2.1		2
Bracket 2.1.1		2
Bracket 3.1		1
Bracket 3.1.1		2

Table 6-6: List of Parts of *Sub-Assembly 3*

As it can been observed, this Sub-Assembly contains exactly the same parts in the same quantities of the *Sub-Assembly 1*. This can be explained due to the Boom's symmetry. But this is considered as a different sub-assembly because of the position of the Diagonals, which makes the two modules different. Regarding the transport of the Boom's three Sub-Assemblies, an overlap is recommended like the one proposed in the following figure. Notice that these sub-assemblies can be transported already as one piece, but in order to protect the exposed flanges, there must be an offset between each two consecutive piled sub-assemblies.

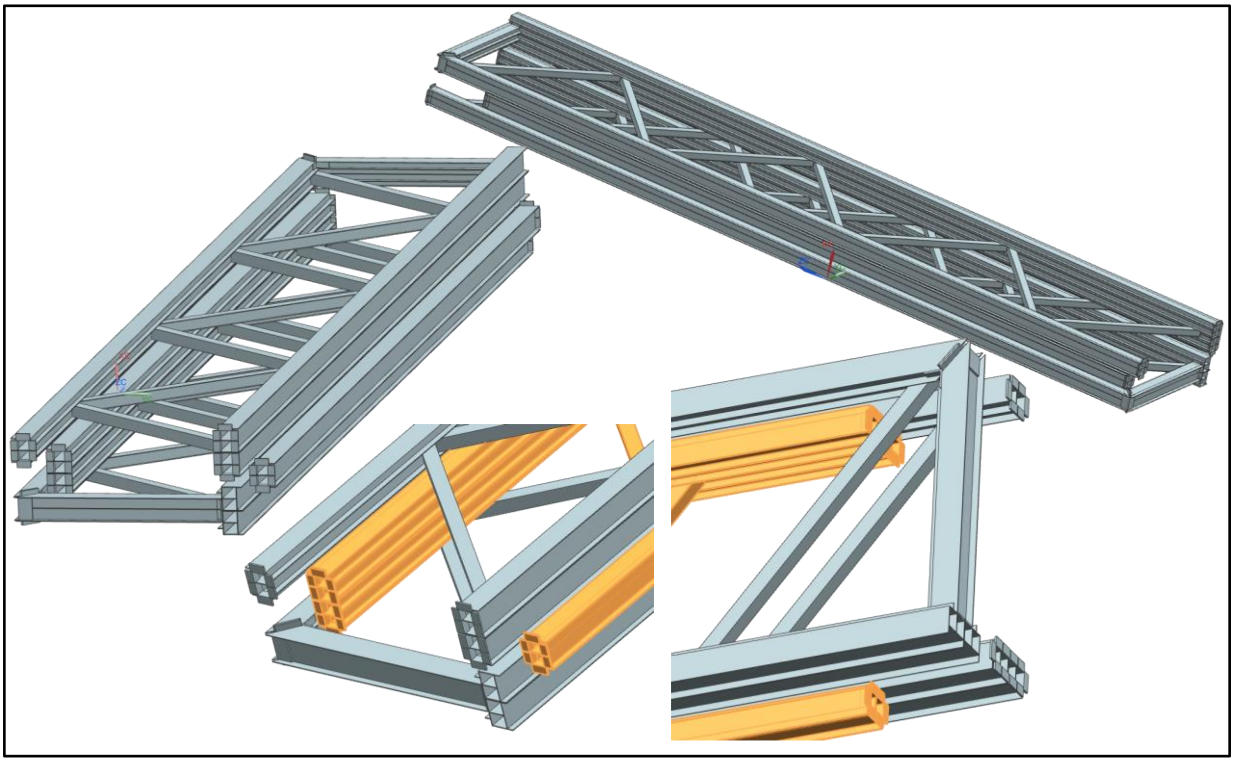


Figure 6-36: Boom's Sub-Assemblies transport configuration proposal

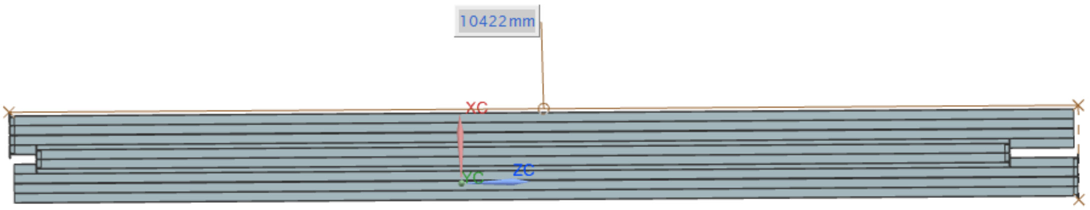


Figure 6-37: Boom's Sub-Assemblies transport configuration proposal: Total length

Sub-Assembly 4: Leg Module

Lastly, the Sub-Assembly that forms the Leg set is going to be addressed. This is a simpler assembly regarding the total number of parts, as can be assessed by the table with the parts' information.

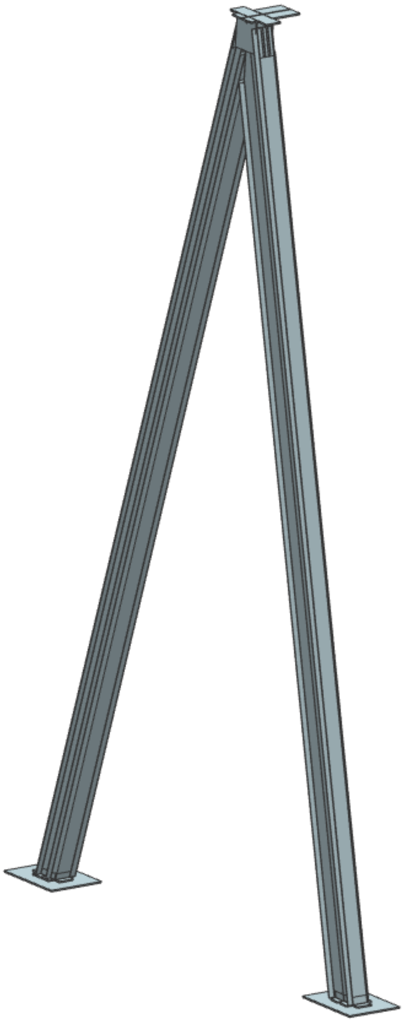


Figure 6-38: *Sub-Assembly 4*: Leg

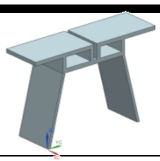
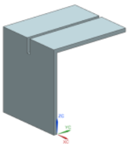
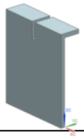
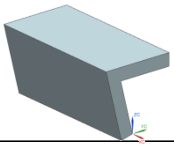
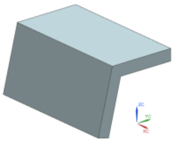
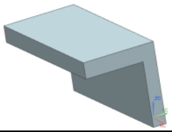
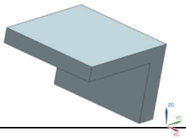
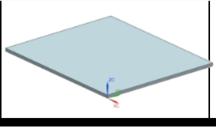
Part Name	Image	Quantity
Leg		2
Bracket Leg		1
Bracket Leg Inner Side		1
Bracket Leg Outer Side*		1
Bracket 4.1		2
Bracket 4.1.1		2
Bracket 4.2		4
Bracket 4.2.1		4
Baseplate		1

Table 6-7: List of Parts of the *Sub-Assembly 4*

* The presented Leg Set (the *Sub-Assembly 4*) was referred to a Side Leg Set, thus it contains one "Bracket Leg Inner Side" and one "Bracket Leg Outer Side". Obviously, the Central Leg Set has no "Bracket Leg Outer Side" but two "Bracket Leg Inner Side". In order to avoid the repetition of the information exposed in this section, this small variation was neglected and it was presented only one Sub-Assembly type for the Legs.

Regarding the transportation of each Leg Set, it is proposed that it should be done without the sub-assembly already fully mounted. To optimize the space, it is proposed that only one Leg is attached to the Leg Bracket (and both Legs to the correspondent base brackets, excluding the baseplates). This way, the Legs will be transported separately.

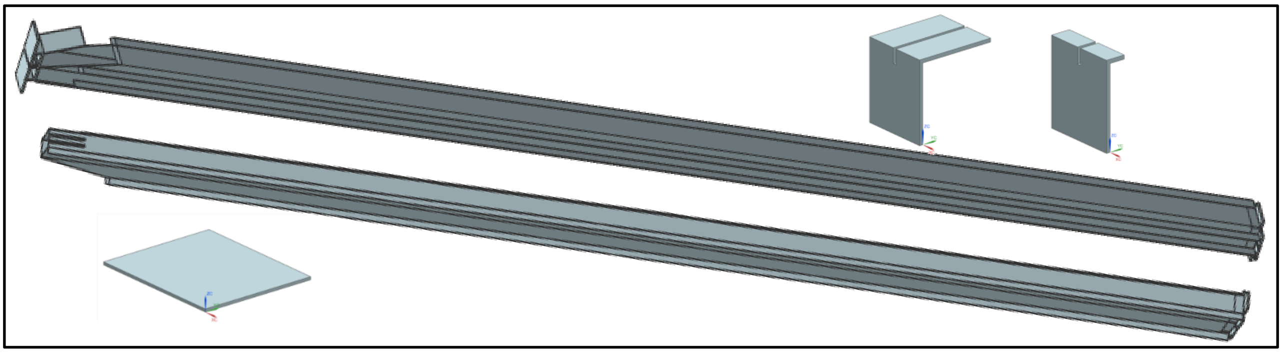
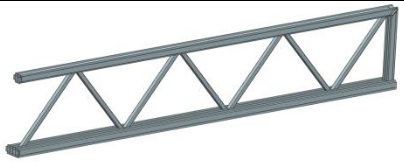
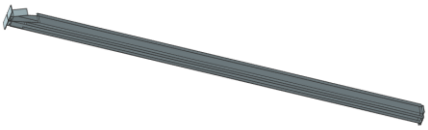
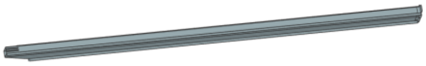


Figure 6-39: ***Sub-Assembly 4*** **transport configuration**

The following table resumes the total independent parts (sub-assemblies or singular parts) to be transported to the installation site.

Transported Part Name	**Image**	**Quantity**
Sub-Assembly 1		1
Sub-Assembly 2		1
Sub-Assembly 3		1
Sub-Assembly 4: **Leg1 + Leg Bracket +** **Base Brackets**		3
Sub-Assembly 4: **Leg2 + Base Brackets**		3

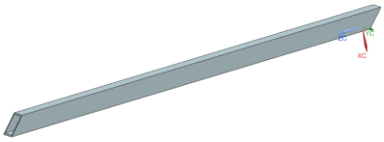
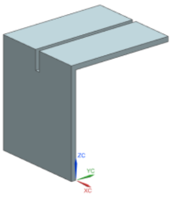
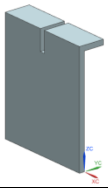
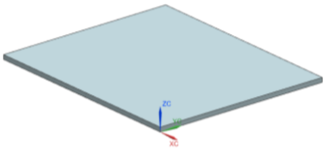
Diagonal Beam		2
Bracket Leg **Inner Side**		4
Bracket Leg **Outer Side**		2
Baseplate		6

Table 6-8: List of Parts to be transported

Regarding the installation of the Gantry, the main steps are going to be addressed. To assemble the Boom, each module is connected by one Diagonal (highlighted in the next figure) and by the external bolting of the brackets.

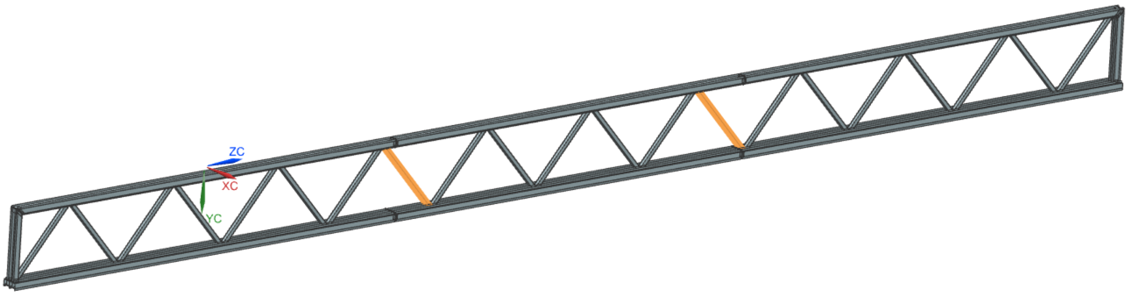


Figure 6-40: Assembled Boom

For each Leg Set, the free Leg (*Leg2*) should be placed in the Leg Bracket (already fixed to the other Leg (*Leg1*)), and then the Inner and Outer Brackets should be bolted. The Baseplates are also ready to be fixed and then each Leg Set can be attached to the correspondent Foundations, as the following figure suggests.

Figure 6-41: Assembled Leg Sets

The *VMS*(s) should be placed with the Boom still on the ground, to ease the procedure. The remaining task is the most complex one requiring the traffic interruption. To place the Boom on top of the Leg Sets, it is lifted by a crane and positioned until the top of all Leg Brackets mate with the inferior surface of the Boom's Bottom Beams. Then, this connection is bolted and the Gantry is assembled and installed.

6.3 Modularity: Possibility of Multiple Sizes

The annual production of *Lattix* Gantries is relatively low. Therefore, the company follows a *Pull* strategy, where the production starts only after a client's order (contrarily to a *Push* strategy, where the products go to stock before being sold).

Each order from each different client needs to cover slightly different requirements and consequently multiple Gantry sizes must be provided. A modular concept would provide some advantages as the possibility to move the production from an engineer-to-order approach to a more efficient configure-to-order approach. Aiming this, the products need to be designed for modularity. As an example, what if a customer orders three 30m span Gantries, but, besides a 30m, one of them must have 28m and other 31m? The proposed design offers the possibility of these small adjustments by the tuning of three parameters:

- Main Beams' Lengths;
- Number of Diagonal Beams;
- Diagonals Beams' Angle and Length.

In the manufacturing stage, the transversal cuts after the extrusion must be adapted to these span (or height) variations, so the Main Beams' lengths can vary. This does not represent an additional work load, because the cuts are exactly the same. The difference is that we are using more or less material. Then, to meet the increase or decrease on the total span, the number of Diagonal Beams must integer. This way, by removing or adding one Diagonal (or more), their angle (and consequently their length) must be adjusted in a matter than the Diagonals' configuration results in an angle as close to 45º as possible (as the baseline models have). This is also a zero additional labour cost operation, since the only variables are the Diagonal's extrusion length and the cutting angle, neglecting the fact that we're adding or removing one or two Diagonals. The adjustment of the Diagonal Beams must consider the location of the Boom's horizontal joint sections, because they cannot coincide with the brackets.

The approach to comply with different size adjustments, inside the same order from one client, was described so far in this section. This considers relatively small adjustments, since the original design was optimized for the baseline span (and height) target. If the demanded variation in span is quite relevant, the alteration of the members' section sizes must be considered.

The dimensions of all the brackets used in the proposed Gantry design are dependent of the beams' section dimensions. This means that the redesign of the profiles implicates also a redesign of the brackets' profiles, or at least a difference in their lengths. Another characteristic of the design is that the main profile is dependent of the Diagonal's profile width. The top surface of the main profile must consist of half the Diagonal's width, a flange, the Diagonals' width, the other flange and again, half of the Diagonal's width, respectively. This means, that a major part of the design is dependent on relations between the different elements. Therefore, an implementation of a program that automatically could redesign the new ordered Gantry would be very interesting and relevant to the company. It is being suggested the implementation of a *software* that recurring to the structural analysis suggests the minimum stiffness required, and then designs the main sections, in order to comply with the relation between the main profiles and the Diagonal beams. Lastly, all the secondary parts, in other words, the brackets, would be updated to fit the new sections. This implementation would enable the reduction of some hidden costs related to the redesign of current solutions, in order to comply with new orders, and with the organizational structure and chain of information from the order to the production plant.

Concerning the cost opportunity of redesign the sections to comply in an optimized way to every new order, the number of ordered Gantries is the main factor to consider. Here, the ruler is the extrusion Dies' life. For example, if each Die has the capacity of extrude the beams equivalent to five Gantries, this should be the minimum order size that justifies the built of new Dies, due to the alteration of the profile sizes. In short, depending on the order (quantity of Gantries and sizes) it must be assessed the original redesign of the sections and the adjustments to comply with size variations, if that is the case.

6.4 Flanges: Possibility of External Fittings

This section is dedicated to address the advantage of using the same profile for the Main Boom Beams and also for the Legs.

The main profile was designed with the goal of make the connection of the Boom's main beams with the Diagonals and also to laterally attach both Bottom Beams. As a result, since there is only one main profile, there are many flanges that have no use in certain members, since in all the main beams not all the flanges are used to connect members. This gives the potential to the *Model III* Gantry's design to include fittings, without adding parts, for external accessories like lighting, a ladder, a walkaway and more importantly, to ease the fixation of the *VMS*s or other signs.

The main potential fittings for accessories will be addressed below.

6.4.1 Attach a Ladder

A ladder can be mounted in one Leg, from any of the Leg Sets, using the outer flanges. The basic fittings can be made by the drilling of holes in the flanges enabling bolted connections to the accessory parts.

This would originate an angled ladder (76º in this case) where the user could climb in an erected position. This represents a safer and easier ladder, than the mostly used in current Gantry models, which are vertical and require the use of the hands. The Ladder can be fixed in the most desired Leg, according to the preference of the offset between the flanges, as the figure 6-42 shows.

6.4.2 Attach a Walkaway

Following the same reasoning of the previous section, a walkaway can be fixed on top of the Boom's Top Beams or/and on top of the Bottom Beams. The fixing points would be equally located at the non-used flanges, as the figures 6-43 and 6-44 suggests.

6.4.3 Attach *VMS*s, Signs or Illumination Devices

Lastly, for the attachment of illumination devices or for the support structures for Signs or *VMS*s, the Boom's flanges can also be used. The figure 6-45 demonstrates these fitting opportunities.

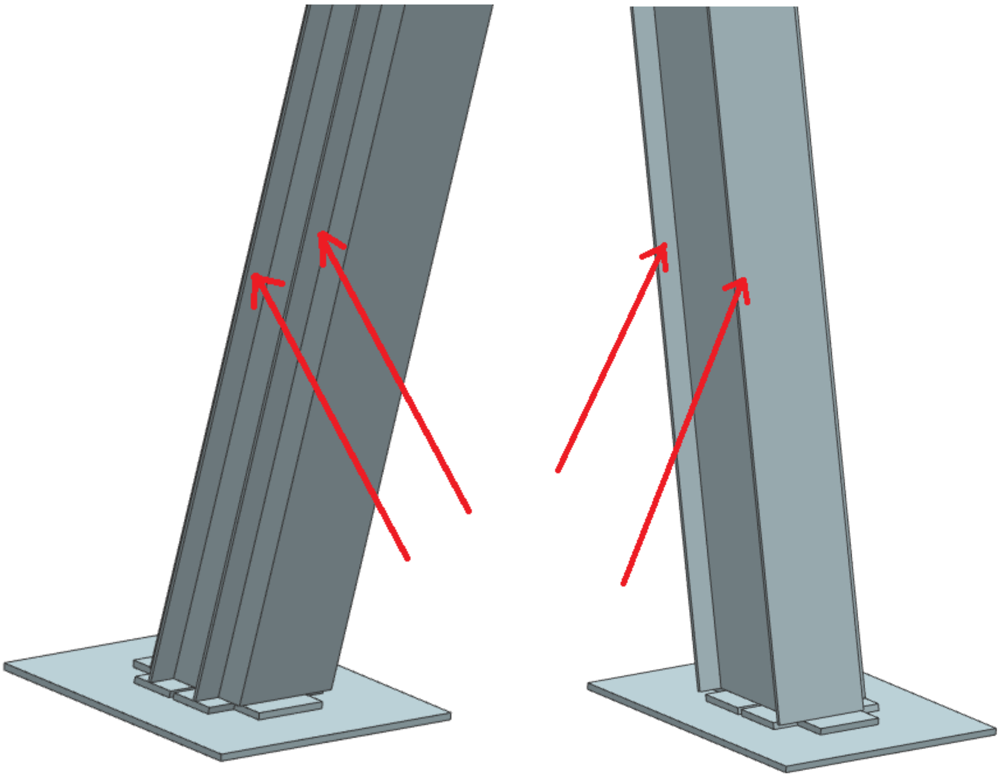


Figure 6-42: Ladder fixing proposal: Legs' flanges

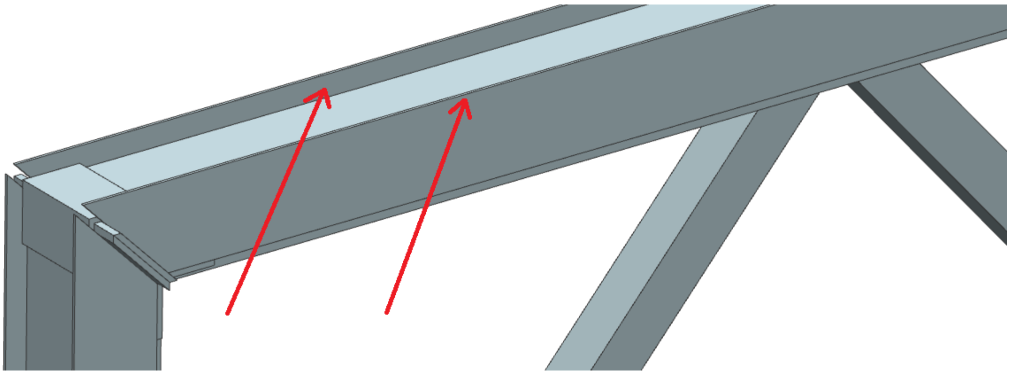


Figure 6-43: Walkaway fixing proposal: Top Beams' flanges

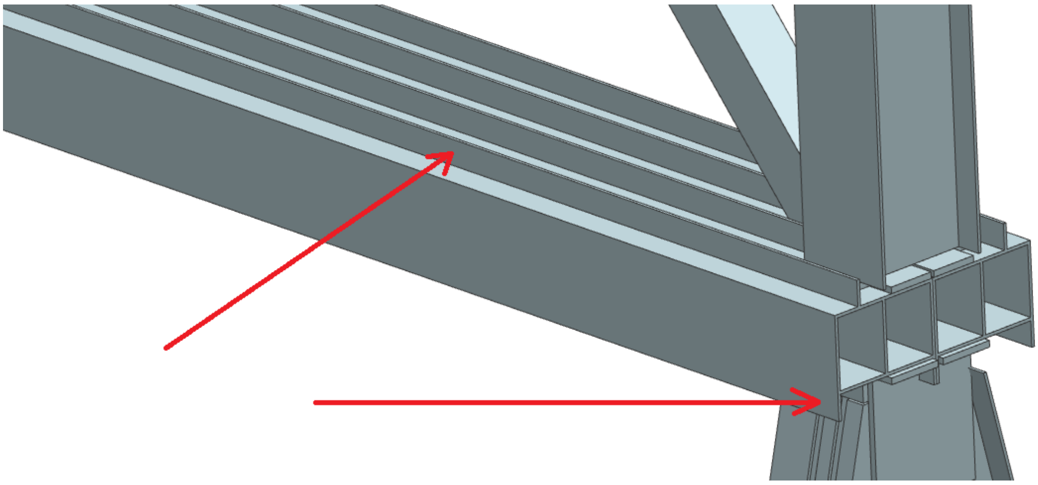


Figure 6-44: Walkaway fixing proposal: Bottom Beams' flanges

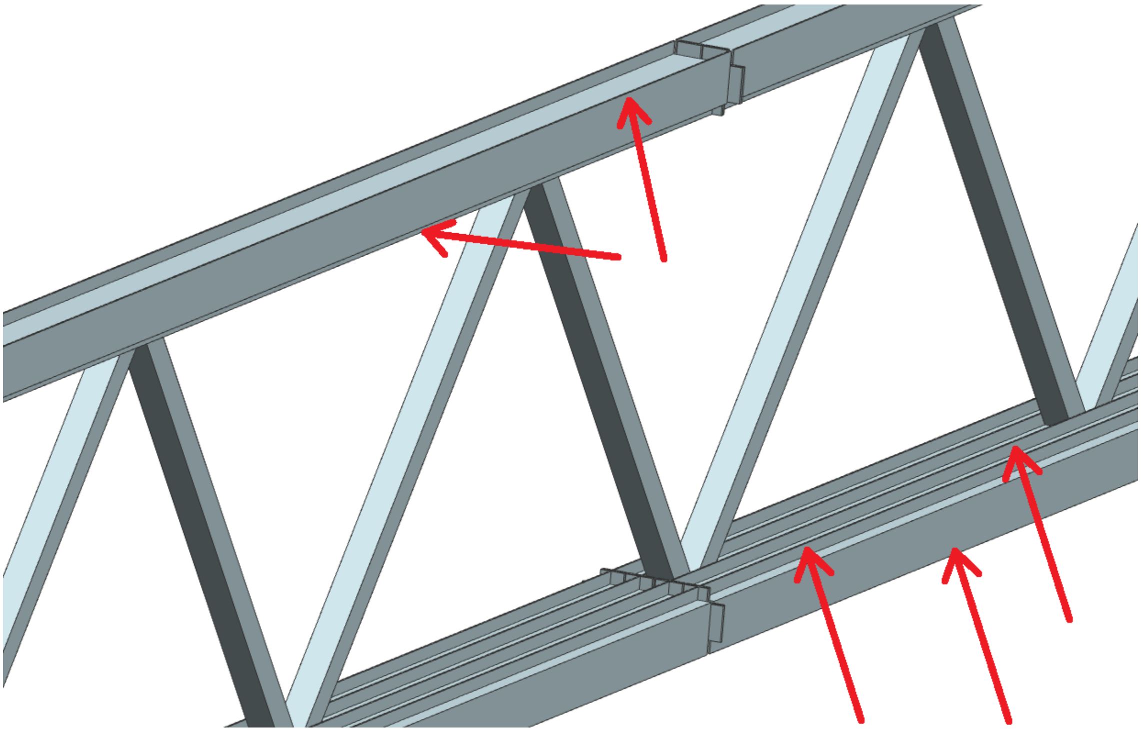


Figure 6-45: *VMS*, Sign or Illumination devices fixing proposal: Boom's flanges

In short, the design of the main profiles (presented in the section 5.1.1), with the use of outer flanges, enable this Gantry model proposal to have a lot of potential for customization, regarding its purpose and the customer's desire. The flanges allow the possibility of a vast number of fittings practically anywhere on the Gantry's structure, being this way, an easy and low cost method for comply with the vast majority of accessory related needs and requirements from each customer.

6.5 Gantry's Recycling

Recycling used materials consists of a very important task, due to the positive impact on the environment, by reducing the production from scratch of the same materials. This way, it is possible to decrease energy consumption, thus reduce production costs and emissions. Regarding aluminium, it is a recyclable material, where only about 5% of the original energy used to its production is spent (source: www.aluminium.org).

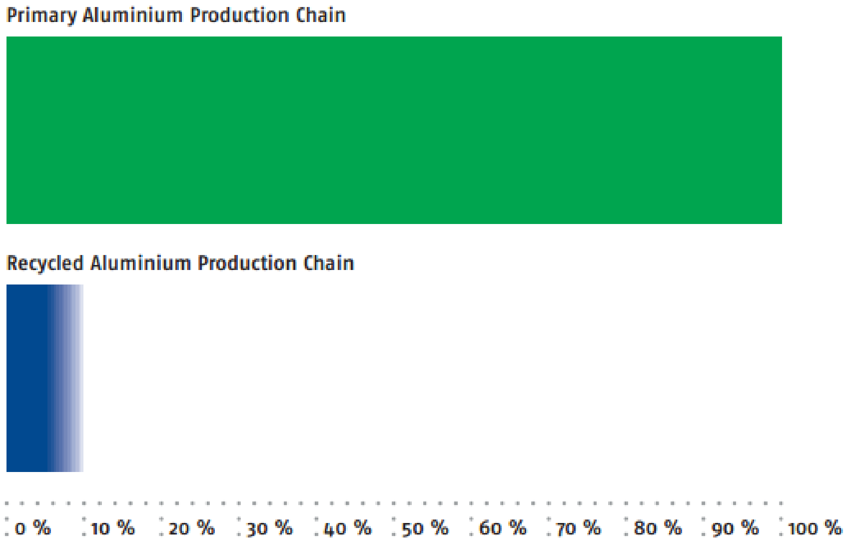


Figure 6-46: Energy Needs for Primary and Recycled Aluminium Production – ***in www.aluminium.org***

This way, aluminium scrap has value, since it is used to produce new aluminium billets. This fact motivates entities to recycle, contributing positively for the environment for the reasons previously addressed. An average scrap value for extruded aluminium can be around 0.90$/kg (0.67€/kg) (source: www.evelynrecycling.com.au). This means that, regarding the recycling of a Gantry system with 2500 kg of aluminium parts, it could be recovered 1675€ (considering the scrap value previously presented).

The design include the secondary parts, namely all the brackets and baseplates, made from an aluminium alloy, as mentioned before. Therefore, the total Gantry's scrap value is being majored, since the aluminium scrap has higher value than steel for example (values for stainless steel scrap can be found in the order of 0.60$/kg). Also, the recycling process is being eased, since all the parts can be recycled in the same plant. The elements that need to be independently recycled are the bolts and nuts, made of steel, and the signs' or illumination devices' materials, which can be very diverse. The accessories like the ladder or the walkaway, being made from aluminium, also contribute for a more efficient recycling and increase the return value of the Gantry in end-of-life.

7. Discussion of Methodology

7.1 Uncertainties

This chapter is dedicated to summarize the uncertainties that were raised after and during the application of the presented methodology in this work.

1. **Hollow box sections approximations:**

In order to enable a quick tune of the sections of the models proposed by the author, it was frequently used hollow box sections for the beam elements. For the purpose of this study, this does not imply a big error. But, if the designs were all further developed and “real” sections applied to them, the predicted relative cost results could vary something. The problem is that the iterative process of dimension the sections until achieving the same range of displacements for all the models, tuning the section with real profiles would be much more laborious. It was considered that to develop all the models, in order to have realistic sections to compare, was not worthy, due to the disparity between the gains in accuracy and the required add of workload. When, on the other hand, with box sections, the *software* allows a quick tune without have to remodel the sections.

2. **Immense possibilities when tuning the sections:**

The process addressed in the previous topic, besides being iterative, has many degrees of freedom: for each different profile, the width (B), height (H), and thicknesses of the horizontal (t_B) and vertical (t_H) walls (considering a hollow box section). This means that each iterative tune towards achieving the displacement target has a huge amount of possible adjustments.

It is considered that, for all the models, probably there are further section dimensioning configurations that would enable an equally stiff structure (or more) and a less utilization of material, leading mainly to slightly different material cost result.

3. Static analysis neglect stability problems:

The *FEA* performed to dimension the sections and verify the maximum displacements were static analysis (using beam elements). This means that any eventual stability problem is neglected. This required some good sense on the proportions used between the profile's walls and their thicknesses, in order to avoid eventual buckling problem in real life. A manual verification was performed only in two cases were the *VMS* load was transferred directly to the central Leg resulting in high compressive forces.

4. Lack of real inputs for the cost models:

Other relevant issue that relates to the cost models are the input cost parameters that the comparison is based one. The big majority of the values are assumed due to the lack of information. The relevance of this uncertainty lies in the comparison between the *Model W* with the remaining ones (that share the same input parameters), because it uses different cost inputs like for example welding productivity and labour cost. The remaining models, by depending on the same input values, have the same relation between their costs, which was the goal of the cost analysis and not the achievement of real final cost values.

5. Cost Breakdown only considers costs dependent of the structural configuration:

The cost comparisons only take into account the type of costs that are directly influenced by the Gantry models' structural configurations. This approach is neglecting many other cost types, like installation or the secondary parts' costs (like brackets or plates for the member or modules' connections). To include this type of costs would require a detailed design development for all the models, in order to assess the type of parts needed, as well as their design and production.

6. Cost Breakdown does not account the production costs of the *Lattix*'s masts:

The *Lattix*'s masts used in the *LWG 1000* Gantry models have a major production phase after the extrusion, which enable to form the characteristic "X" pattern to the masts. The production costs in the implemented cost model only considered transversal cuts and drilling operations (for the bolted connection between the main beams with the Diagonals). This way, the production cost of the *LWG 1000* would be higher than the considered, being the referred operations neglected due to lack data. But, since this is the baseline model, the relative results between the compared Gantry models will remain the same.

7. Lack of a complex *FEA* to the 3D total Gantry assembly:

After the development of the selected concept (*Model III*) and its detailed design, including all the parts needed to the feasibility of the model, it is relevant to study its detailed structural performance. With the 3D *CAD* of all the total assembly, a *FEA* takes a huge amount of time and require a very good computational performance. The justification to this is the big number of total parts that originate an enormous quantity of contact surfaces required for a contact and bolt analysis. Other very time consuming task, which this analysis requires, is the meshing of the model, with a good quality mesh that gives accurate results and at the same time does not contributes in excess for the total required computational solving time. It is also relevant to perform a stability analysis for different load cases.

8. Dimension of the bolted connections and brackets:

One major task that was left to be done was the dimensioning of the bolted connections. By assessing the type and magnitude of the forces at each connection, the number and the normalized bolts' sizes can be determined. The thickness and area of the brackets is also dependent of the bolts' dimensions and required quantity per joint. The design of all the connections should be done in a way that the Gantry structure only requires two or three bolt sizes. Consequently, instead of having a bolt size for each different connection, by ordering more bolts from the same type the purchasing cost can be slightly lower and the assemblage simpler.

Since this is naturally a mandatory step for the design of any structure recurring to bolted connections and the focus of this work is the methodology behind the evaluation and development of a Gantry concept and the solutions present in it, the bolts' dimensioning was left to be done.

9. **Realistic cost assessment of the detailed design and comparison to the *LWG 1000*:**

Lastly, a realistic cost assessment should be performed to the detailed design. This includes real values for the production of such parts, real assembly and installation time and costs and other hidden costs that experienced engineers and technicians may encounter.

7.2 Weaknesses of the Model

Along the development of the Gantry concept, the decisions made were justified and their positive impacts enhanced. Therefore, it is also necessary to focus on the main weaknesses that the chosen solutions represent and make a summary of them.

The main weakness of the *Model III* is its Boom's low horizontal stiffness when compared to the high vertical stiffness. This is a direct trade-off from the lightness and the reduction of the correspondent costs that the Boom's configuration implies. This aspect requires a more detailed analysis to the structure's stability, namely regarding the Diagonal beams' dimensions as well as the overall Boom's torsional resistance. This factor is counteracted by the dimensioning of the main profile, which should enhance its horizontal principal moment of inertia, and the double beamed Boom's bottom, which doubles the horizontal stiffness. The shape of the Legs, namely their angle, also contributes to minimize this weakness, in a way that the Legs can carry axial forces from the Boom's horizontal loads.

With the latter part of previous paragraph, the next characteristic considered relevant, which can be taken as a weakness, arises: the sensibility to the presence of a central Leg set. In other words, the *Model III*'s versions with larger spans reveal a much larger benefit and lower cost if they contain a third Leg set. This way, the presence of the extra Leg set is almost a requirement to achieve the best results on cost reduction and Boom's light-weight. The central Leg, besides allowing a reduction of the Boom's sections, reinforces it, since the central Leg set enables a more direct load flux mostly of the horizontal loads from the *VMS*'s wind pressures, from the *VMS*'s supports to the ground.

The last weakness is the dependency of the beams' connectors from the profiles' dimensions. This means that the redesign of the sections, in order to comply in an optimal way to a new size ordered, also imply the proportional redesign of the connecting brackets. This weakness can be overcome with the prediction of the die's working life. If a new order implies the manufacture of new dies for the main profiles (main beams and diagonals), it also requires the manufacture of new dies for the brackets (independently if the brackets are outsourced or not). So, the dimension of the order should be consistent with the dies' life, in a way that after the manufacture of all the parts correspondent to the last Gantry (from one order), the dies are at their end of working life. Therefore, a new order, or in order words, for the manufacture of the next Gantries, either with the same section sizes or with their redesign, the manufacture of new dies is required. This way, the change of the die's dimensions would not affect the production costs. Naturally, this reveals a weakness in a way that is not possible to coincide all the orders (number of total parts necessary to be manufactured) with the dies' life. This aspect requires a study regarding the logistics of the production plant, concerning the possibility of using the remaining effective dies for produce parts for stock, for example.

A proposal to avoid the constant redesign to better comply in the most efficient way to new ordered sizes is a simple product matrix, where the sections are dimensioned for the 20m span case. Then for orders of in the range of 30m spans, the same sections could be used, considering the use of a central Leg set. This dissolves in part the advantages of the use of a central Leg set, since, as it was observed during the dimensioning of the models, it enables a significant reduction of the sections, even comparing with the 20m span case. So, using the 20m version's section on the 30m with third Leg set would result in remaining potential to improve the weight reduction. This way, a most detailed cost analysis from a practical point of view should be done. Namely, if it is better to redesign in the more efficient and optimal way the sections when the span is changed or use the sections for the smaller span versions without central Legs, which besides not representing the optimal solution, does not require the change in the profiles manufacture, or in the connecting brackets.

8. Overall Experiences

Across the entire globe, there is a huge network of road transportation including roads and vehicles. The optimization of space available for roads and minimization of traffic congestion, while ensuring road user safety represents a major issue in today's society. This issue is dealt by the traffic management. Traffic management includes mainly legislation and support structures, which carry the informative devices to the users.

Lattix develop structures for traffic management purposes such as Gantries Cantilevers and Masts. Their products offer competitive, light-weight solutions to the customers. Although, a major issue is raised, mainly regarding the Gantry products: the total cost. The target is to reduce cost. High cost arises due to complex production processes, lack of standard solutions and high customization costs. Therefore, a new Gantry concept that considers these challenges and aims to minimize the cost would represent added value for *Lattix* and its customers.

The first stages of a product development process involve recognition of the problem, needs and requirements both from the customers and from the company that is developing the product. After identifying the major problem of the current Gantry solution, all the requirements that the design must comply with are listed and their importance is rated, understanding the major role of the costs.

Some Gantry concept models were proposed and compared against *Lattix*'s current model, the *LWG 1000*, which was the reference for all the evaluations performed. A concept proposed by *Lattix* and a current Gantry solution from a competition company (*Model W*) were also added to the comparison.

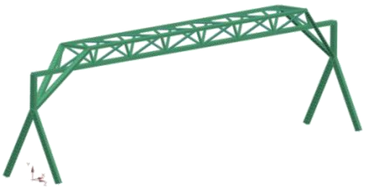


Figure 8-1: ***Model I***

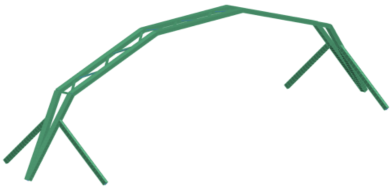


Figure 8-2: ***Model II***

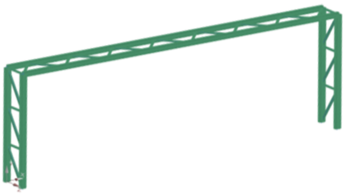


Figure 8-3: ***Lattix's concept***

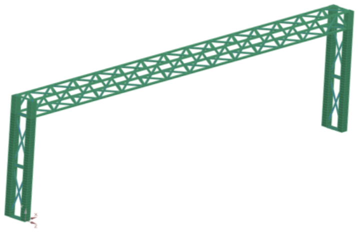


Figure 8-4: ***LWG 1000***

Figure 8-5: ***Model W***

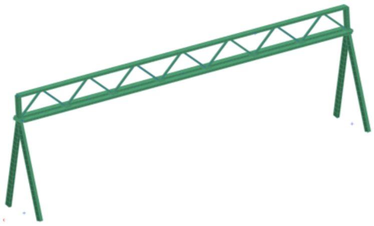


Figure 8-6: ***Model III***

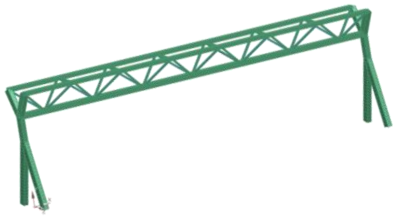


Figure 8-7: ***Model IV***

With these seven models, different structural configurations could be evaluated relative to the baseline's values regarding two major aspects: a cost breakdown and a benefit assessment. Having the two evaluations performed, it was possible to assess the value of each model by examining the ratio between the benefit and the cost. This methodology was performed for three cases based on the Gantry's span: 20m, 30m and 30m with a central Leg set.

Prior to the cost assessment, the models' sections had to be dimensioned to comply with the allowable displacements range, for the corresponded span case. Also, the models had to have roughly the same use of material, or in other words, the same range of displacements for the same load case. This would enable to establish a fair relation between the weights of each model.

The models' cost breakdown for each span case depended on several cost inputs, where some were given and others were assumed. However, since the *Model W* relies on the use of welding of aluminium sheets to extruded profiles, different cost inputs were required. Only the costs directly dependent on the structure configuration were considered. The results were read as a relative ratio to the baseline model.

The requirements were listed in a *House of Quality* matrix, where their relationships with the technical descriptors that define a Gantry system were assessed. Through this evaluation and from the rating of the requirements, it was possible to attribute a relative weight for each technical descriptor. The relative weights were used in the benefit evaluations, where the capacity of each model to fulfil all the requirements was assessed, through a *Pugh Matrix*.

After executing the described evaluations for the three span cases, it was possible to analyse the performance of each model based on three criteria: cost, benefit and value. Having in mind that the results were directly dependent of the cost inputs, type of costs considered, sections' dimensioning performed and rating of the requirements, one model could be seen as the best in the three cases: the *Model III*.

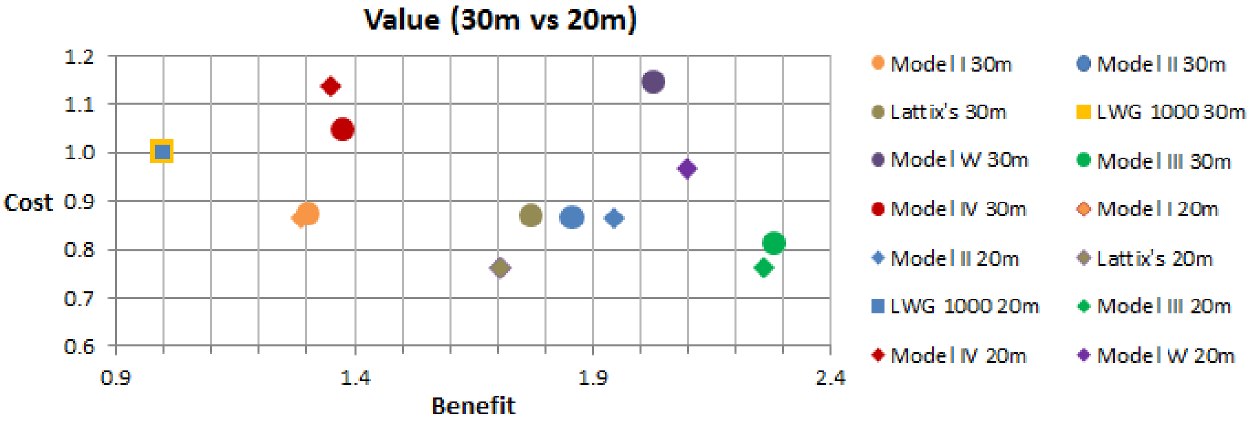


Figure 8-8: 30m vs 20m Span Model's Benefit vs Cost

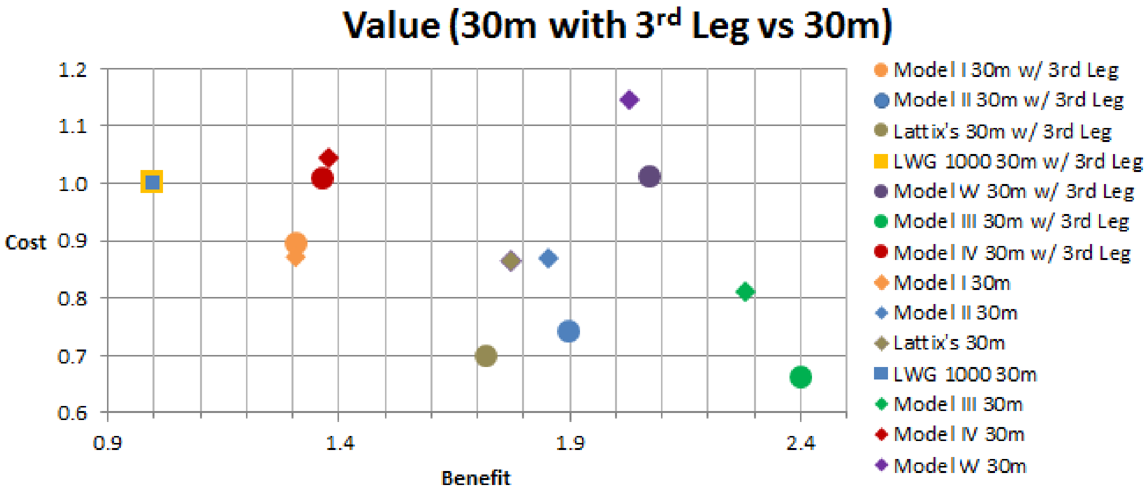


Figure 8-9: 30m with 3rd Leg vs 30m Span Model's Benefit vs Cost

The *Model III* consists of a Gantry concept with a planar Boom or, in other words, with a Boom with just one row of Diagonal Beams, vertically. The innovative feature of its design is that, in order to improve the Boom's low horizontal stiffness, the Boom's bottom part is formed by two main beams coupled laterally. This leads to a section that can be larger than the limit dimensions possible to extrude. It enables also higher stiffness where it is more needed, while maintaining just one main profile, thus saving die costs. Therefore, regarding beams, this model needs only two different profiles (thus two extrusion dies): one for the main beams from the Boom and Legs and other, much simpler, for the diagonals. Also the Legs are designed with the goal of reducing the horizontal displacements by being disposed in angle. This avoids excessive bending forces in the Legs while increasing the axial loads. The design considers the *VMS* supported and centred in the bottom beams, where the horizontal stiffness is higher.

Since, as a rule observed in the results, the models' versions with a central Leg set represent a solution with a value increase, the development of the *Model III* was applied to the 30m span with central Legs version. The *Model III* is particularly sensitive to the adding of the central Leg set because the Legs can carry most of the combined loads from the *VMS*. This factor enables a significant reduction of the main sections. A preliminary buckling verification was performed to check the maximum axial loads for the section considered.

The following step involved the conversion of an ideal model to a feasible one, where the connections between all the beams are considered and proposed.

The strategy behind the design of the Gantry's connections, with the goal of minimization of costs, considered four main aspects:

- Minimization of secondary parts' (connecting brackets) production costs and relying on extrusions as the main production operation;
- Ease of assembly;
- The transport of the sub-assemblies;
- Time required for the installation of site.

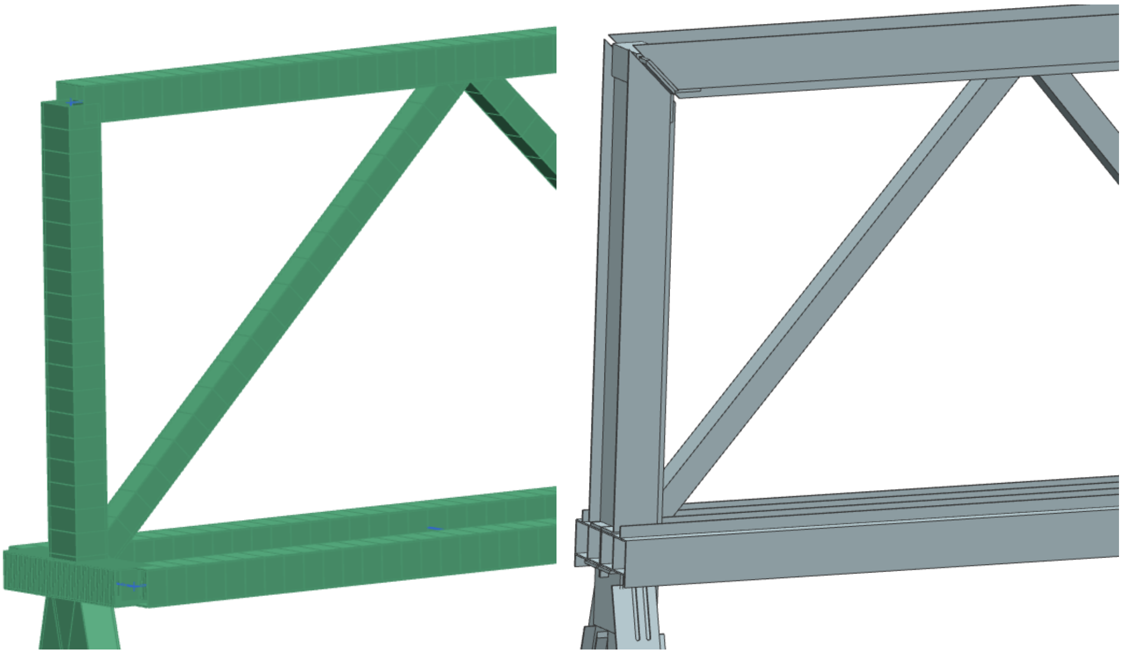


Figure 8-10: ***Model III*** **modelled with: beam elements and 3D with the connections designed, respectively**

A solution was proposed for each type of connection: from the diagonal beams to the main profiles, to the 90 degree joints, longitudinal connections of the Boom's modules, the Legs' connections with the Boom, etc. The proposed design suggests the use of extruded brackets that enable a direct fit between the beams, through bolted connections. The bolts were not dimensioned within the scope of this work. Therefore, the brackets' dimensions would depend of the required number and bolts' diameters, namely the thickness and the contact areas with the profiles.

The Gantry model was designed to require easy and simple alterations to comply with small changes in size. For instance, a customer order of five Gantries each differing in span by one meter, can be complied by the adjustment of certain operations in production. These adjustments include the length of the main beams and the angle and length of the Diagonals, in order to result in an integer number. Therefore, these are just tunings in the inputs for the operations after the extrusions.

A major change in the ordered Gantry sizes, between customer deliveries, implies an optimization of the sections, in order to comply with the maximum displacements requirements and keeping a light-weight solution, avoiding wasting material costs. The change of the main profile's sections directly influences the Diagonals' profile dimensions, as well as the brackets'. Therefore, a relation between all parts' dimensions can be found and used as a modelling tool.

9. Conclusion

9.1 Summary

This work consisted of a methodological evaluation of different Gantry concepts and the development of one model.

In the course of this work, the purpose of traffic support structures and mainly Gantries was addressed, namely their function and importance for the traffic management and road users' safety. Then, the main products for traffic support (gantries, cantilevers and masts) were presented along with the main structural configurations that a Gantry can be based on, namely frames and trusses.

The principles of mass-customization were introduced, as well as their importance to the product's value recognition from the customers. Afterwards, in the context of *Lattix*, the main production of such structures was addressed, as well as the preferred material. To conclude the introductory chapter, the type of connection methods was briefly described.

Then, the methods and approaches used as tools in the work were summarized: a cost model, the *House of Quality* matrix, which relates the requirements to the technical descriptor's importance, the *Pugh Matrix*, which is an instrument to compare all the models and define their benefit values and lastly the *CAD* and *FEM softwares*, which enable the virtual modelling and analyses of the concepts.

The work progressed with the listing of all the requirements that the design must meet, as well as their rating and relationship with the technical descriptors, which define the parameters of a Gantry model. The goal was to obtain a rate for their importance. Then, *Lattix*'s current Gantry model was presented, which acted as the baseline for all the concepts' comparison. The models used in the concept evaluation were introduced, as well as their dimensioning method. The cost breakdown was described and performed for all models and for three span cases: 20m, 30m and 30m with central Leg set. Analogously, the benefit assessment was described and performed for all the cases and the results were presented. It was observed that the *Model III* revealed the best value for the three studied cases.

Based on the results of the concepts evaluation, the *Model III* was developed in more detail. The sections' design was carried out and a proposal for each type of member's connection. A structure breakdown was then performed, where the total list of parts, their required production operations, the different sub-assemblies and their transportation logistics were presented. Lastly, the adaptation of the design to new sizes, the customization opportunity given by the external flanges and the Gantry's recycling were addressed.

After the presented method was followed, the uncertainties and major questions to be solved were summarized, as well as the weaknesses of the proposed design.

9.2 Conclusions

With the realization of this work, a method to evaluate and develop new Gantry concepts was established. The evaluation could be divided in two subjects: the cost breakdown and the benefit assessment. Through the cost breakdown, the proportion between the different types of costs could be assessed, as well as the potential of each concept regarding the cost savings related to the reference model. It was taken that the models' weight and different number of extrusion dies played a big role in the cost results. Also it was observed that the use of a solution based on welding technologies increases the assembly costs significantly.

Subsequent to the cost breakdown, a benefit assessment was performed through the evaluation of each model's technical descriptors compared to the baseline model. This revealed the weaknesses and strengths of each model in the most significant categories such as profile's complexity, total number of beams, Boom's stiffness or use of welding cords. It was possible to notice the disadvantage of the models with a triangular Boom section, which require more complex main beams' profiles. Also the disadvantage of the *Model W* is that it relies on welding as the main connecting process. The use of welding implies extra cost related to productivity and labour, it weakens the aluminium's mechanical properties and requires inspections to the welding cords.

After performing the described steps for the three span cases analysed, it was possible to conclude that the model that revealed a better benefit-cost relation for all the cases was the *Model III*. It offers a relatively simple Boom, where the bottom part of the Boom consists in two profiles laterally attached, with the goal of supporting the *VMS*(s) and increasing the horizontal stiffness.

Regarding the results of the previous evaluations, the *Model III*'s structural configuration was developed, in order to perform the structural connections. A method was followed that focused on the use of extruded brackets and bolted connections. Their production was considered in order to keep the parts as simple as possible with minimum cost associated. The sub-assemblies were described, as well as their transportation method to the installation site. The proposed design enables a small amount of assembly operations on site, since most of the sub-assemblies can be transported already mounted.

The proposed design can be adapted to relatively small size adjustments by tuning small parameters in the production phase after the extrusion. For major size differences, an alteration of the sections' dimensions is required, which also requires a proportional change in the brackets' geometries. The design is easily adaptable to different sizes within the same range of spans, but requires a redesign of the sections' dimensions to comply the most efficient way with the new sizes. A practical cost assessment is proposed, in order to determine if it would be better to redesign the sections for larger span orders. Or to use bigger sections than needed, from smaller span models without central Legs in larger spans with central Legs ones, with the goal of using the same parts for the different models. This would facilitate the establishment of a product matrix within a certain range of sizes. Outside that range, the sections and brackets would need to be re-dimensioned.

Regarding the *Model W* Gantry, it uses welding technologies to join aluminium sheets to extruded profiles, in order to generate a larger section than what would be possible to extrude. This means that the cost inputs are different from the other models. Even though this model was one of the best regarding the benefit assessment, the higher cost decreased its value. Therefore, it is important to state that the use of this solution should not be discarded and it is believed that a possible hybrid-solution would lead to reduced extrusion costs having just one or two dies and reducing the total welding cord, by resort also to bolted joints. The disadvantage of such application would be the need of a mandatory inspection to the welding cords.

9.3 Further Work

This section aims to propose possible future works, having as a starting point the methodology and the results presented in this document.

First, the dimensioning of the bolted connections, from the proposed design, and the corresponding adjustment of the brackets' geometries is suggested. Then a structural analysis of the assembly should be performed, checking the overall structural performance, regarding the displacements and the integrity of the bolted connections. Also a dynamic analysis should be performed checking the structure's stability integrity.

A more realistic cost assessment of the detailed design is also recommended. This study should include real data inputs, in order to preview the cost of all parts' manufacturing. This prediction would also enable one to make the decision between producing the brackets "in-house" or to outsource production. The total cost should be compared with the current *Lattix*'s model, as a reference, and through the cost breakdown the sources of the higher cost values should be identified, recognizing this way the future scope for improvement.

An assessment regarding the implementation of a product matrix in alternative of the redesign of the sections' dimensions for every different order is suggested. This exercise should evaluate the total cost of a re-scaling of the sections and consequently of the brackets, mainly the production of new extrusion dies, over the cost of having a Gantry with sections that probably are overdesigned and material could be saved. The last option is the case of using, for example, the sections of the 20m span models in the 30m with central Legs to allow using the same connecting brackets. This assessment would afford understanding of the range of spans that each solution would be the optimal.

Related to the redesign of the Gantry, in order to comply efficiently with a new ordered size (mainly for a different span) the implementation of a *software* is suggested. Knowing that all the dimensions from the proposed design are dependent from each other, the program would receive the dimensions as the input. Then through a series of *FEA* for different load cases, it would understand the minimum values for the section's inertias (for both main profiles and diagonals). Afterwards, it would model the main profile, in order to comply with the minimum value of inertias and to fit the diagonals width (the diagonals, which must have a minimum stiffness value too) in a way that the flanges of the profile comply with their role of both attach the Diagonals in both sides (See figure 6-4). After the beams' profiles are generated, all the brackets would be updated to fit the new sections. Lastly a bolt dimension routine should be done, in order to find the required number of bolts for each type of connecting joint and its metric size. After that, adjust the brackets in terms of thickness and contact area to comply with the bolts' dimensions and spacing.

The last proposal for a future development is a detailed study with real input data to the *Model W'*s solution. Based on the cost breakdowns and value assessments performed during this work there was noticeable potential of this solution. If the real costs associated with the welding processes are really its major downside, a hybrid solution using both bolted and welded connections can be proposed and assessed.

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11. Annexes

Annex I: Detailed Cost Model

This annex presents a cost model adapted from the work of Harald Vestøl (1998) in cost modelling of extruded aluminium components for automotive structures. It was used the same cost breakdown between the main production steps but moulded to an aluminium Gantry product architecture.

For each cost breakdown phase, it is presented a symbolic circular graph representing what can be extracted from the results of the cost calculation. It is a visual support that enables to identify the major stages that consume more resources and contribute the most for the total sum, in each phase.

I-A Introduction

Structure Breakdown:

In this section, a configuration for a Gantry's structure breakdown will be suggested. It can be distinguished into two major phases: the assembly phase, where the components are joined in sub-assemblies after the fabrication stages, and the installation phase, where the Gantry is installed on site and the sub-assemblies as well as other remaining parts will be connected.

In the presented model, the denomination component **c** is used for fabricated parts and outsourced components **o** for purchased parts from suppliers.

Gantry *(Assembly)*

Assembly phase:

- Transom "10m" Section *(Sub-assembly 1 – s1)*
    - Main Boom Beam *(Component 1 – c1)*
    - Diagonal Beam *(Component 2 – c2)*
    - Brackets *(Component 3 – c3)*
    - Bolts *(Component 10 – o1)* – *Outsourced 1*
    - Nuts *(Component 11 – o2)* – *Outsourced 2*
- Leg (Sub-assembly 2 – s2)

- Mast *(Component 4 – c1 or c4)*
- Mast Connection Plates *(Component 5 – o3)* – *Outsourced 3*
- Bolts *(Component 10 – o1)* – *Outsourced 1*
- Nuts *(Component 11 – o2)* – *Outsourced 2*

Installation phase:

- Section Connection Plates *(Component 6 – o4)* – *Outsourced 4*
- Transom/Leg Interface plate *(Component 7 – o5)* – *Outsourced 5*
- Baseplate *(Component 8 – o6)* – *Outsourced 6*
- Foundation *(Component 9 – o7)* – *Outsourced 7*
- Bolts *(Component 10 – o1)* – *Outsourced 1*
- Nuts *(Component 11 – o2)* – *Outsourced 2*
- Ladder *(Component 12 – o8)* – *Outsourced 8*

Production Phases:

As it was stated before, four main steps during a Gantry production will be considered. Note that the stages of the fabrication of components step are exemplificative; there can be more, less or different processes.

1) Extrusion;
2) Fabrication of components:
    a. Cutting;
    b. Machining;
    c. Hole piercing.
3) Assembly;
4) Installation;

Cost Breakdown:

Concerning the cost breakdown, naturally the structure is similar to the production phases presented in the previous section. The difference is that is also taken into account the cost of the outsourced components which instead of being fabricated in-house are purchased from suppliers. In order to sum every cost category from each phase, the last step of the model consists of the cost summary.

1) Extrusion Cost;
2) Component Fabrication Cost;
3) Outsourced Component Cost;
4) Assembly Cost;
5) Installation Cost;
6) Cost Summary.

Type of Costs:

Before start with the cost model, is relevant to introduce the different types of cost that will be considered to preview the total cost of each product phase, and ultimately the total cost.

There are two main types of cost, the variable and the fixed cost. Variable costs are the ones that relate directly to the production of each part. On the other hand the fixed costs are the ones that are considered independent of the production volume.

Below are shown within each type of cost the different categories that will be considered in the presented Cost Model.

Variable Costs:

- Material Cost;
- Labour Cost.

Fixed Costs:

- Equipment Cost;
- Tooling Cost;
- Capital Cost;
- Maintenance Cost;
- Additional Cost.

I-B Information Required

In the beginning of the application of the Cost Model to be presented, there is much different information related to the production that is required. This data will be used in the different cost categories (presented in the cost breakdown) and the denomination to be used will be as presented in the next table.

Analogously, in the beginning of each cost category it will be presented a table with more specific data required to solve the proposed cost equations.

- ✓ N_{ext}^{tot} – Total number of different extrusions (**e**) / different profiles;
- ✓ N_{comp}^{tot} – Total number of different fabricated components (**c**);
- ✓ N_{out}^{tot} – Total number of different outsourced (**o**) components;
- ✓ N_{sub}^{tot} – Total number of subassemblies;
- ✓ N_{inst}^{tot} – Total number of installation steps;
- ✓ N_{yr} – Annual production volume;
- ✓ N_{days} – Number of working days per year;
- ✓ N_{hr} – Number of working hours per day;
- ✓ n_{rec} – Capital recovery rate;
- ✓ $\mathrm{N}_{\mathrm{comp,total}}^{\mathrm{c}}$ – Total number of fabricated components in the final assembly;
- ✓ $\mathrm{N}_{\mathrm{out,total}}^{\mathrm{o}}$ – Total number of outsourced components in the final assembly.

I-C Extrusion Cost

This section will focus on the costs related to the extrusion process. This way the total cost will be decomposed in material, equipment (press) and die cost.

It is calculated for each extrusion **e** (each different profile/die). So, e = 1…N_{ext}^{tot}.

For example, if there are 3 different profiles, N_{ext}^{tot} = 3.

Information required:

- ✓ Press number (identification code – information table):
  - c^e_{press} – Total cost per hour to run the actual press [cost/hour]

- ✓ Alloy number (identification code):
  - c^e_{billet} – Billet cost per unit mass [cost/mass];
  - c^e_{scrap} – Material scrap value per unit mass [value/mass].

- ✓ m^e_{ext} – Extrusion weight per unit length [kg/m];
- ✓ v^e_{ext} – Net extrusion speed in mass per unit time [kg/min];
- ✓ c^e_{die} – Die cost per mass extruded material [cost/kg extruded];
- ✓ n^e_{ext} – recovery rate (% of scrap that can be recovered).

- ○ Net material cost per kg of finished extrusion [cost/kg extruded]:

$$\mathbf{C^e_{mat}} = c^e_{billet} + \frac{1-n^e_{ext}}{n^e_{ext}}\left(c^e_{billet} - c^e_{scrap}\right) \quad \text{(AI.1)}$$

- ○ Net extrusion cost per unit mass of finished extrusion [cost/kg extruded]:

$$\mathbf{C^e_{press}} = \frac{c^e_{press}}{v^e_{ext}} \quad \text{(AI.2)}$$

- ➢ Total extrusion cost <u>per unit mass of finished extrusion</u> [cost/kg extruded]:

$$\mathbf{C^e_{ext}} = \mathbf{C^e_{mat}} + \mathbf{C^e_{press}} + \boldsymbol{c^e_{die}} \quad \text{(AI.3)}$$

$$\text{Eg:} \quad \text{if } N^{tot}_{ext} = 3, \qquad C^e_{ext} = \begin{bmatrix} C^1_{ext} \\ C^2_{ext} \\ C^3_{ext} \end{bmatrix}$$

So far, per each different profile it is possible to visualize the extrusion cost distribution, as the following graphs exemplify.

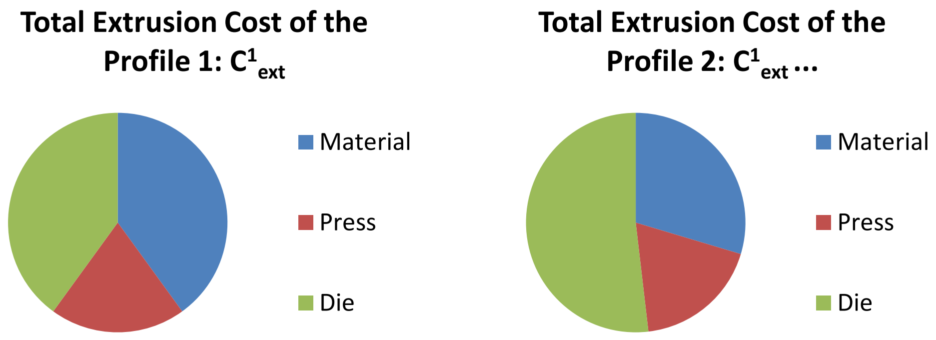

Figure AI-1: Graph representing a Total Extrusion cost breakdown

I-D Component Fabrication Cost

This section addresses the fabrication of each component. This refers to the different processes that each extruded component is submitted until the final part is ready for assembly.

The cost is then calculated for each component (**c**). c = 1…N_{comp}^{tot}

For example, if the structure has 5 different fabricated components and 3 processes after the extrusion: c = 1…5 and p = 1…3.

- Component 1:
    - Process 1
    - Process 2
    - Process 3

- Component 2:
    - Process 1
    - Process 2
    - Process 3

- (…)

	P1	P2	P3
C1	…	…	…
C2	…	…	…
C3	…	…	…
C4	…	…	…
C5	…	…	…

Information required for each component (c):

- ✓ N^{c}_{proc} – Number of processes in process route]

  For each process:

  - Process code (data from a process table):
    - ○ $c^{c,p}_{eq}$ – Cost of process equipment (cost per line);
    - ○ $t^{c,p}_{rec}$ – Recovery period for the actual equipment;
    - ○ $c^{c,p}_{labour}$ – Total labour cost per hour per labourer on the process;
    - ○ $c^{c,p}_{add}$ – Additional cost per hour the process is running;
    - ○ $t^{c,p}_{down}$ – Ratio of downtime for the actual equipment;
    - ○ $c^{c,p}_{main}$ – Annual maintenance cost as a ratio of the equipment cost
  - $N^{c,p}_{prod}$ – Production rate per hour;
  - $N^{c,p}_{labour}$ – number of labourers to perform the process;
  - $n^{c,p}_{scrap}$ – Scrap rate;
  - $n^{c,p}_{ded}$ – Dedicated ($n^{c,p}_{ded}$ =1) /Non-dedicated ($n^{c,p}_{ded}$ =0) equipment.
- ✓ e^{c} – Extrusion number (Number of the profile);
- ✓ l^{c}_{ext} – Extrusion length;
- ✓ m^{c}_{comp} – Weight of the finished component.

- ○ Effective production rate: $N^{c,p}_{eff} = N^{c,p}_{prod}\left(1 - t^{c,p}_{down}\right)$ (AI.4)

$$\text{Eg:}\ N^{c,p}_{eff} = \begin{bmatrix} N^{1,1}_{eff} & N^{1,2}_{eff} & N^{1,3}_{eff} \\ N^{2,1}_{eff} & N^{2,2}_{eff} & N^{2,3}_{eff} \\ N^{3,1}_{eff} & N^{3,2}_{eff} & N^{3,3}_{eff} \\ N^{4,1}_{eff} & N^{4,2}_{eff} & N^{4,3}_{eff} \\ N^{5,1}_{eff} & N^{5,2}_{eff} & N^{5,3}_{eff} \end{bmatrix}$$

- ○ Average number of cycles process number **p** must be run to produce one finished component:

$$N^{c,p}_{cyc} = \prod_{j=p}^{N^{c}_{proc}} \frac{1}{1-n^{c,j}_{scrap}} \quad \text{(AI.5)}$$

- Number of lines for process number **p** in the fabrication of the component number **c**:

$$\begin{cases} \mathrm{N}_{\mathrm{lines}}^{\mathrm{c,p}} = \dfrac{\mathrm{N}_{\mathrm{yr}}\,\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}\,\mathrm{N}_{\mathrm{cyc}}^{\mathrm{c,p}}}{\mathrm{N}_{\mathrm{day}}\,\mathrm{N}_{\mathrm{hr}}\,\mathrm{N}_{\mathrm{eff}}^{\mathrm{c,p}}} \quad \text{for } \mathrm{n}_{\mathrm{ded}}^{\mathrm{c,p}} = 0 & (\mathrm{AI}.6) \\ \\ \mathrm{N}_{\mathrm{lines}}^{\mathrm{c,p}} = \mathrm{INT}\left(\dfrac{\mathrm{N}_{\mathrm{yr}}\,\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}\,\mathrm{N}_{\mathrm{cyc}}^{\mathrm{c,p}}}{\mathrm{N}_{\mathrm{day}}\,\mathrm{N}_{\mathrm{hr}}\,\mathrm{N}_{\mathrm{eff}}^{\mathrm{c,p}}} + 0.9999\right) \quad \text{for } \mathrm{n}_{\mathrm{ded}}^{\mathrm{c,p}} = 1 & (\mathrm{AI}.7) \end{cases}$$

$\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}$ – Gross number of component the component **c** that is required to produce one finished product.

Assuming cost per line for process **p**, $c^{c,p}_{eq}$, is paid in a period of $t^{c,p}_{rec}$ years with an interest rate n_{rec}:

- Capital cost per finished component **c**:

$$\mathbf{C}_{\mathbf{cap}}^{\mathbf{c}} = \sum_{\mathrm{p}=1}^{\mathrm{N}_{\mathrm{proc}}^{\mathrm{c}}} \left[\mathrm{c}_{\mathrm{eq}}^{\mathrm{c,p}}\,\frac{(1+\mathrm{n}_{\mathrm{rec}})^{\mathrm{trec}}\,\mathrm{n}_{\mathrm{rec}}}{(1+\mathrm{n}_{\mathrm{rec}})^{\mathrm{trec}}-1}\,\frac{\mathrm{N}_{\mathrm{lines}}^{\mathrm{c,p}}}{\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}\,\mathrm{N}_{\mathrm{yr}}}\right] \qquad (\mathrm{AI}.8)$$

Ex: Processes: Cutting > Machining > Piercing. – **$\mathbf{N^{c}_{proc}}$ = 3**.

- Total maintenance cost per finished component:

$$\mathbf{C}_{\mathbf{main}}^{\mathbf{c}} = \sum_{\mathrm{p}=1}^{\mathrm{N}_{\mathrm{proc}}^{\mathrm{c}}} \left[\mathrm{c}_{\mathrm{eq}}^{\mathrm{c,p}}\,\mathrm{c}_{\mathrm{main}}^{\mathrm{c,p}}\,\frac{\mathrm{N}_{\mathrm{lines}}^{\mathrm{c,p}}}{\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}\,\mathrm{N}_{\mathrm{yr}}}\right] \qquad (\mathrm{AI}.9)$$

- Cost of consumed extruded material:

$$\mathbf{C}_{\mathbf{ext}}^{\mathbf{c}} = \mathrm{N}_{\mathrm{cyc}}^{\mathrm{c,1}}\,\mathrm{l}_{\mathrm{ext}}^{\mathrm{c}}\,\mathrm{C}_{\mathrm{ext}}^{\mathrm{e^c}} \qquad (\mathrm{AI}.10)$$

- Scrap value per component:

$$\mathbf{C}_{\mathbf{scrap}}^{\mathbf{c}} = \left(\mathrm{N}_{\mathrm{cyc}}^{\mathrm{c,1}}\,\mathrm{m}_{\mathrm{ext}}^{e^c}\,\mathrm{l}_{\mathrm{ext}}^{\mathrm{c}} - m_{comp}^{e^c}\right) c_{scrap}^{e^c} \qquad (\mathrm{AI}.11)$$

- Labour cost per component:

$$\mathbf{C^{c}_{labour}} = \sum_{p=1}^{N^{c}_{proc}} \left[\frac{N^{c,p}_{cyc}\, c^{c,p}_{labour}\, N^{c,p}_{labour}}{N^{c,p}_{eff}} \right] \qquad \text{(AI.12)}$$

- Additional cost per component:

$$\mathbf{C^{c}_{add}} = \sum_{p=1}^{N^{c}_{proc}} \left[\frac{N^{c,p}_{cyc}\, c^{c,p}_{add}}{N^{c,p}_{eff}} \right] \qquad \text{(AI.13)}$$

- Total production cost <u>per component</u>:

$$\mathbf{C^{c}_{comp}} = \mathbf{C^{c}_{cap}} + \mathbf{C^{c}_{main}} + \mathbf{C^{c}_{ext}} - \mathbf{C^{c}_{scrap}} + \mathbf{C^{c}_{labour}} + \mathbf{C^{c}_{add}} \qquad \text{(AI.14)}$$

$$\text{Eg: } C^{c}_{comp} = \begin{bmatrix} C^{1}_{comp} \\ C^{2}_{comp} \\ C^{3}_{comp} \\ C^{4}_{comp} \\ C^{5}_{comp} \end{bmatrix}$$

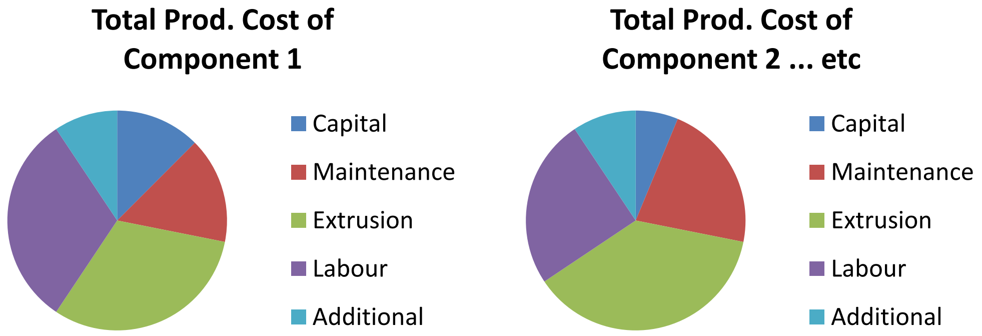

Figure AI-2: Graph representing a Total Production (for each component) Cost breakdown

I-E Outsourced Component Cost

The cost related to the Outsourced Components is practically the purchase price from the supplier. If this model assumes that the outsourced component is directly used in the assembly and don't suffer any process before it, the final cost is the purchase cost: $\mathbf{C^o_{out}} = c^o_{out}$.

Information required:

Outsourced component number **o**:

- ✓ c^o_{out} – Gross purchase price;
- ✓ c^o_{scrap} – Scrap value;
- ✓ n^o_{scrap} – Ratio of bad parts.

- ➢ Net cost per component:

$$\mathbf{C^o_{out}} = \frac{c^o_{out} - n^o_{scrap} c^o_{scrap}}{1 - n^o_{scrap}} \qquad \text{(AI.15)}$$

I-F Assembly Cost

The assembly phase consists of the connection of the fabricated parts with some of the outsourced parts into sub-assemblies. The model gives avail to have sub-assemblies within sub-assemblies, but for the application in study that won't occur. These sub-assemblies will be after transported to the installation site in order to be mounted into the final assembly structure.

It is considered that in a Gantries' assemblage (before the installation on site), there are two different sub-assemblies: the Boom "10m" sections (s_1) and the Leg sections (s_2).

The complete assembly process is divided into N_{sub}^{tot} separate sub-assembly processes **s** (fabricated components, outsourced components or sub-assemblies).

For example, considering the 2 sub-assemblies: $N_{sub}^{tot} = 2$ (s = 1, 2).

Information required for each sub-assembly s:

- ✓ Process code;
  - ○ c^s_{eq} – Cost of process equipment (cost per line);
  - ○ t^s_{rec} – Recovery period for the actual equipment;
  - ○ c^s_{labour} – Total labour cost per hour per labourer on the process;
  - ○ c^s_{add} – Additional cost per hour the process is running;
  - ○ t^s_{down} – Ratio of downtime for the actual equipment;
  - ○ c^s_{main} – Annual maintenance cost as a ratio of the equipment cost.

- ✓ N^s_{prod} – Process production rate per hour;
- ✓ N^s_{labour} – Number of labourers to run the process;
- ✓ n^s_{scrap} – Process scrap rate;

- ✓ N^s_{comp} – Number of different fabricated components included in the sub-assembly;

  For each N^s_{comp}:

  - c – the fabricated component;
  - $N^{c,s}_{comp}$ – The number of fabricated component number **c** that are included in the actual sub-assembly.

- ✓ N^s_{out} – Number of different outsourced components included in the sub-assembly;

  For each N^s_{out}:

  - o – the outsourced component;
  - $N^{o,s}_{out}$ – The number of outsourced component number **o** that are included in the actual sub-assembly.

- ✓ N^s_{sub} – Number of different sub-assemblies included in the subassembly;

  (in this structure breakdown, $N^s_{sub} = 0$: no sub-assemblies inside a sub-assembly)

  For each N^s_{sub}:

  - s' – the sub-assembly;
  - $N^{s',s}_{sub}$ – The number of sub-assemblies **s'** that are included in the actual sub-assembly.

- ✓ n^s_{ded} – Dedicated (n^s_{ded} =1) /Non-dedicated (n^s_{ded} =0) equipment.

- Average number of cycles of the subassembly process **s** that are required per finished component:

$$\begin{cases} \mathrm{N_{cyc}^{s}} = \dfrac{\sum_{\mathrm{j=1}}^{\mathrm{N_{sub}^{tot}-s}} \left(\mathrm{N_{cyc}^{s+j}}\ \mathrm{N_{sub}^{s,s+j}}\right)}{1-\mathrm{n_{scrap}^{s}}} \mathrm{N_{as}^{tot}} \quad \text{for } \mathrm{s} < \mathrm{N_{sub}^{tot}} \quad (\mathrm{AI.16}) \\ \\ \mathrm{N_{cyc}^{s}} = \dfrac{1}{1-\mathrm{n_{scrap}^{s}}} \mathrm{N_{as}^{tot}} \quad \text{for } \mathrm{s} = \mathrm{N_{sub}^{tot}} \quad (\mathrm{AI.17}) \end{cases}$$

$\mathrm{N_{as}^{tot}}$ – Average number of finished assemblies that are required to produce one finished product.

$$\text{Eg: } \mathrm{N_{cyc}^{s}} = \begin{bmatrix} \mathrm{N_{cyc}^{1}} \\ \mathrm{N_{cyc}^{2}} \end{bmatrix}$$

- Gross number of the component **c** that are required per final product:

$$\mathrm{N_{comp,gross}^{c}} = \sum_{\mathrm{s=1}}^{\mathrm{N_{sub}^{tot}}} \left(\mathrm{N_{comp}^{c,s}}\ \mathrm{N_{cyc}^{s}}\right) \quad (\mathrm{AI.18})$$

- Gross number of the outsourced component **o** that are required per final product:

$$\mathrm{N_{out,gross}^{c}} = \sum_{\mathrm{s=1}}^{\mathrm{N_{sub}^{tot}}} \left(\mathrm{N_{out}^{o,s}}\ \mathrm{N_{cyc}^{s}}\right) \quad (\mathrm{AI.19})$$

- Effective production rate:

$$\mathrm{N_{eff}^{s}} = \mathrm{N_{prod}^{s}}(1-\mathrm{t_{down}^{s}}) \quad (\mathrm{AI.20})$$

$$\text{Ex: } \mathrm{N_{eff}^{s}} = \begin{bmatrix} \mathrm{N_{eff}^{1}} \\ \mathrm{N_{eff}^{2}} \end{bmatrix}$$

- Required number of lines:

$$\begin{cases} \mathrm{N}^{\mathrm{s}}_{\mathrm{lines}} = \dfrac{\mathrm{N}_{\mathrm{yr}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{cyc}}}{\mathrm{N}_{\mathrm{day}}\ \mathrm{N}_{\mathrm{hr}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{eff}}} \quad \text{for } \mathrm{n}^{\mathrm{s}}_{\mathrm{ded}} = 0 \quad (\mathrm{AI.21}) \\ \\ \mathrm{N}^{\mathrm{s}}_{\mathrm{lines}} = \mathrm{INT}\left(\dfrac{\mathrm{N}_{\mathrm{yr}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{cyc}}}{\mathrm{N}_{\mathrm{day}}\ \mathrm{N}_{\mathrm{hr}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{eff}}} + 0.9999\right) \quad \text{for } \mathrm{n}^{\mathrm{s}}_{\mathrm{ded}} = 1 \quad (\mathrm{AI.22}) \end{cases}$$

- Capital cost per finished sub-assembly:

$$\mathbf{C}^{\mathbf{s}}_{\mathbf{cap}} = \mathrm{c}^{\mathrm{s}}_{\mathrm{eq}} \frac{(1+\mathrm{n}_{\mathrm{rec}})^{\mathrm{trec}}\ \mathrm{n}_{\mathrm{rec}}}{(1+\mathrm{n}_{\mathrm{rec}})^{\mathrm{trec}}-1} \frac{\mathrm{N}^{\mathrm{s}}_{\mathrm{lines}}}{\mathrm{N}_{\mathrm{yr}}} \qquad (\mathrm{AI.23})$$

- Maintenance cost per finished sub-assembly:

$$\mathbf{C}^{\mathbf{c}}_{\mathbf{main}} = \mathrm{c}^{\mathrm{s}}_{\mathrm{eq}} \mathrm{c}^{\mathrm{s}}_{\mathrm{main}} \frac{\mathrm{N}^{\mathrm{s}}_{\mathrm{lines}}}{\mathrm{N}_{\mathrm{yr}}} \qquad (\mathrm{AI.24})$$

- Labour cost per finished sub-assembly:

$$\mathbf{C}^{\mathbf{s}}_{\mathbf{labour}} = \frac{\mathrm{N}^{\mathrm{s}}_{\mathrm{cyc}}\ \mathrm{c}^{\mathrm{s}}_{\mathrm{labour}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{labour}}}{\mathrm{N}^{\mathrm{tot}}_{\mathrm{as}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{eff}}} \qquad (\mathrm{AI.25})$$

- Additional cost per finished sub-assembly:

$$\mathbf{C}^{\mathbf{s}}_{\mathbf{add}} = \frac{\mathrm{N}^{\mathrm{s}}_{\mathrm{cyc}}\ \mathrm{c}^{\mathrm{s}}_{\mathrm{add}}}{\mathrm{N}^{\mathrm{tot}}_{\mathrm{as}}\ \mathrm{N}^{\mathrm{s}}_{\mathrm{eff}}} \qquad (\mathrm{AI.26})$$

Before arriving to the total assembly cost is relevant to demonstrate the results that can be visualised at this point. It can be retrieved the cost distribution per each sub-assembly as exemplified below.

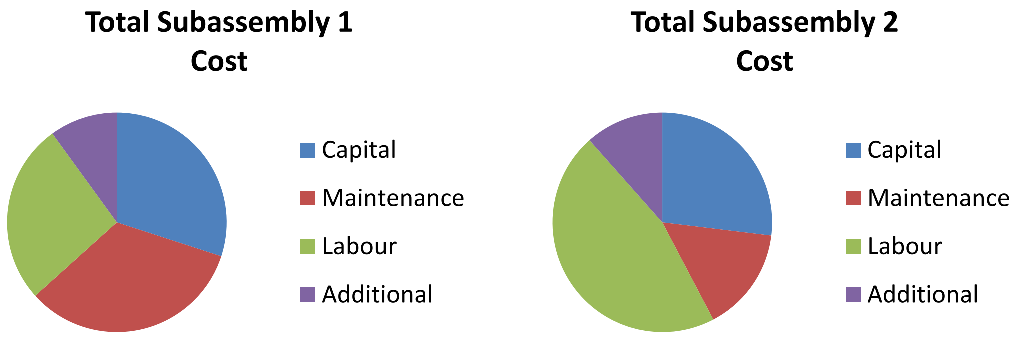

Figure AI-3: Graph representing a Total Subassembly cost breakdown

- Total assembly process cost:

$$\mathbf{C^{s}_{as}} = \mathbf{C^{s}_{cap}} + \mathbf{C^{s}_{main}} + \mathbf{C^{s}_{labour}} + \mathbf{C^{s}_{add}} \qquad \text{(AI.27)}$$

I-G Installation Cost

This section deals with the installation cost. This phase considers the transportation from the factory to the site and the assemblage of the pre-mounted sub-assemblies with the remaining parts in order to form the Gantry system.

Installation steps ($\mathrm{N^{inst}_{steps}}$ – Number of installation steps)**:**

1. Transport;
2. Foundation;
3. Connect Leg to the foundation;
4. Connect Boom sections;
5. Connect Boom to the legs;
6. Accessories (ladder).

Information required per each step (i):

- ✓ $N_{labour}{}^{i}$ – Number of workers required to perform each step;
    - ○ c_{labour} – cost per worker per unit time;
- ✓ $t_{step}{}^{i}$ – Time required to perform the step;
- ✓ $N_{tools}{}^{i}$ – Number of different tools needed per step;
    - ○ $n_{tools}{}^{j}$ – Number of each tool;
    - ○ $c_{tools}{}^{j}$ – cost of each tool per unit time.
- ✓ $t_{stop}{}^{i}$ – time required for the traffic stop;
- ✓ c_{stop} – cost of stopping the traffic per unit time.

- Total labour cost during installation:

$$\mathrm{C}^{\mathrm{inst}}_{\mathrm{labour}} = \sum_{i=1}^{N^{inst}_{steps}} \left(\mathrm{N}_{\mathrm{labour}^{i}}\ \mathrm{c}_{\mathrm{labour}}\ \mathrm{t}_{\mathrm{step}^{i}}\right) \quad \text{(AI.28)}$$

- Total tooling cost during installation:

$$\mathrm{C}^{\mathrm{inst}}_{\mathrm{tools}} = \sum_{i=1}^{N^{inst}_{steps}} \left(\left(\sum_{j=1}^{N^{i}_{tools}} c^{j}_{tools}\ n^{j}_{tools}\right)\ \mathrm{t}_{\mathrm{step}^{j}}\right) \quad \text{(AI.29)}$$

- Total stopping cost during installation:

$$\mathrm{C}^{\mathrm{inst}}_{\mathrm{stop}} = \sum_{i=1}^{N^{inst}_{steps}} \left(\mathrm{t}_{\mathrm{stop}^{i}}\ \mathrm{c}_{\mathrm{stop}}\right) \quad \text{(AI.30)}$$

- Total installation cost:

$$\mathbf{C}^{\mathbf{inst}}_{\mathbf{total}} = \mathbf{C}^{\mathbf{inst}}_{\mathbf{labour}} + \mathbf{C}^{\mathbf{inst}}_{\mathbf{tools}} + \mathbf{C}^{\mathbf{inst}}_{\mathbf{stop}} \quad \text{(AI.31)}$$

Similarly as before, the installation cost can be visually decomposed into the three main components, in order to identify the main cost contributor.

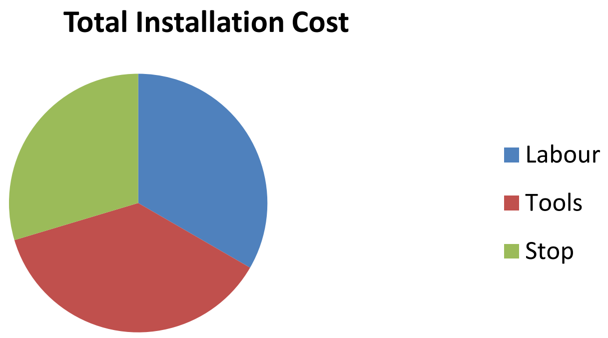

Figure AI-4: Graph representing a Total Installation cost breakdown

I-H Cost Summary

This final section deals with the total Gantry cost by associating the same type of costs from all the previously presented categories.

- Total cost of extruded material:

$$\mathbf{C}_{\mathbf{ext}}^{\mathbf{tot}} = \sum_{c=1}^{N_{ext.comp}^{tot}} \left(C_{ext}^{c}\ N_{comp,total}^{c}\right) \qquad \text{(AI.32)}$$

- Total cost of outsourced components:

$$\mathbf{C}_{\mathbf{out}}^{\mathbf{tot}} = \sum_{o=1}^{N_{out.comp}^{tot}} \left(C_{out}^{o}\ N_{out,total}^{o}\right) \qquad \text{(AI.33)}$$

- Total value of scrap from fabrication process:

$$C_{scrap}^{fab} = \sum_{c=1}^{N_{ext.comp}^{tot}} \left(C_{scrap}^{c,1}\ N_{comp,total}^{c}\right) \qquad \text{(AI.34)}$$

- Net number of process cycles of sub-assembly number **s** per finished assembly:

$$\begin{cases} \mathrm{N}_{\mathrm{cyc,net}}^{\mathrm{s}} = \sum_{\mathrm{j}=1}^{\mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}}-\mathrm{s}} \left(\mathrm{N}_{\mathrm{cyc}}^{\mathrm{s+j}}\ \mathrm{N}_{\mathrm{sub}}^{\mathrm{s,s+j}}\right) \quad \text{for } \mathrm{s} < \mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}} \quad (\mathrm{AI}.35) \\ \mathrm{N}_{\mathrm{cyc,net}}^{\mathrm{s}} = 1 \quad \text{for } \mathrm{s} = \mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}} \quad (\mathrm{AI}.36) \end{cases}$$

- Net number of fabricated component number **c** per finished assembly:

$$\mathrm{N}_{\mathrm{comp,net}}^{\mathrm{c}} = \sum_{\mathrm{s}=1}^{\mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}}} \left(\mathrm{N}_{\mathrm{comp}}^{\mathrm{c,s}}\ \mathrm{N}_{\mathrm{cyc,net}}^{\mathrm{s}}\right) \qquad (\mathrm{AI}.37)$$

- Net number of fabricated outsourced component number **o** per finished assembly:

$$\mathrm{N}_{\mathrm{out,net}}^{\mathrm{o}} = \sum_{\mathrm{s}=1}^{\mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}}} \left(\mathrm{N}_{\mathrm{out}}^{\mathrm{o,s}}\ \mathrm{N}_{\mathrm{cyc,net}}^{\mathrm{s}}\right) \qquad (\mathrm{AI}.38)$$

- Total value of scrap from the assembly process:

$$\mathrm{C}_{\mathrm{scrap}}^{\mathrm{as}} = \sum_{\mathrm{s}=1}^{\mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}}} \left[\sum_{\mathrm{c}=1}^{\mathrm{N}_{\mathrm{comp}}^{\mathrm{tot}}} \left(\left(\frac{\mathrm{N}_{\mathrm{comp,gross}}^{\mathrm{c}}}{\mathrm{N}_{\mathrm{as}}^{\mathrm{tot}}} - \mathrm{N}_{\mathrm{comp,net}}^{\mathrm{c}}\right) \mathrm{m}_{\mathrm{comp}}^{\mathrm{c}}\ \mathrm{c}_{\mathrm{scrap}}^{\mathrm{e^c}}\right) + + \sum_{\mathrm{o}=1}^{\mathrm{N}_{\mathrm{out}}^{\mathrm{tot}}} \left(\left(\frac{\mathrm{N}_{\mathrm{out,gross}}^{\mathrm{o}}}{\mathrm{N}_{\mathrm{as}}^{\mathrm{tot}}} - \right.\right.\right.$$

$$\left.\left.\left. - \mathrm{N}_{\mathrm{out,net}}^{\mathrm{o}}\right) \mathrm{c}_{\mathrm{scrap}}^{\mathrm{o}}\right)\right] 4.45 \qquad (\mathrm{AI}.39)$$

- ➢ Total value of produced scrap per finished product:

$$\mathbf{C}_{\mathbf{scrap}}^{\boldsymbol{tot}} = \mathrm{C}_{\mathrm{scrap}}^{\mathrm{fab}} + \mathrm{C}_{\mathrm{scrap}}^{\mathrm{as}} \qquad (\mathrm{AI}.40)$$

- ➢ Total capital cost per finished product:

$$\mathbf{C}_{\mathbf{cap}}^{\mathbf{tot}} = \sum_{\mathrm{c}=1}^{\mathrm{N}_{\mathrm{comp}}^{\mathrm{tot}}} \left(\mathrm{C}_{\mathrm{cap}}^{\mathrm{c}}\ \mathrm{N}_{\mathrm{comp,total}}^{\mathrm{c}}\right) + \sum_{\mathrm{s}=1}^{\mathrm{N}_{\mathrm{sub}}^{\mathrm{tot}}} \left(\mathrm{C}_{\mathrm{cap}}^{\mathrm{s}}\ \mathrm{N}_{\mathrm{as}}^{\mathrm{tot}}\right) \qquad (\mathrm{AI}.41)$$

- Total maintenance cost per finished product:

$$\mathbf{C^{tot}_{main}} = \sum_{c=1}^{N^{tot}_{comp}} \left(C^{c}_{main}\ N^{c}_{comp,total}\right) + \sum_{s=1}^{N^{tot}_{sub}} \left(C^{s}_{main}\ N^{tot}_{as}\right) \tag{AI.42}$$

- Total labour cost per finished product:

$$\mathbf{C^{tot}_{labour}} = \sum_{c=1}^{N^{tot}_{comp}} \left(C^{c}_{labour}\ N^{c}_{comp,total}\right) + \sum_{s=1}^{N^{tot}_{sub}} \left(C^{s}_{labour}\ N^{tot}_{as}\right) \tag{AI.43}$$

- Total additional cost per finished product:

$$\mathbf{C^{tot}_{add}} = \sum_{c=1}^{N^{tot}_{comp}} \left(C^{c}_{add}\ N^{c}_{comp,total}\right) + \sum_{s=1}^{N^{tot}_{sub}} \left(C^{s}_{add}\ N^{tot}_{as}\right) \tag{AI.44}$$

- Total product cost:

$$\mathbf{C} = \mathbf{C^{\mathit{tot}}_{ext}} + \mathbf{C^{\mathit{tot}}_{out}} - \mathbf{C^{\mathit{tot}}_{scrap}} + \mathbf{C^{\mathit{tot}}_{cap}} + \mathbf{C^{\mathit{tot}}_{main}} + \mathbf{C^{\mathit{tot}}_{labour}} + \mathbf{C^{\mathit{tot}}_{add}} + \mathbf{C^{inst}_{total}} \tag{AI.45}$$

The final result enables to see, during the total production of the Gantry until it is ready for use, where the most percentage of cost was spent and in what category. The result is exemplified in the graphic presented below.

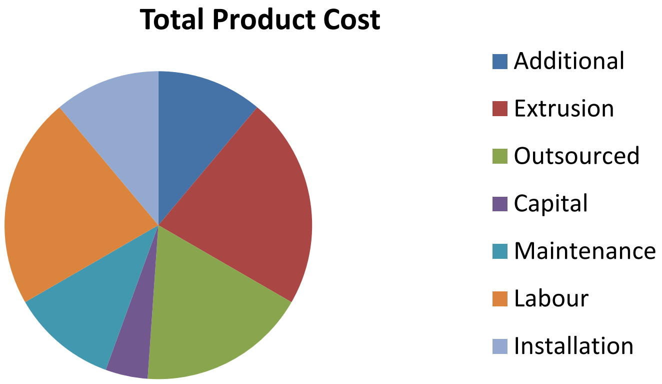

Figure AI-5: Graph representing a Total Production cost breakdown

With these final figures and also all the information at the end of each section it can be analysed where the most saving potential is. This way, the goal of reducing the total cost for a new Gantry model can be approached in a more direct way.

Annex II: *Lattix*'s Gantry Concept

This annex will address the concept proposed by *Lattix*. It is interesting to study the feasibility of the solution in terms of structural behaviour. Most importantly, the boom's displacements, and the manufacturability of the required section sizes to meet the displacement requirements.

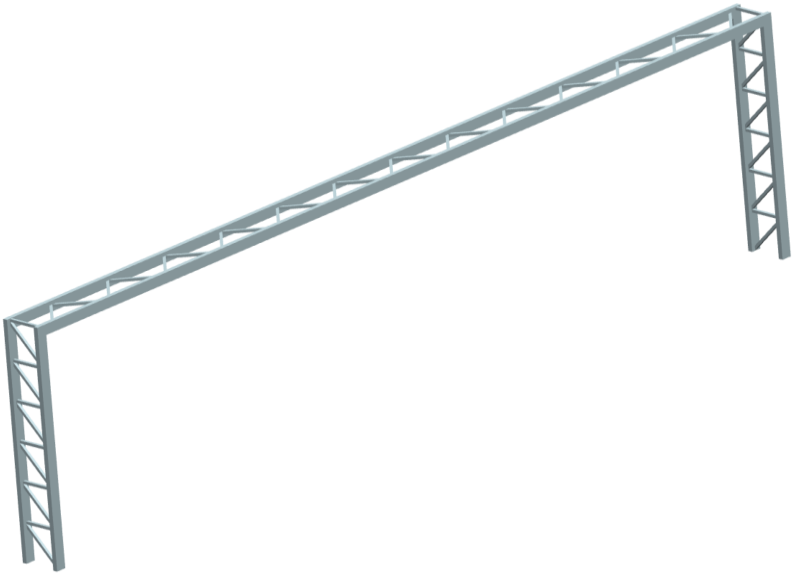

Figure AII-1: *Lattix*'s Proposed Gantry Model

A structure like this, by having a planar Boom instead of a square section, result immediately in a smaller total number of parts, because the number of diagonal beams is reduced in one fourth, comparing with the current Gantry Model scheme. This enables a faster and thus more economical assembly, due to the fact that the fewer number of parts, the fewer connections are to be made. This doesn't represent automatically also less material use and extrusion cost savings. In order to maintain the structural integrity and comply with the stiffness requirements the Boom sections has to be large enough to have the minimum required Inertia Moments.

This balance between using fewer parts, but on the other hand requiring large sections for the main beams needs to be accessed. Primarily, it will be studied the proposed structure with the proposed section sizes. Then regarding the results the feasibility of the model will be addressed.

II-A Preliminary Analyses:

The first step was to study the main deflections of this structure with the proposed sections sizes. In order to avoid meshing problems during the *FEA*, the proposed section for the main beams was simplified, but with similar second moments of inertia. This study was performed using a 3D model, hence, a tetrahedral mesh.

Below the simplified section and its values are presented.

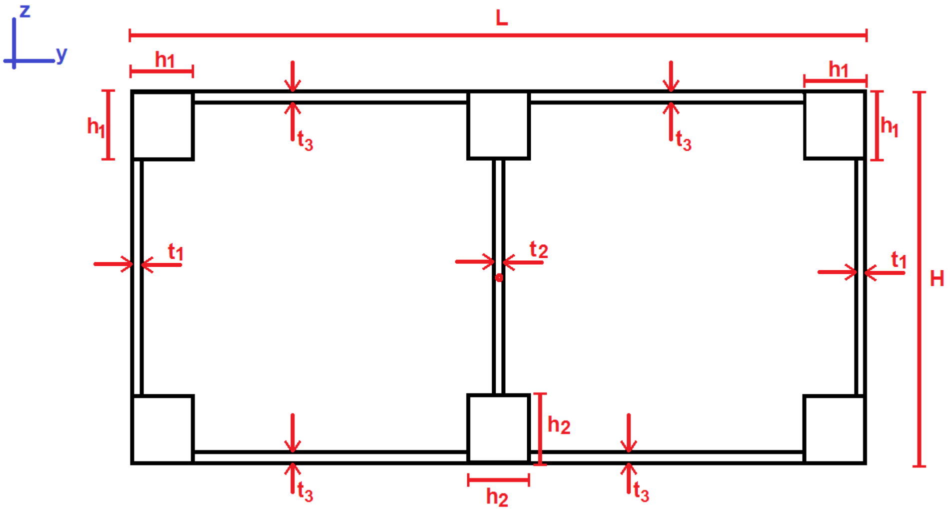

Figure AII-2: Simplified *Lattix*'s Proposed Main Section

L	340 mm	**h1**	30 mm	**t1**	5 mm
H	150 mm	**h2**	25 mm	**t2**	4 mm
				t3	5 mm

Table AII-1: Section dimensions used the preliminary analysis

It is relevant to present the main material properties of the alloy used in the *software* for these analyses. The mechanical properties that will describe the structure's behaviour were taken from an aluminium 6063 alloy and the main ones are presented in the next table.

Al 6063 Mechanical Properties	
ρ	$2.711x10^{-6}$ Kg/mm^3
E	68.98 GPa (20ºC)
σ_{yield}	241.7 MPa (20ºC)
σ_{ultimate}	276 MPa (20ºC)

Table AII-2: Alloy's main mechanical properties

For the approximated section, the inertia values, area and weight per unit of the beam's length are shown in the table below.

Second Moment of Inertia				Area	Weight/m
Approximated Section		Reference			
Izz	Iyy	Izz	Iyy		
130 363 915 mm^4	32 687 726 mm^4	105 000 000 mm^4	34 400 000 mm^4	8 750 mm^2	23,721 Kg/m
13 036 cm^4	3 268 cm^4	10 500 cm^4	3 440 cm^4		

Table AII-3: Section properties

Judging the inertia moments of the approximated structure relative to the reference one designed by *Lattix* and considering all the details within it, it can be affirmed that the properties are similar and the results should be realistic. The Inertia relative to the vertical deflection (**I_{zz}**), are higher due to the geometric approximations that having solid squares at the ends, the extra material at the top flanges will increase the Inertia value.

The structural analysis made on *NX* was done recurring to 3D solids, with a 3D mesh. That's why the section of the main beams of the Boom and Legs needed to be simplified. Otherwise, the details that the proposed section has would generate many mesh conflicts that would complicate the solution of the analyses.

The big question about having a Gantry with a planar Boom instead of a square section Boom is its ability to resist to the vertical deflections caused by the self-weight and by the *VMS*'s weight and induced forces and torsional moments from the wind. The worst scenario that is previewed is the 30m span model with the *VMS* above the Boom which adds torsional moments to it due to the wind pressure on the sign surface.

This preliminary study was done for some combinations regarding the span, Leg's height, wind pressure and sign sizes and its position on boom. The next table summarizes the five cases studied.

Case	Span (S)	Height (H) to Boom's centre	VMS size	Position of the VMS on Boom	Wind Pressure
	[m]	[m]	[l x h] m^2		[kN/m^2]
1	20	6.3	[2 x 8.5]	Centric	2.2
2	20	6.3	[2.7 x 10]	Above	1.1

3	20	7.5	[3 x 10]	Centric	2.2
4	30	6.3	[2.7 x 10]	Above	1.1
5	30	7.5	[3 x 10]	Centric	2.2

Table AII-4: Case studies for the model's preliminary analyses

Then, for each case is presented its requirements, concerning the Boom and Leg's deflections.

Case	**Boom's Maximum Vertical deflection**		**Boom's Maximum Horizontal deflections**		**Leg's Maximum Horizontal deflections**	
1	S/200	100 mm	S/100	200 mm	H/100	63 mm
2	S/200	100 mm	S/200	100 mm	H/50	126 mm
3	S/200	100 mm	S/100	200 mm	H/100	75 mm
4	S/200	150 mm	S/200	150 mm	H/50	120 mm
5	S/200	150 mm	S/100	300 mm	H/100	126 mm

Table AII-5: Structural requirements

Finally, the next table presents the results for the five cases. Before, it is important to remember the orientation of the Cartesian coordinated system to visualize the direction of the presented displacements.

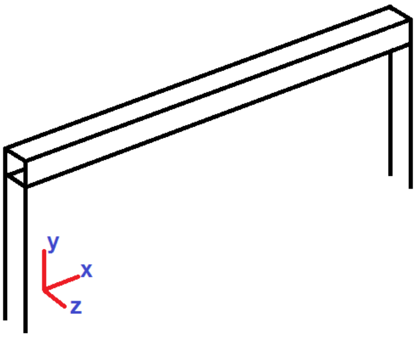

Figure AII-3: Referential of Coordinates

Case	**Boom's Maximum Vertical deflection [mm]**		**Leg's Maximum Horizontal deflection [mm]**	
	Vertical (y)	**Horizontal (z)**	**Horizontal (z)**	**Horizontal (x)**
1	50	37	14	4.6
2	91!	9	3.5	5.3
3	60	59	26	7
4	320!	87	14	14
5	230!	152	32	12.3

Table AII-6: Results of the preliminary analyses

As we can see in these preliminary results, with the [340x150] mm sections for the main Boom and Leg's beams, this model is not feasible for the 30m span Gantries. The vertical deflection limited to 150 mm is largely exceeded on both 30m cases.

It can be noticed that in the second case (the 20m span with the sign 2 above the Boom) the resulted vertical deflection is 91mm or in other words, 91% of the allowed value. This can be an indication that this case should be studied in more detail. This, because on the cases with the sign above the Boom, in the simulation file, in order to be able to apply a force above the boom (representing the centre of gravity of the *VMS* where it's being applied the equivalent force from the wind pressure on its surface) is necessary to create a spider mesh. This mesh connects the Boom's length in contact with the *VMS* with the point representing the *VMS*'s centre of gravity. By doing this, the torsional moment resulting of the sign's position on the boom is not being neglected, which contributes to the accuracy of the results. The drawback of this approach is that the spider mesh virtually adds some stiffness to the boom, which will minimize the vertical deflection.

Regarding the Boom and Legs' horizontal displacements, the results show that the values are well within the acceptable range.

With the goal of understanding the feasibility of this model as a new Gantry structure it is relevant to consider the same study, but with the largest sections that the manufacturing entities are able to extrude. The objective is to comprehend if the largest sections are enough to comply with the 30m span's requirements and if so, with how much material use. That will be discussed in the following section.

II-B Feasibility of the model:

This section will deal with the applicability of the biggest sections that are possible to extrude. The profiles are limited to the press sizes and power and also to the billet sizes, so it is important to know the dimensional limits.

The profile for the Legs and Boom's main beams will the same as before, but with the outer dimensions slightly bigger. The maximum dimensions that the profiles must obey are [420 x 230] mm.

The goal is to bring the deflection at the middle of the Boom for the 30m span models to the allowable range, which is a maximum of 150 mm. The "new" profiles have larger area and thus larger Inertias, but the question that rises is how much more material do we actually need to comply with the deflection requirements?

The design parameters of the main profiles are the wall thicknesses, because the outer dimensions are limited by the presented values. Therefore, before modelling and solving the problem in the *software*, it is relevant to preview the required increase of the Second Moment of Inertia around the axis that result in the Boom's vertical deflection. This study is important because it must exist always a balance between the structural stiffness and the amount of material that is used and that should be minimized as much as possible.

Below the simple calculations that were used to preview the new required Inertia will be described.

To make this estimation it was considered that the Boom's behaviour were equivalent to a beam pinned at the ends subjected to a uniformly distributed load. The distributed load represents mostly the structure's self-weight but also the additional snow and sign's loads.

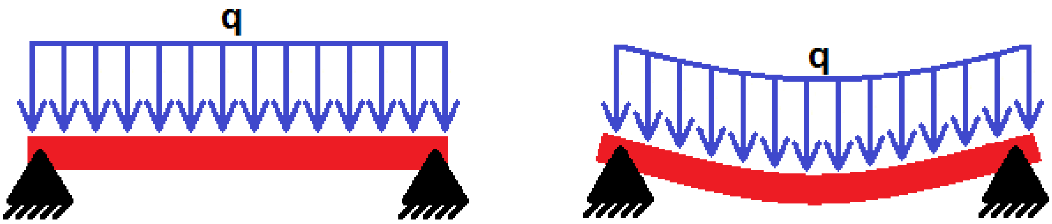

Figure AII-4: Deflection of a beam simply supported at the ends

The maximum central deflection can be found by the following expression.

$$\delta_{\max} = \frac{5\ qL^4}{384\ EI} \quad \text{(AII.1)}$$

Where $\boldsymbol{\delta_{\max}}$ is the maximum central deflection, **q** is the uniformly distributed force, **L** is the beam's length between the supports, **E** is the Young's Modulus of the beams' material and lastly, **I** is the Second Moment of Inertia.

The behaviour of the Boom lies between a beam simply supported at the ends and a beam fully fixed at both ends. This means that the Boom's ends are allowed to rotate but are still subjected to a restraining moment given by the connection to the Legs, which enables its rotation but maintaining the 90 degree relation between the two members. The following figure exemplifies in an augmented scale, the described rotation of the 90 degree connections on a result of the Gantry model studied on the beginning of this chapter.

Figure AII-5: Behaviour of the Boom's deflections in a Gantry

This way, is relevant to introduce the case of a beam fully fixed at both ends subjected equally to a uniformly distributed load and consider the central maximum deflection.

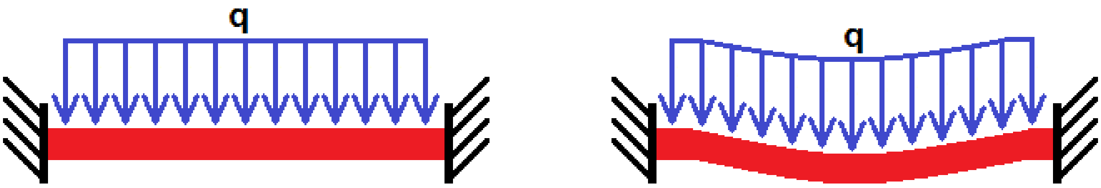

Figure AII-6: Deflection of a beam fully fixed at the ends

The maximum central deflection can be found by the following expression:

$$\delta_{\max} = \frac{qL^4}{384\ EI} \quad \text{(AII.2)}$$

As it can be directly taken from the maximum deflection expressions, the same beam fully fixed at both ends is 5 times stiffer than as if it was simply supported at the ends. For the estimation of the required Inertia Moment to the bigger section, in order to reduce the deflection, it was considered, as already stated, that the Boom's behaviour was equivalent to a beam pinned at both ends. This consideration is the most conservative regarding the stiffness of the real structure.

At this point we have the expression that describes the equivalent deflection of the Boom. Regarding the section, this study was done with the approximated section presented early in this chapter. So the following information can be known.

$$\delta_{\max} = \frac{5\ qL^4}{384\ EI} \Leftrightarrow 320\ = \frac{5 \text{ x } q\ \text{ x } 30\ 000^4}{384 \text{ x } 68\ 980 \text{ x } 130\ 363\ 915} \quad \text{(AII.3)}$$

Where in the $\boldsymbol{\delta_{\mathrm{max}}}$ was considered the worse result which was of 320mm, **L** is the span (30 000 mm), **E** for the aluminium allow used in the simulation is 68,98 GPa, **I** is 130 363 915 mm^4. With this data it is possible to deduce an equivalent uniformly distributed load (**q**). So, resolving the last equation we get the value of **q**.

$$\mathrm{q} = 0.273\ \mathrm{MPa} \quad \text{(AII.4)}$$

Since the objective of this study is to find the order of magnitude of the required Inertia of the bigger section, the applied loads (q), the span (L) and the material (E) will be the same. So we can describe the deflection's variation between the two sections by the following steps.

$$\delta_{\mathrm{max}} - \delta_{\mathrm{max}}^{\mathrm{new}} = \frac{5\ \mathrm{qL}^4}{384\ \mathrm{E}}\left(\frac{1}{\mathrm{I}} - \frac{1}{\mathrm{I}^{\mathrm{new}}}\right) \Leftrightarrow \delta_{\mathrm{max}} - \delta_{\mathrm{max}}^{\mathrm{new}} = \frac{5\ \mathrm{qL}^4}{384\ \mathrm{E}}\left(\frac{\mathrm{I}-\mathrm{I}^{\mathrm{new}}}{\mathrm{I}\ \mathrm{I}^{\mathrm{new}}}\right) \quad \text{(AII.5)}$$

Or considering the Inertia increase required to complying with a certain deflection reduction:

$$\Delta\delta_{\mathrm{max}} = \mathrm{Cte}\left(\frac{\Delta \mathrm{I}}{\mathrm{I}\ \mathrm{I}^{\mathrm{new}}}\right) \quad \text{(AII.6)}$$

where,

$$\mathrm{Cte} = \frac{5\ \mathrm{qL}^4}{384\ \mathrm{E}} = \frac{5\ \mathrm{x}\ 0.273\ \mathrm{x}\ 30\ 000^4}{384\ \mathrm{x}\ 68\ 980} = 4.17\mathrm{x}10^{10} \quad \text{(AII.7)}$$

We arrive then to the expression that can relate the increase in the section's Inertia Moment with the reduction on the Boom's deflection.

$$\boxed{\Delta\delta_{\mathrm{max}} = 4.17\mathrm{x}10^{10}\left(\frac{\Delta \mathrm{I}}{\mathrm{I}\ \mathrm{I}^{\mathrm{new}}}\right)} \quad \text{(AII.8)}$$

As the current value of deflection (for the worse 30m span case) is 320mm, in order to comply with the requirement of a maximum of 150mm, the deflection must be reduced at least in 170mm. So, solving the last equation, where the value for the current section is known (130 363 915 mm^4) and the $\Delta\delta_{\mathrm{max}} = 170$ mm we get the minimum required value for the new section's Inertia Moment.

$$\mathrm{I}^{\mathrm{new}} = 278\ 216\ 000\ \mathrm{mm}^4 \quad \text{(AII.9)}$$

With this estimation, it is stated that the Inertia of the [420x230] mm section has to be at least around the double of the current [340x210] mm section.

In order to estimate the values for the wall thicknesses for the new bigger section, it was conceived an Excel that enable to tuning the section and preview the values of the Moments of Inertia, Areas and the beam's Weight. The implementation was made resourcing to the same approximated section presented in the figure AII-2.

As can be seen, the section resists better to deflections around the **zz** axis and therefore the goal is to maximize **Izz**. By the Parallel Axis Theorem is known that in order to increase the Second Moment of Inertia we have to maximize the section's area as further away of the section's centroid. This means that the major contribution for the increase on the section's **Izz** will the increase of the wall thickness **t1**.

Consequently it was studied the influence of **t1** to the Inertia Moments. The thicknesses **t2** and **t3** were kept the same as in the [340 x 210] approximated section in order to save material as much as possible. The values used to preview the influence of the variation of **t1** and its results are shown in the following tables.

L	340 mm	**h1**	30 mm	**t1**	?
H	150 mm	**h2**	25 mm	**t2**	4 mm
				t3	5 mm

Table AII-7: Section dimensions used to preview the influence of t1

The section's aluminium walls must have a minimum thickness of 4 mm. About the maximum thickness it was considered a maximum of 15 mm. This value is dependent mostly on the billet sizes.

t1 [mm]	Izz [mm^4]	Iyy [mm^4]	Area [mm^2]	Kg/m
4	188 366 670	57 989 000	8 880	24.074
5	200 191 163	58 446 333	9 160	24.833
6	211 900 857	58 903 667	9 440	25.592
7	223 496 310	59 361 000	9 720	26.351
8	234 978 083	59 818 333	10 000	27.110
9	246 346 737	60 275 667	10 280	27.869
10	257 602 830	60 733 000	10 560	28.628
11	268 746 923	61 190 333	10 840	29.387

12	279 779 577	61 647 667	11 120	30.146
13	290 701 350	62 105 000	11 400	30.905
14	301 512 803	62 562 333	11 680	31.664
15	312 214 497	63 019 667	11 960	32.424

Table AII-8: Influence of t1 on the Inertias, Area and Weight per unit of length

Comparing the calculated required Inertia for the new bigger section necessary to reduce the deflection to the maximum allowable, which was 278 216 000 mm^4, we can estimate by the presented table that the thickness **t1** should be at least 12 mm. The maximum deflections resulting of the application of this bigger section must be reduced to the allowable interval, which means that must be smaller than 150 mm. In other words, the section must not be design to work on the limit, but inside the deflection's allowable range. So the selected **t1** should be such that the resulting **Izz** is higher than the required one calculated before.

Adding to this last reasoning, it should be reminded that the calculations in the previous table were made to the approximated section. The simplified version of the section present slightly higher values of the Inertia **Izz**, comparing to the equivalent real section with all its detail. This is caused by the solid squares approximation at the corners that increase the area at the top flanges, as mentioned before. This also means that the Inertias previewed in the table AII-8 will be actually lower, when applying the real sections.

Due to both reasons explained in the previous paragraphs it was decided to use a thickness (**t1**) of 15 mm on the new [420 x 230] mm sections.

For the modelling and computation solving of the proposed Gantry with the bigger sections it was used this time 1D analyses recurring to beam elements.

Regarding the structure's sections used for this study, it was considered two combinations. The first, both the Legs and Boom's main beams have the [420 x 230] mm sections with a thickness of 15 mm at the top flanges. In the second case, the Boom has the same bigger section, but the Legs keep the smaller [340 x 210] mm section. This approach was considered relevant because of the potential of the weight saving in the case of using the smaller Leg sections.

Before presenting the tables with the cases to be studied with the new sections is relevant to present its Inertia Moments, Area and Weight per unit of length both for the actual section and for the approximated ones that were used to preview the required Inertia **Izz**.

	"Real" Section				Approximate Section			
	Izz [cm^4]	Iyy [cm^4]	Area [mm^2]	[Kg/m]	Izz [cm^4]	Iyy [cm^4]	Area [mm^2]	[Kg/m]
[340x210]	8 977	2 997	7 019	19	10 500	3 440	8 750	23,7
[420x230] (t1=15mm)	28 800	5 992	11 269	30.5	31 221	6 302	11 960	32.4

Table AII-9: Case studies for the use of the [420x230] mm Boom's sections

Below are shown the four section profiles that the previous table refers.

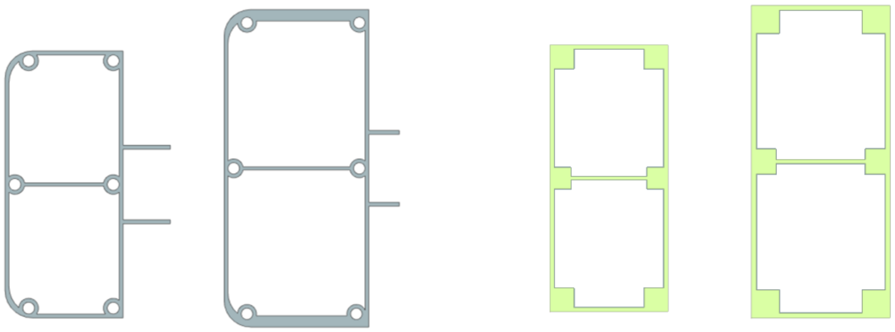

Figure AII-7: [340x210] mm and [420x230] mm sections: real vs approximated

The next table summarizes the four cases studied in this section. It is considered the two 30m span cases from the previous section, each of them with the two Leg's section combination.

Case	Span (S)	Height (H)	VMS size	Position of the VMS on Boom	Boom Main Section	Leg Main Section	Wind Pressure
	[m]	[m]	[l x h] m		[l x h] mm	[l x h] mm	[kN/m^2]
1.1	30	6.3	[2.7 x 10]	Above	[420x230]	[420x230]	1.1
1.2	30	6.3	[2.7 x 10]	Above	[420x230]	[340x210]	1.1
2.1	30	7.5	[3 x 10]	Centric	[420x230]	[420x230]	2.2
2.2	30	7.5	[3 x 10]	Centric	[420x230]	[340x210]	2.2

Table AII-10: Case studies for the use of the [420x230] mm Boom's sections

The requirements are presented again, in the next table, this time regarding the maximum Boom and Legs' torsion since the 1D analysis gives this result.

Case	Boom's Maximum Vertical deflection		Boom's Maximum Horizontal deflections		Leg's Maximum Horizontal deflections		Maximum Torsion (Leg or Boom)
1.1	S/200	150 mm	S/200	150 mm	H/50	126 mm	1º
1.2	S/200	150 mm	S/200	150 mm	H/50	126 mm	1º
2.1	S/200	150 mm	S/100	300 mm	H/100	75 mm	2.29º
2.2	S/200	150 mm	S/100	300 mm	H/100	75 mm	2.29º

Table AII-11: Structural requirements

The following table show the results for the four cases.

Case	Boom's Maximum Vertical deflection		Leg's Maximum Horizontal deflection		Maximum Torsion (Leg or Boom)
	Vertical (y)	Horizontal (z)	Horizontal (z)	Horizontal (x)	
1.1	112.3 mm	43 mm	6 mm	13 mm	2º
1.2	151.8 mm	47.2 mm	12.5 mm	17 mm	2º
2.1	122.8 mm	138.2 mm	9.2 mm	36 mm	0.87º
2.2	180 mm	150.7 mm	17.8 mm	46.2 mm	1.14º

Table AII-12: Results of the application of the [420x230] mm Boom's sections

Analysing the results presented on the previous table, is shown that the cases that have the Legs' smaller sections fail to comply with the 150 mm of the Boom's maximum vertical deflection. This can be explained due to the Legs' smaller stiffness that enables the angle at the Leg/Boom connections to be higher and thus there's a decrease in the resisting moment, which makes the Boom's behaviour approximate more like a pinned supported beams instead of a fully fixed one.

Since the results are much closer to the limit, is expected that a slight increase on the side wall thickness (**t3**) and the effect of this increase on the Inertia **Izz** should be enough to comply with that failing requirement.

Regarding the maximum torsion, it is shown that both cases with the *VMS* on top of the Boom end in a Boom's maximum angle above the 1 degree limit. This result is considered normal due to the position a size of the considered signs exposed to the wind pressure. This result can be contradicted by equally increasing **t3** but also increase the width of the section in a way that the total outer width (counting with the outer side flanges) does not exceed the imposed limit of 230 mm.

By the results of the performed studies, the *Lattix*’s concept seems to be a high risk solution as a Gantry structural configuration. On one hand, can be very rewarding, due to its simplicity, and on the other hand, can have displacements very close to the limits, or even beyond, in the worst load cases.