Master's thesis

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Investigations on the Development of a Cost Model for Large Infrastructure Elements, Exemplified by the Proposal for an Aluminium Suspension Bridge over the Langenuen Fjord in Norway

Master's thesis in Sustainable Manufacturing
Supervisor: Carla Susana A Assuad
Co-supervisor: Geir Ringen
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Abstract

Aluminium has the potential to enable extended service life and reduced maintenance of infrastructure elements. Nevertheless, aluminium is not as popular as steel and concrete for the construction of large infrastructure elements such as bridges, mainly due to higher initial costs.

This master thesis investigates whether a cost model could be a suitable tool to address concerns about higher initial costs, how such a cost model would have to be built and which specific uses it could serve. The research in this thesis is based on the concepts for the construction on an aluminium bridge crossing the Langenuen Fjord, which is part of the Norwegian E39 Coastal Highway Route project. A bottom-up process-based cost model that also incorporates feature-based approaches was created. Feature-based tests and a sensitivity analysis have proven the suitability of the model to reveal dynamics of costs depending on different design and process parameters. In addition, the ability of cost models to contribute to the understanding of costs and to stimulate discussion, as mentioned in literature, was confirmed.

Based on the test results, experiences from the modelling process, as well as related literature, a hybrid bottom-up process and feature-based cost model was identified as a suitable approach to cost modelling for large infrastructure elements. Integration with CAD software, feature databases and simulation software were found to be indispensable. Several conceivable applications for this type of cost model were discussed, including target costing and the achievement of objectives such as sustainability. For a comprehensive cost comparison of different material options, life cycle cost models were evaluated to be more suitable than the proposed cost model.

The findings of this thesis demonstrate that cost models can support cost-effective product and process design, reducing initial costs and increasing the competitiveness of aluminium for infrastructure elements.

Sammendrag

Aluminium har et stort potensial som materiale i store konstruksjonsprosjekter, spesielt med tanke på dens egenskaper som kan gi redusert vedlikehold og økt levetid på konstruksjonene. Likevel er bruken av aluminium liten i store konstruksjoner i motsetning til mer tradisjonelle valg som stål og betong, noe som ofte er begrunnet med høyere investeringskost eller innkjøpspris på aluminium.

Denne masteroppgaven undersøker om en kostnadsmodell kan være et egnet verktøy til å imøtekomme bekymringer om høyere startkostnader, hvordan en slik modell skal bygges opp, og hvilke spesifikke anvendelser den kan tjene. Arbeidet i denne masteroppgaven er basert på konseptet for en ny bro i aluminium over fjorden Langenuen, som er en del av veiprosjektet Ferjefri E39. En buttom-up prosessbasert kostnadsmodell med hensyn til egenskapsbaserte fremgangsmåter ble utviklet. Egenskapsbaserte tester og en følsomhetsanalyse har vist at modellen er egnet til å avdekke kostnadsdynamikken avhengig av forskjellige design- og prosessparametere. Dessuten ble kostnadsmodellens evne til å bidra til forståelse av kostnader, og fremme diskusjon som nevnt i litteraturen, bekreftet.

På grunnlag av testresultatene, erfaringene fra modelleringsprosessen, og relevant litteratur, ble en hybrid buttom-up prosess og egenskapsbasert kostnadsmodell identifisert som en passende fremgangsmåte for kostnadsmodelleringer av store konstruksjonselementer. Integrering med CAD-programmer, databaser for egenskaper, og simuleringsverktøy har vist seg uunnværlig. Flere tenkelige anvendelser for denne type kostnadsmodell har blitt drøftet, herunder målkostnad og oppfyllelsen av målsetninger som f.eks. er tilknyttet bærekraft. For en omfattende sammenligning av kostnader ved ulike materialvalg, er livsløpskostnadsmodeller vurdert som mer velegnet enn den foreslåtte kostnadsmodellen.

Resultatene fra denne oppgaven viser at kostnadsmodeller kan støtte kostnadseffektive produkt- og prosessdesign, redusere investeringskostnadene i prosjekt, og øke konkurransedyktigheten til aluminium i konstruksjonselementer.

Preface

I would like to thank my supervisors for their valuable guidance, sharing their knowledge and providing useful and inspiring literature.

I would also like to thank the working group on the production of the Langenuen suspension bridge, which has added value to my work through its input. Many thanks in particular to the direct reference contacts from this working group, Geir Mosaker, Harald Vestøl and Roy Blien.

Special thanks to Geir Ringen, who has been a knowledgeable advisor in his dual function of supervising the thesis and being involved in the Langenuen project.

Last but not least, I would like to thank Håkon. Thank you for the stimulating discussions we had, for proofreading my thesis, helping with the translation of the abstract into Norwegian, and for technical support. And an even bigger thank you for making the breaks from writing worthwhile and helping me find a balance during this time of home office and contact restrictions.

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List of Abbreviations (or Symbols)

A0	Area billet
ABC	Activity-based costing
Af	Area extrusion cross section
ar	Arc rate
arc	Arc time per bridge deck section
Aw	Cross-sectional area of the weld groove (MIG welding)
Bds	Butt discard
Bu	Buffer length on profile ends
CAD	Computer-aided design
Ccd	Circumscribing circle diameter
Ccost	Consumable’s cost
CO_2	Carbon dioxide
ct	Cycle time
db	Depth of bevel (MIG welding)
Dcost	Depreciation cost
De	Deposition efficiency
Ded	Durability of extrusion die
DES	Discrete event simulation
dfw	Filler Wire diameter
Dlc	Direct labour cost per month
Dp	Depreciation period
Dt	Durability of tool
dtc	Dead cycle time per billet
Ec	Energy cost per kwh
Ecost	Energy cost
Ed	Energy distribution cost per kwh
Eeg	Energy efficiency welding gun
Eg	Energy consumption welding gun
Et	Energy total
Etb	Extrusion time per billet
FBC	Feature-based costing
FSW	Friction stir welding
Gc	Shielding gas consumption
Gcost	Cost of shielding gas per module
Gp	Price of shielding gas
Ic	Investment cost
Kwh	Kilowatt hour
L0	Billet length
Lcost	Labour cost
LME	London Metal exchange
Lp	Panel length
Lp	Panel length
Lprt	Profile length total
Lprtb	Profile length total incl. buffer
Ls	Length scrapped per continuous extrusion
Lt	Runout table length
Lw	Weld length per module

Mcm	Material cost per module
Mcost	Material cost including recovery
Mct	Material cost per tonne
MIG	Metal inert gas
Mpm	Mass of primary material
Nbm	Number of billets per top deck module
Ncav	Number of die cavities
Nh	Number of welding heads
No	Number of Operators
NOK	Norwegian kroner
Np	Number of passes (MIG welding)
Npe	Number of parts per runout extrusion
Npl	Number of panels length direction
Npw	Number of panels width direction
NTNU	Norwegian University of Science and Technology
Oc	Overhead cost per hour
occ	Occupancy of production line
Ocost	Overhead cost
Od	Overhead direct per month
PBCM	Process-based cost modelling
pd	Planned downtime
Pg	Input power welding gun
Plb	Extruded length of one billett
ra	Ram acceleration time per billet
RQ	Research question
SD	System dynamics
st	Set-up time
Tco	Cost of tool
Tcost	Tooling cost
ud	Unplanned downtime
VAT	Value-added tax
vf	Exit speed
Vg	Volume of 1 kg shielding gas
Vrec	Income of internal scrap (recovery)
Vsc	Value of internal scrap
wfr	Wire feed rate
Wp	Panel width
ws	Welding speed
Ye	Yield
α	Groove angle (MIG welding)
ρ	Density of input material

1 Introduction

Bridges are an integral part of infrastructure worldwide and come in a variety of shapes, lengths and materials, with steel and concrete being the dominant materials in existing bridges in Europe and North America, but also in new constructions [1, 2]. However, bridges made of these materials are susceptible to corrosion, often related to the ingress of de-icing salt, leading to structural deficiencies, reduced service life and high maintenance intensity. In addition, the cost of replacing or renewing such bridges is high [2, 3]. Material alternatives such as fibre-reinforced composites and aluminium seem to be a promising solution to this challenge, as they do not rust, do not require any protective treatment, and are lighter, faster to produce and erect [3]. In addition to being maintenance-free, eliminating the need for corrosion protection, lighter weight and shorter fabrication time, the advantages for aluminium in particular include a good recycling rate. Thus, when end-of-life aspects are taken into account, aluminium bridges have a lower carbon footprint than comparable steel structures. Yet this is always dependent on where the material is sourced and where production and assembly take place [4].

Aluminium in bridge construction is not a new idea: the first aluminium bridge span was built in the USA in 1946 as part of a modernisation project. The first all-aluminium bridge was built in Canada in 1950. The world's first welded aluminium bridge was the Clive Road Bridge over interstate highway I-80 in Des Moines, Iowa, with a length of 67 m and a width of 10,97 m [3]. Although used in bridge construction for some time, and despite its many advantages, aluminium and other alternative materials are not widely used in this industry. This is mainly due to the higher initial cost compared to steel and concrete [3]. However, these initial costs are only a part of the total cost of a bridge. At the end of the last century, the useful service life of a bridge in the United Kingdom was about 120 years [2]. Considering the total lifetime of a bridge, the costs for it can be divided into different stages, the first stage being the high initial costs for the design and construction of the bridge. The next stage is the cost of regular inspections and maintenance over the life of the bridge. This is followed by the cost of expected repairs during the life of the bridge, including the cost of disrupting traffic for repairs. The fourth cost stage includes possible reinforcement measures to account for increased traffic loads or changes in design specifications, again considering the cost of possible traffic disruption. Lastly, the possibility of modifying or replacing the bridge due to the widening of the road carried or crossed must be included in the whole life cost [2]. Even though the consideration of costs beyond construction has gained in importance, in most cases the initial costs determine which design proposal is realised [2, 3]. This can be expected to change when sophisticated methods for estimating life cycle costs are available and commonly used. Furthermore, efforts to reduce initial costs will increase the competitiveness of aluminium in bridge construction [3].

This thesis investigates the determination and possible reduction of initial costs of large infrastructure elements by means of cost models, exemplified by a specific case. As part of the Norwegian Coastal Highway Route E39 project, which aims to establish a ferry-free connection of the Norwegian west coast between Kristiansand and Trondheim, reducing travel time and emissions, a suspension bridge is to be built over the Langenuen fjord [5, 6]. In a project between industry and the Norwegian University of Science and Technology (NTNU), the substitution of conventional steel with aluminium as a construction material for long suspension bridge girders is investigated, and two concepts for an aluminium bridge across the Langenuen fjord were developed. The Langenuen Suspension Bridge Project is a pilot project whose implementation would represent a ground-breaking step in bridge construction, not least because of the bridge's length of 1775 m, but also because a span of 1235 m is planned as a suspension bridge [4]. To the knowledge of the research group and author of this thesis, such a bridge has not been built from aluminium before.

A study [4] found, that the concepts for the Langenuen suspension bridge, that were developed in a cooperation between Hydro, Leirvik AS, NTNU and Dr. Techn. Olav Olsen, can compete with steel regarding costs. The study estimated the costs of the main structural elements of the bridge and compared them to the costs of a steel alternative. This was done for all concepts developed and within these concepts for the elements of concrete towers, main girders, steel hangers and main steel cables. The result of this investigation is that the aluminium bridge girder itself is more expensive than its steel counterpart. The higher costs for the girders are offset by lower costs for the other main elements, for example cables and hangers. This compensation is achieved through the lower weight of aluminium, which means that other elements can be reduced, e.g., in load-bearing capacity, which saves material and costs. However, the potential to reduce the cost of the aluminium main girders through design or process changes within a single concept remained unexplored. The study [4] of the Langenuen suspension bridge concepts shows that aluminium is a promising material for bridge construction that can be both economically and ecologically worthwhile. Since however, decisions regarding construction concepts are made based on the initial costs, as mentioned earlier, the mere compensation of the increased costs for aluminium girders makes aluminium at most as attractive as steel. This assessment does not consider the possible pros and cons of the many years of experience in bridge construction with steel compared to the limited experience in bridge construction with aluminium. It is therefore assumed that without a reliable, quantitative comparison of the life cycle costs of steel and aluminium bridges, aluminium concepts must undercut steel concepts in initial costs to be truly competitive.

With regard to the Langenuen suspension bridge project, it is important to find out how margins in design and process can be optimally utilised in order to manufacture a bridge girder in the most cost-effective way.

1.1 Goal and scope

The previous section indicates an unexploited potential of aluminium in bridge construction, mainly due to higher initial costs compared to conventional materials. In 2006, Siwowski [3] predicted a major opportunity in the replacement of "deteriorated bridges with aluminium decks and/or girders without strengthening the foundations and piers". He continued that this "could generate a significant market for aluminium plates and extrusions, as more and more bridges worldwide are reported to be in serious to urgent need of replacement".

The aim of this master thesis is to find out whether a cost model could be a suitable tool to address concerns about higher initial costs by reducing costs before they occur. In this context, a cost model is developed, and it is assessed whether cost models could ultimately increase the competitiveness of aluminium as an infrastructural construction material. Additionally, the opportunities for the use of cost models for large infrastructure elements and their advantages as well as limitations are to be examined.

Due to time constraints and to limit the complexity, only one of the developed concepts for the Langenuen bridge, and only the top deck, is considered in the development of a cost model. Although the Langenuen case is used as an example, it is not part of this thesis to make a reliable prediction of the costs of bridge elements or to arrive at recommendations on cost effective product and process design for the Langenuen case.

1.2 Research question and objectives

The research questions (RQ) in this thesis address the initial costs for large infrastructure projects such as bridges, which are the main decision criterion in the selection of design proposals. These initial costs need to be predicted reliably and early in the design process in order to generate cost-effective, competitive designs.

RQ1: In what way can a comprehensive cost model for large infrastructure elements be established?

RQ2: In what uses might cost models for large infrastructure elements be of benefit?

Three objectives have been set up to help reach a conclusion regarding the research questions.

- Developing a cost model based on the specific case of the Langenuen suspension bridge
- Determining requirements for cost models for large infrastructure elements in general
- Deriving suitable uses for a cost model for large infrastructure elements from related literature

1.3 Structure of the thesis

The structure of this thesis, and the content of each section, is as follows:

1. **Introduction** – This section provides information on aluminium in bridgebuilding and on the motivation for this thesis. Furthermore, the research questions and objectives are stated.
2. **Theoretical background** – This section contains information on aluminium in general, and on the processes in the building of an aluminium bridge. In reference to the plans for the Langenuen suspension bridge the manufacturing processes extrusion, friction stir welding, and metal inert gas welding are presented and explained. Furthermore, background information on the topic of cost estimation is provided and a literature review on cost modelling is carried out.
3. **Method** – In this chapter the choice of method for creating a cost model is justified, and the scope of the model is defined. A flowchart of the processes relevant for the model is presented and basic assumptions to base the model on are made. Additionally, tests to carry out with the model are named.
4. **The model** – This section provides a detailed description of the developed model, including structure, equations, and assumptions for inputs.
5. **Results** – In this section the results of the performed tests are presented and analysed.

6. **Discussion** – In this section, the developed model is evaluated, based on the results obtained from the tests. Solutions to the limitations of the model are discussed and suggestions for the development of more advanced models are made. In addition, the possible applications of cost models for large infrastructure elements are discussed.
7. **Conclusion** – This final section of the thesis summarizes the findings and answers the research questions. The weaknesses of the study are reflected upon and areas for future research are identified.

2 Theoretical background

The following section of the thesis provides background knowledge that is relevant to understanding the work. The production and characteristics of aluminium are outlined. A brief introduction to the individual processes involved in the manufacture of a bridge is given, based on the case of the Langenuen suspension bridge. Furthermore, important aspects of cost estimation are outlined, and different approaches and areas of application are presented by means of a literature review.

2.1 Aluminium

Aluminium is a metal that requires several steps to produce. The primary ore from which aluminium is produced is bauxite. Bauxite is a hard, clay-like material with a reddish colour, found mainly in tropical and sub-tropical areas [7]. Bauxite consists mainly of hydrated aluminium oxides [8]. Bauxite is mined and first dissolved in a process known as the Bayer process. Aluminium hydroxide is then precipitated from the liquid, and alumina (aluminium oxide) is obtained by calcination. Finally, molten aluminium metal is produced from alumina in an electrolysis process in a smelter [7, 8]. This last process step releases carbon dioxide (CO_2) [8] and is moreover very energy-intensive. The latter leads to the availability of cheap electricity often determining where aluminium smelters are located [7]. Approximately four tonnes of dried bauxite are needed to produce one tonne of aluminium [9].

With a density close to one third that of steel, aluminium is a light metal. Furthermore, aluminium is a good conductor of heat and electricity [7, 9]. It is non-toxic, non-magnetic and non-sparking, easily formed, machined or cast [7]. There are numerous aluminium alloys that are grouped into eight series, each series having different properties and application areas [10]. Common metals or elements with which aluminium is alloyed are copper, magnesium and silicon [7]. Aluminium is highly resistant to corrosion, and so are its alloys of the 1000, 3000, 5000, 6000 and 8000 series [10].

Aluminium is used in a number of industries, most of all in the production of aircrafts, cars, trains and ships, but it is also used in the production of packaging, window frames, in the electrical industry and other areas [7]. The aforementioned properties of aluminium and its alloys implicate advantages for products made of it, such as a long service life, low maintenance and preserved appearance [10]. A further advantage of aluminium is its recyclability. To produce secondary aluminium from scrap requires only about 5% of the energy needed to produce a same mass of primary aluminium from the ore. Hence, recycling of aluminium does not only save resources, but also cuts energy costs significantly, which makes it economically attractive [8].

2.2 Processes in the building of an aluminium bridge

The assumptions for the construction of aluminium bridges made in this thesis are based on the concept for the Langenuen suspension bridge, the planning of which initiated this thesis. In the project report [4] published in June 2020, two main concepts for the construction of the bridge girders are presented: a panel concept and a plate concept.

The panel concept serves as a starting point and guiding example for the construction of aluminium bridges in this thesis.

The concept, which was developed in cooperation between Hydro, Leirvik AS, NTNU and Dr. Techn. Olav Olsen envisages the construction of bridge girders from panels consisting of aluminium profiles. The alloy to be used for all profiles is EN AW6005A-T6. The cross-section of a bridge girder of this type is shown in Figure 1. The panels can be aligned either longitudinally or transversely to the traffic lane [4].

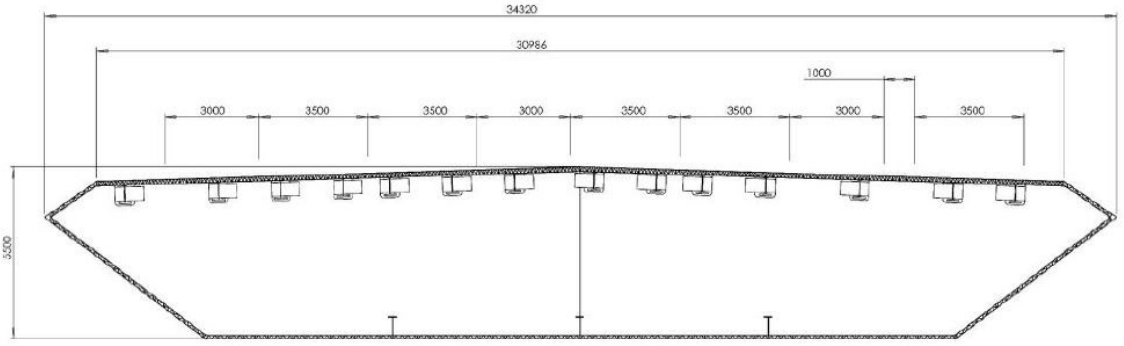


Figure 1: Cross-section bridge girder, panel concept [4]

A girder section for the Langenuen suspension bridge is ca. 34 m wide, 5,5 m high and 12 m long. In the longitudinal version, the panels are arranged lengthwise in the girder and are as long as one entire section. The alignment of the panels in the bridge girder is shown in Figure 2. The 12 m long sections are assembled into 120 m long modules with a bulkhead every 12 m, and are transported to the construction site where they are connected with the other structural elements to form the final bridge [4].

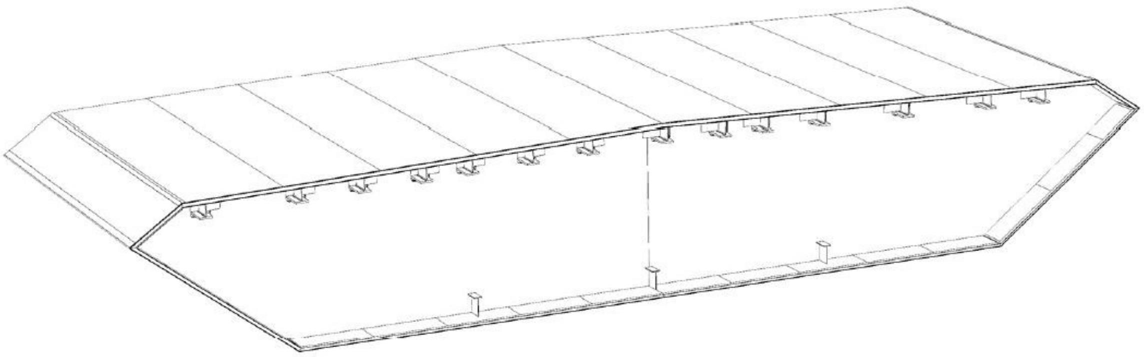


Figure 2: Girder section with longitudinal panels [4]

Longitudinal and transversal concepts differ only in the orientation of the panels, and some construction details that this entails. For the outer hull, both concepts use the same panels made of extruded profiles and the geometrical key data of the design also correspond. In the transverse concept the panels are arranged transversely to the direction of the bridge and transverse bulkheads support the deck at intervals of 3.9 m. A schematic illustration of a bridge girder cross-section in the transverse panel concept is shown in Figure 3.

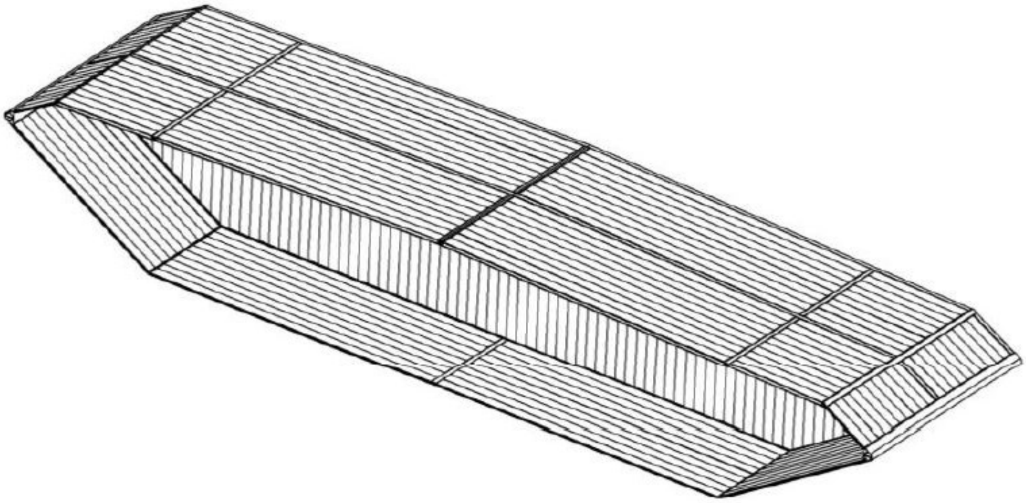


Figure 3: Girder section with transverse panels [4]

As explained above, a girder section consists of panels, which are made up of profiles. These profiles are extruded and then joined into panels using friction stir welding (FSW). This manufacturing process is the same for the top deck panels, as well as the bottom and side panels, although varying profile thicknesses are provided in the concept presented in [4]. The panels are joined together by metal inert gas (MIG) welding [4].

The panel concept for the construction of the Langenuen suspension bridge made of aluminium includes further construction details. For example, different types of joiner profiles are intended to connect the different types of panels i.e., top, sides, bottom, as well as the bulkheads. However, this work focuses on the fabrication of the top deck. The aforementioned details are therefore outside the scope of this work and will not be further explained here. In summary, the production processes for the top deck of a girder section are extrusion of aluminium profiles, the use of FSW to join the profiles into panels and the joining the panels to top deck sections and those to modules, using MIG welding. An explanation of the individual processes is provided below.

2.2.1 Extrusion

Extrusion is a forming process used to produce long metal components of solid or hollow type with a consistent cross-section. A ram pushes metal billets through a die opening, the design of which determines the shape of the extruded component [11]. A distinction is made between cold extrusion and hot extrusion. In cold extrusion the billet is at room temperature when it is fed into the extrusion press. In hot extrusion, the billet is heated beforehand. The billet temperatures depend on the material and are between 340-595 °C for aluminium alloys. Hot extrusion can be classified into non-lubricated, lubricated, or hydrostatic extrusion. In lubricated extrusion, a suitable lubricant, e.g., molten glass, is used to reduce the sliding friction stress between the tool and the workpiece. In hydrostatic extrusion, a film of liquid keeps the ram and die from direct contact with the billet [12]. For aluminium alloys, the non-lubricated extrusion is typical and that can be carried out direct (forward) or indirect (backward). In direct extrusion, the heated billet is placed in the container and a ram pushing a dummy block forces the material through the die. In indirect extrusion, the die is installed at the front of a hollow ram. The material is forced through the die as the heated billet, located in a closed container is pushed onto the fixed ram stem [12]. A schematic illustration of both processes is provided in Figure 4.

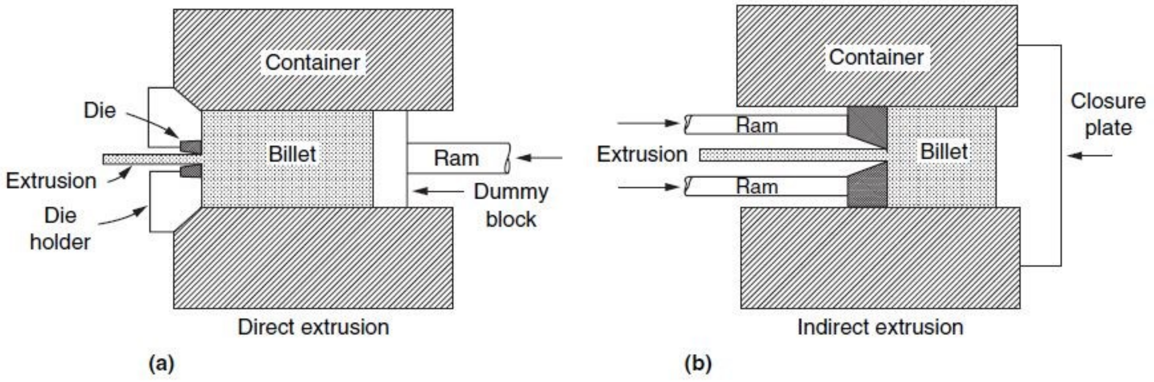


Figure 4: Schematic illustrations of (a) direct and (b) indirect extrusion [12, 13]

Indirect extrusion has advantages, such as no relative motion between container wall and billet, resulting in minimal friction stress. However, the need for a hollow ram creates limitations in this process, e.g., in the achievable extrusion size. For this reason, hot extrusion processes are mostly direct [13]. To produce profiles for bridge girders such as the one described in 2.2, non-lubricated, direct hot extrusion is assumed. When extrusion is referred to hereafter in this paper, the process of non-lubricated, direct hot extrusion is meant, unless explicitly stated otherwise.

A set of different parameters can be used to describe size and complexity of an extrusion and consequently the effort it takes to produce it. The circumscribing circle diameter (Ccd) and the shape factor are the widely used metrics in the industry. [11]. The circumscribing circle diameter is obtained by tracing a minimum circle around the cross-section of the shape to be extruded. It is used to express the size of an extrusion [12]. The shape factor describes how much surface area is generated per unit weight of extruded material. It is calculated by dividing the perimeter of the cross-section by the weight of a unit of length of the extrusion [11, 12]. This parameter is often used by extruders as a basis for pricing, as it affects the production rate, as well as tooling and maintenance costs [12].

To improve extrudability and the surface finish of the extruded part, aluminium billets usually undergo a heat treatment called homogenization, prior to extrusion. This process is part of the billet preparation, which is one of the critical parameters for successful and efficient hot extrusion [12]. Another critical parameter is the billet temperature. A too high temperature can lead to cracking or tearing, while a too low temperature reduces the tool life and increases the pressure requirements for extrusion [12]. The amount of pressure or force required is another critical parameter and this is influenced, apart from the working temperature, by the extrusion ratio, the deformation speed and the friction conditions between the billet and the tool [13]. The extrusion ratio describes the ratio between the initial cross-sectional area of the billet and the final cross-sectional area of the extruded part [13]. Determining pressure requirements is a complex process that can be based on various formulas as well as empirical values [12]. Furthermore, essential for hot extrusion is the ram speed. Too low speed reduces productivity and can cause the billet to cool down, which increases pressure requirements. Too high speed on the other hand can cause overheating of the billet and lead to surface defects. Typical ram speeds for aluminium are between 12,7–25,4 mm/s [12].

During extrusion, a puller system and a run-out table support and guide the product. A stretcher straightens the extruded product and a cut-off saw cuts the parts to the required length. After extrusion, quenching is usually carried out [11].

2.2.2 Friction stir welding

Friction stir welding is a solid-state welding process and a further development of the conventional friction welding process. Solid state welding takes place below the melting temperatures of the base material and therefore requires no filler material and no inert environment for the emergence of the oxide phase. In conventional friction welding friction between a moving part and a stationary one creates heat, while a lateral force is applied. The heat from the mechanical friction together with the pressure causes the materials to fuse together [14]. In the FSW process, a rotating tool generates frictional heat and pressure. The tool has a shoulder and a profiled pin and is plunged into the joint line between two materials to be connected [14]. A schematic representation of this process is shown in Figure 5.

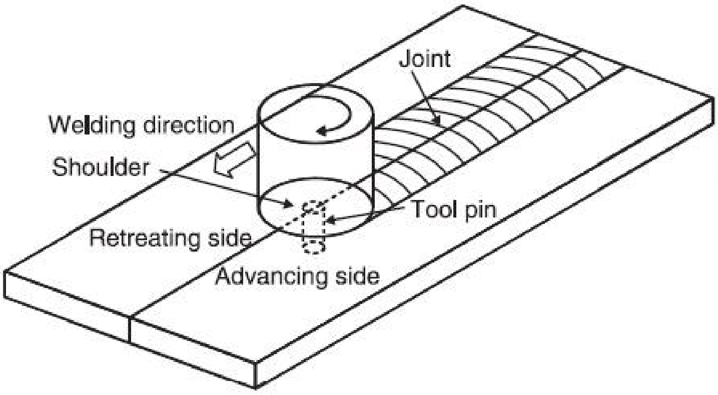


Figure 5: Schematic of FSW process [14]

In FSW no protective equipment for the personnel is needed, as opposed to for example manual MIG welding. This eliminates the time needed to put on protective clothing before welding and take it off again after welding [15]. Further advantages of FSW are that it is an energy efficient and environmentally friendly process. As there is no weld pool, the process can be carried out in any position. It is easily automated, which results in lower set-up costs and less training. Moreover, with FSW, the need for post-weld finishing is reduced, as generally a good appearance of the weld is achieved with minimal thickness mismatch [14]. Financial benefits are derived from the above-mentioned advantages. The elimination of protective clothing and extensive post-processing saves time and thus costs. The same applies to the simplified welding preparation, because with FSW only cleaning of the plates with alcohol is necessary. In addition, the costs for the purchase of filler material and shielding gas are eliminated and the low energy consumption leads to low costs at this end [16]. There are also some disadvantages associated with the process, for example the need for large downward forces and heavy clamping devices to hold the parts to be joined [14]. The main process parameters in FSW that impact the appearance and quality of a weld are rotation speed, down force, welding speed and tilting angle [16].

2.2.3 MIG welding

MIG welding, short for metal arc inert gas shielded process, is the most common manual arc welding process for the joining of aluminium [17]. The process is characterised by relatively high productivity due to its ease of starting and stopping. It is most dominant in thin sheet welding but is used in a vast range of plate thicknesses [18]. In MIG welding, a wire used as both electrode and filler material is melted in an arc. To replace the metal that has melted away, the wire is continuously fed forward. The welding arc is an electrical discharge between two electrodes and requires a welding power source to supply electrical energy. The arc and the molten material, called the weld pool, are protected by a shielding gas [17, 18]. The principle and features of this process are illustrated in Figure 6.

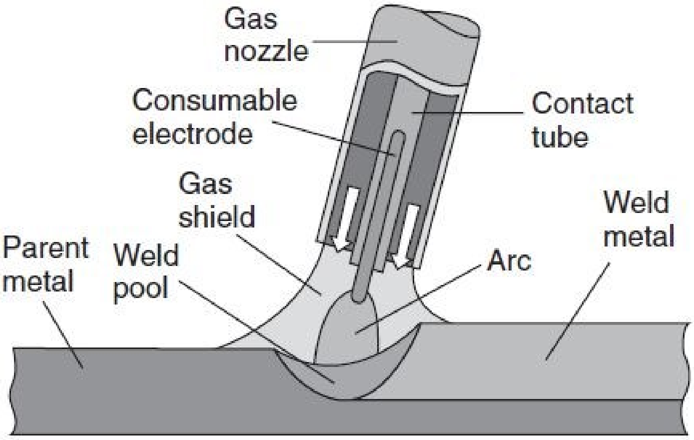


Figure 6: Principle and features of MIG welding [17]

The shielding gas is necessary because active gases such as oxygen or nitrogen can cause porosity and contamination problems. The inert gases helium and argon are used in MIG welding of aluminium, with argon being the most commonly used one. It is used mainly for manual MIG welding processes, but also for some automated processes. Argon is cheaper than helium, but provides a lower level of heat input, which limits the welding speed [17]. Using helium as shielding gas, welding speeds are up to three times higher than when producing a similar joint using argon as shielding gas. The reason for this is that helium leads to a much hotter arc, as the arc voltage is increased by up to 20%. The higher arc voltage also results in an increased penetration and a wider weld bead, making the positioning of the arc less critical [17]. When welding thick-walled aluminium, the increased heat input from helium offers the possibility to compensate for the high heat conduction of the material [18]. The disadvantages of helium are a less stable arc and a higher price. Helium is mostly used in mechanised or automatic welding. In some welding applications mixtures of argon and helium are used [17].

The MIG welding process is easy to automate [17, 18]. Some of the benefits of automated MIG welding are a more consistent quality of the welds, higher welding speeds, a hotter weld and reduced porosity, as well as more continuity in the process. These advantages result in less welding time being required and reduced need for rework. Hence, productivity is improved and costs are reduced [17]. Several methods exist, that increase the productivity of mechanised MIG welding. For example, the wire stick-out can be preheated by extended resistance heating. This allows a higher feed rate to be achieved without increasing the current accordingly. Productivity can also be increased by using two filler wires. The wires can be connected to the same power source, as in twin wire welding, or each can have its own power source, as in tandem welding. Welding with two wires in a common weld pool can double the welding speed, but it can complicate the setting of welding current and voltage. Hybrid welding, the combination of MIG and laser welding, also leads to increased welding speed and productivity compared to conventional MIG welding [18]. In addition to the parameters mentioned above, such as welding speed, wire feed speed, current and voltage, there are other important parameters that influence the welding process. Wire size, inductance or dynamic properties, wire stick-out, choice of shielding gas and gas flow rate, torch and joint position, torch weaving pattern, and pulsed wire feed complete the list of parameters on which the MIG welding process depends [18].

Welding costs are mainly composed of labour costs, machine costs, consumables costs and energy costs [15, 18]. The literature states that in manual MIG welding, labour accounts for a large proportion of the costs. In automated welding, this proportion is lower, and the machine costs are more significant. Consumables account for about 11% of the costs, of which 7% for filler wire and 4% for shielding gas. However, depending on the material, the cost of filler wire can vary greatly. Energy costs typically account for 4% of the total cost of the manual MIG welding process [18]. A detailed and case specific description of the calculation of the costs for MIG welding is given in 4.4.

2.3 Cost estimation

Costs are an important factor in the manufacturing industry, as costs largely determine the competitiveness of a product. They decide which design proposal is realised [3], or whether a project will be continued or terminated. The assessment of cost effectiveness is an important part of risk management in preliminary studies carried out before launching the main project [19]. For such assessments, cost estimates are needed. Cost estimates describe what costs can be expected for the manufacture of a product or execution of a project before the actual realisation is initiated. The accuracy of cost estimates depends on the level of detail, the calculation basis and the reliability of the data used [20].

In their research work on cost optimisation of new ship developments, Caprace and Rigo [21] briefly analyse benefits and shortcomings of top-down, bottom-up and life cycle approaches for the estimation of production cost. Even though the analysis refers to ships, much of what is written is also valid for this master thesis. For example, Caprace and Rigo [21] say that the top-down approach, because it relies on historical data, is not appropriate for new developments. Moreover, in shipbuilding this approach often uses parameters such as size of the ship, or weight of the hull, as a reference. The impacts of new production technologies, or changes in design that do not affect weight, would therefore not be reflected in the cost estimation. The top-down approach is only applicable if a similar design already exists [21]. The bottom-up approach, on the other hand, breaks down the project to be analysed to the most basic manufacturing steps and thus considers the manufacturing effort for a product. This approach is more time-consuming and requires more information, but it considers different cost drivers and therefore provides realistic estimates [21]. Lifecycle approaches take into account not only pre consumer costs, but also any service costs that may be incurred, such as maintenance, repair and overhaul [21].

Conventional cost estimation methods provide a quantitative basis on which a decision to continue or terminate a project is made. However, they do not offer the possibility to explore which variants of alternative solutions for projects or products could lead to acceptable cost estimates. This type of decision support is considered particularly helpful for new product developments [22]. In engineering, this type of decision support is commonly provided through mathematical models using analytical methods. Decisionmakers, can thus understand the consequences of their decisions before they are put into practice. The same approach is followed in the development of cost models [23].

2.3.1 Literature review on cost modelling

Costs depend on the context in which products are designed and manufactured. They are an evolving property whose analysis must be based on a consistent and transparent representation of this context [24]. One way to do so is to develop cost models that can help avoid costly strategic mistakes in product development and launch [23]. The literature shows that cost management, modelling and estimation methods are continuously being reviewed, developed, and refined.

Field, et al. [24] state, that "a product cost is dependent upon the architecture and composition of the product, the properties of the elements employed in that composition, and the processes whereby those elements are shaped to yield that desired architecture" [24]. Based on this statement, they define the underlying principle of building cost models as converting the complex and interrelated effects of changes in design and/or process technology into a cost metric. This metric can then serve as a basis for discussing costs and their underlying factors with diverse groups, but also as analytical tool to support decision making in questions regarding design, material or process [24]. Field, et al. [24] state that cost models can be used to identify the technological obstacles to achieving a specific cost target for production. These obstacles can be identified not only in general terms, but in relation to specific technological, operational, or financial factors.

Specially developed for the achievement of cost targets is the method of target costing. The principle of target costing is that rather than calculating the cost of the completed design, cost and value drive the design process [25]. The starting point of target costing is the determination of a realisable sales price for the product to be developed and based on this, the allowable costs for the development and manufacture of the product. Early cost estimates are needed to meet the cost target [26]. Techniques often used in the process of target costing are value engineering, Quality Function Deployment, Cost Deployment Flowcharts as well as Design for Manufacture and Assembly [27]. Pazarceviren and Dede [28] developed a lifecycle costing model which is based on target costing and activity-based costing (ABC). ABC is a method in which costs in form of resources are allocated to activities which consume resources. The resulting activity costs are then allocated to products, services, or customers, so called cost objects [28, 29]. The lifecycle costing model proposed in [28] considers all costs in the product life cycle, from the design phase to any service costs incurred after the sale. Pazarceviren and Dede [28] say that while target costing can identify market requirements and cost targets and estimate the cost of a product before it is produced, ABC is able to provide information on the cost of design alternatives. Consequently, ABC can serve as a tool for achieving target costs and is considered a reasonable complement to target costing by the aforementioned researchers. They also point out the value of ABC for the identification and control of indirect costs, especially with regard to the post-production stages of the product life cycle. Pazarceviren and Dede [28] conclude that the use of ABC as an alternative to conventional techniques used in target costing allows for more accurate cost estimates. Philpott, et al. [30] criticise that ABC is a time-consuming cost estimation approach and is furthermore dependent on experiences and knowledge from manufacturing or cost engineers and therefore not accurate. The use of expert judgement in cost estimation methods is also discussed in other research papers, and is found to be subjective and intuitive, yet a commonly used tool [31-33]. Roy, et al. [31], who conducted a study on data requirements for cost estimation in the automotive industry, emphasise the need for better information not only for the generation of sound cost estimates but also for a better understanding of them. Locascio [33] says that cost-relevant decisions are often made based on experience or rules of thumb and refers primarily to the design phase. In her work, she presents a design cost model that uses the ABC method, and only includes activities that directly affect the design. According to her, the resulting model is transparent, easy to understand and to apply, and "generates the quantitative proof for the intuition that design and manufacturing engineers have for cost improvements" [33]. The model presented is able to quantify the impact of design decisions on manufacturing, but it does not give an indication of the total cost of the product and its manufacture. Consistent with the statements of Locascio [33], Philpott, et al. [30] say that design choices made early in product development cause a significant fraction of a parts cost. They state that the lack of early cost estimates leads to additional manufacturing costs because the opportunity to optimise costs through early, informed decisions is denied. Since Philpott, et al. [30], as mentioned earlier, see deficits in ABC and process-driven cost models, they invented a tool that predicts costs in real time based on design features. The approach is called integrated real-time feature-based costing (FBC) by its inventors and enables the estimation and optimization of manufacturing cost and assemblies of parts feature by feature during the design process. This is possible through the integration of the invented tool into a computer-aided design (CAD) system. Memory management techniques and genetic algorithms are used "to rapidly search through possible combinations of tool paths and routings to arrive at the lowest cost method of processing the part" [30] while a designer generates a CAD model. Philpott, et al. [30] note that the proposed FBC system has the effect of allowing designers to learn interactively how their decisions affect costs. Caprace and Rigo [21], who applied FBC to the shipbuilding industry come to a similar conclusion. They state that ship designers gain a better understanding of the cost implications of design decisions and that this results in the design of more cost-effective ships in the long run. The FBC module they developed is connected to a CAD database. It represents a prototype, which for the time being only estimates the cost of building the external structure of a ship. The development is to be extended in subsequent studies so that the so-called outfitting of a ship, i.e. aspects such as heating, piping or electricity, are also taken into account in the FBC [21].

The model of Chayoukhi, et al. [34] is also linked to a database, which they created especially for their purposes. It stores information about dimensional, geometrical, and technological characteristics of weld seams, which the researchers refer to as preparation features. The developed model is able to calculate the costs for suitable preparation processes based on the preparation features and to select the most favourable process. Several operations, such as polishing or chamfering, make up the preparation process. Based on the estimated costs it is for example chosen, if chamfering is carried out by means of thermal cutting or machining. Nieto [11] developed a FBC model, in form of a spreadsheet, which estimates the costs of aluminium parts made by hot extrusion. It calculates the unit cost for a part, from the sum of all recurring costs, and uses an algorithm to select the optimal combination of press and billet size, depending on the shape to be extruded. The sum of the non-recurring costs results in the amortised investment. Finally, the cost of manufacture is the sum of the unit cost and the amortised investment. The cost model requires the user to enter data on geometric and non-geometric cost drivers. Nieto [11] identified the circumscribing circle diameter, the cross-sectional area, the external and internal perimeter, the maximum wall thickness, the part length, the shape type, and the number of voids as geometric cost drivers. The non-geometric cost drivers are material, batch size, annual production volume and production years. Nieto [11] notes that the model further uses several variables based on assumptions that are grounded in current literature but need to be revised regularly. The analysis of the estimates produced shows that in the extrusion of parts made of the aluminium alloy Al-6063, material costs dominate manufacturing costs. The author points out that changes in e.g., choice of alloy or production volume change the share of different cost items in the manufacturing costs. As a possibility for improvement it is proposed that the model should include manufacturability constraints and a feedback mechanism that lets the user know, if necessary, what makes the design unmanufacturable [11].

According to Field, et al. [24] most cost models are in the end either product- or process-based. Agyapong-Kodua, et al. [35] conducted a literature review on cost modelling techniques and found that the majority of cost modelling techniques are product-based quantitative techniques, although process-based modelling techniques have the important capability to map or translate design solutions into equivalent manufacturing processes and the associated resources required. Agyapong-Kodua, et al. [35] state that the linking of product-based cost modelling techniques and process modelling techniques will help to measure cost and process efficiency with greater accuracy. This, combined with system dynamics (SD) and discrete event simulation (DES) tools that allow manufacturing enterprises to test solutions in a virtual executable scenario before implementing them, is considered useful to create a cost model which can support in decision making related to design and manufacturing [35]. The use of simulation tools in cost estimation is also taken up in the work of Pehrsson, et al. [36] who developed an incremental cost model to be used in multi-objective optimisation. To be able to use the cost model to optimise the financial impact of investments in a production system, a simulation model of the production system is required. Pehrsson, et al. [36] state that integration with simulation significantly increases the ability of methods, such as incremental cost modelling, to serve as a basis for manufacturing management decision support.

In the literature there are cases where cost modelling is supported with SD [37] as well as cases where DES is used [36, 38]. Agyapong-Kodua, et al. [39], who present a multi-product cost and value stream modelling methodology in their research, say that whether to use SD or DES depends on the modelling intent. Pehrsson, et al. [36] state that if decision support in the design and analysis of production systems is the goal, DES is most appropriate.

To investigate the financial impacts of implementing green manufacturing in production Orji and Wei [37] developed a method that incorporates ABC and SD. They determined process parameters and calculated carbon emissions for manufacturing stages and the product life cycle. The costs associated with the manufactured product were calculated based on activities. For this, an ABC model was created, which focuses on carbon emission costs and energy saving activities to reduce carbon tax and therefore costs. The data from this model was used as input to a SD model which was developed to simulate the dynamic behaviour of emission quantities, the expansion of labour and machine capacities, and purchasing discounts and their relationship to costs. The results of the study of Orji and Wei [37] show that a cost model as proposed in [37] can be used to determine the financial impacts of changes made in a production system, in this case implementation of green manufacturing.

How changes made in a production system affect costs can also be investigated by the means of process-based cost modelling (PBCM). PBCM is a method that allows different technology options to be evaluated and can thus support decision-making. According to Bloch and Ranganathan [40], who used the method to analyse the cost of an assembly process in the electronics industry, the applications of the tool are manifold. Material flows to and from each process step are modelled and the costs for each processing step are calculated. The total cost is calculated from the sum of material costs, processing and assembly costs, and costs due to scrap and defects [40]. Bloch and Ranganathan [40] suggest the support of selections regarding material, technology or processes, make-or-buy decisions, or competitive benchmarking as application areas for the tool. Eriksson [41] studied the use of PBCM in the case of a multinational agricultural cooperative. He developed a model to predict the costs of the production process for main and by-products, with the potential to investigate the impact of alternative production layouts and the use of alternative raw materials. Eriksson [41] followed the PBCM approach of separating the cost estimation problem into three modelling parts, namely process, operations, and finance. Flowcharts were used in process mapping, to identify relevant activities and costs by visualizing activities on production level. In operations modelling the contribution factors were determined. For the financial part, several techniques were used, such as absorption costing and continuous operations costing. The total cost of production was calculated using batch costing. Eriksson [41] notes that flowcharts were insufficient in identifying costs at other hierarchical levels than production. The method therefore only identifies direct costs that relate to production costs, and does not effectively visualize all potential costs, such as overhead and common costs. Eriksson [41] suggests the use of cross-functional process mapping and relationship mapping to overcome this limitation. In essence, Eriksson [41] argues, PBCM enables the creation of a contextual understanding of the relationship between production technology and costs. He also indicates that interdisciplinary teams are needed to generate early and precise cost estimates for new products or manufacturing processes.

3 Method

For creating a cost model for large bridge structures, a bottom-up approach is taken. The bottom-up approach, as mentioned in 2.3, is more time-consuming and requires more data, but unlike the top-down approach, it does not require comparative data of similar products or projects. Firstly, each bridge project is unique [42] and secondly, aluminium has only been used sporadically in bridges, so there is no data of similar constructions on which to base cost estimates.

The bottom-up method starts with the smallest measured cost and gradually proceeds by summing up to the next larger unit of cost, until finally the total cost of a product or project is arrived at [43]. The project is broken "down into smaller and smaller intermediate products until the most basic product (e.g. plate) is described" [21]. For the Langenuen project this means breaking the bridge down into modules, these into panels, these into profiles and these into their original state, aluminium billets.

The development of a cost model that includes all processes and parts in bridge construction, from raw material to the finished bridge, is outside the scope of a master's thesis, which is limited to 20 weeks of research time and one student as researcher. In order to achieve a sufficient level of detail under the aforementioned limitations of this thesis, the creation of the cost model is limited to the top deck of an aluminium bridge girder. Focusing on the cost modelling of one part of a complex, large product is an approach similar to the development of the model in [21], where the researchers deliberately focused only on the external structure of a ship. An extension or enhancement of the cost model in subsequent studies is not ruled out.

The individual elements and the associated processes are shown in the flowchart in Figure 7. The aluminium billet, as the starting material, represents the smallest unit of the production process of an aluminium bridge. Due to its high complexity, the consideration of the on-site assembly of the modules to a bridge is excluded from the model. Furthermore, on-site assembly is considered very project-dependent, which makes it difficult to include it in a universal model. Consequently, the flowchart starts with the aluminium billets and ends with the bridge modules.

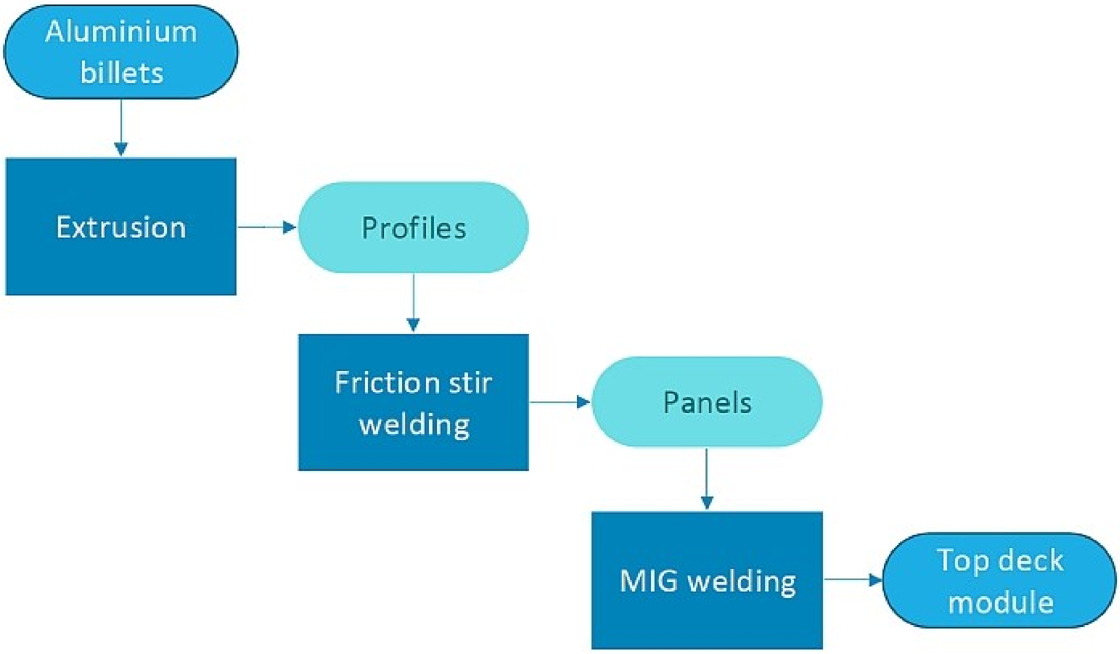


Figure 7: Flowchart of the production process of an aluminium bridge top deck with intermediate products

The literature review shows that there are many approaches to estimating costs, which are not always clearly distinguishable from each other. Among the papers presented, those that are subject-wise related to this thesis, such as cost optimisation of large metal structures, namely ships [21], cost estimation of extrusions [11] or welding [34], mainly followed the FBC approach. However, the features of bridges are innumerable, and it can be assumed that the change of a feature in an infrastructure element has an impact on the performance, e.g., load capacity of a bridge. Changing individual features in a bridge design is therefore only realistic to a limited extent and feature-based cost modelling for bridges only becomes meaningful in connection with CAD programmes or databases as proposed in [21] or [34]. As cited in 2.3.1 from [40], the application areas of PBCM are diverse and include, for example, decision support in the choice of materials and production technologies. In the articles presented in 2.3.1, this method is used to analyse the costs of an assembly [40] and a production process [41]. In view of this, the method of process-based cost modelling is most appropriate for this thesis. However, since the literature emphasises the benefits of integrating product and process in cost estimation [35], a model is created that also incorporates the features of a bridge to a level that is practicable.

To build the model, the correlations between costs of the production process and controllable design and operational parameters must be identified. This is done through the following steps [23]:

1. Identifying relevant cost elements.
2. Isolating the factors that directly determine costs.
3. Understanding how the process in question affects the magnitudes of these factors.

The execution of these steps requires detailed knowledge of the product and production processes. This knowledge is obtained from literature on the production processes in

question, reports on the Langenuen suspension bridge project and discussions with the project group in their monthly meetings and during individual consultations. A list of reference contacts from the project group is attached to this thesis in Appendix A.
The cost elements considered in the model are shown in Table 1. These are, sorted by process, the elements that make up the production costs for the top deck of the aluminium bridge. The selection of cost elements coincides with the commonly considered elements of production costs mentioned in [23], [40] and [24].

Table 1: Relevant cost elements in the production of a top deck of an aluminium bridge

Extrusion	**FSW**	**MIG**
Labour	Labour	Labour
Energy	Energy	Energy
Tooling	Tooling	-
-	Consumables	Consumables
Material	-	Material
Equipment	Equipment	Equipment
Overhead	Overhead	Overhead

Any cost model requires technical modelling inputs such as manufacturing, operational and financial data [24] which can come from a variety of sources [43]. The data for the technical modelling inputs in this work come partly from relevant literature but are largely based on the reference contacts' expert knowledge. Experts are persons who because of privileged access to information have special knowledge, so-called expert knowledge [44]. Expert knowledge is a valuable source of information, because of its particular reflexivity, coherence and certainty [45]. A suitable way to obtain data from expert knowledge is to use open interviews based on general topics, without a fixed guideline and closed questions [44]. In the case of this thesis, the open interviews are conducted as discussions in online meetings, both with individual reference contacts and in the regular meetings of the Langenuen project group. This provides a good overview of the Langenuen project, the production processes involved and their interrelationships, as well as the opportunity to directly request any relevant numerical data.

Financial data, for example on wage and energy costs, are taken from Statistics Norway. Collecting data for technical modelling inputs is time-consuming, which is why a trade-off between the costs and benefits of increased accuracy of information is appropriate [43]. When such trade-offs are made and how they manifest themselves is decided for each input individually and indicated in section 4. Besides technical modelling inputs part-specific inputs are required, that include for example the description of the part, or the kind of process steps that will be carried out [24]. These inputs are taken mostly from the Langenuen project report [4], and this is the type of input that is utilised to incorporate the integration of some features of bridges into the model, as mentioned previously.

To create a model according to these instructions and specifications, a few basic assumptions are made:

- Dimensional changes to the bridge and/or top deck components do not affect the performance of the bridge in a way that would result in changes to the overall construction of the top deck.

- A greenfield factory is assumed. The top deck and all its components are built in one and the same factory, eliminating transport distances between production sites.
- No other items are produced in the plant at the same time as the components for the top deck, eliminating waiting times due to retooling, or machines being occupied with unrelated products.

A detailed explanation of the model created, including the mathematical formulas used, can be found in section 4. This section represents the implementation of the above-mentioned steps 2 and 3 for the creation of a process-based cost model.

The functionality of the model is tested through two types of tests, a feature-based test and a sensitivity analysis. The feature-based test examines how changes in the profile width and the orientation of the panels in the top deck modules affect the production process and its costs. The results of this test are discussed with the experts in the Langenuen project group to verify the validity of the model. Sensitivity analysis serves to find out how sensitive the costs react to fluctuations in process-related parameters. Examining the sensitivity of cost estimates to technical and operational parameters can be used to identify cost drivers [24]. The outcome of the sensitivity analysis, in combination with the results of the feature-based test and a realistic assessment of the range of reasonable variance in the parameters and cost estimates, further indicates the validity of the model.

4 The model

The model is a spreadsheet created in Excel, starting with a design generator. The design generator, which is explained in detail in section 4.1, is used to create integration of design and production in the cost analysis, as suggested by Agyapong-Kodua, et al. [35]. As mentioned in 2.3.1, the literature on cost modelling states that a significant amount of the costs of a product are decided in the design phase [30, 33]. The inclusion of design in the research of cost drivers in aluminium bridge manufacturing is therefore a necessity. The design generator also ensures that the model can be used for bridges of different dimensions, which is important with regard to the second research objective of this thesis. It provides necessary input for the cost calculation in the following part of the model.

According to the structure of the production process depicted in Figure 7 the cost calculation in the model is divided into three parts, namely extrusion costs, FSW costs and MIG costs. For reasons of clarity, user-friendliness and comprehensibility of the model and its calculations, each production process has its own Excel sheet. In addition to the Excel sheet of extrusion costs, there is also a sheet with supplementary and extrusion parameters. This was created by those involved in the Langenuen project and made available to build the model. Of all the production processes, the parameters of the extrusion process are included in the most detail in this model. This is because extrusion, as the first process step, is determinant for the following steps. Furthermore, the entire material requirement for the top deck is decided based on the extrusion process. The extrusion process and its parameters are complex. The derivation of the values of the parameters is beyond the scope of this thesis. Therefore, the Excel sheet of the extrusion parameters will not be discussed in further detail in the following. An explanation of individual parameters is given when it is essential to understand the cost calculation.

Throughout the model, a colour code is followed that distinguishes input cells from calculation cells. There are three types of input cells: Green, which have potentially changeable inputs but remain unchanged for this thesis; yellow, which indicate the case inputs for the feature-based experiments; and orange, which indicate the cells that will be manipulated in the sensitivity analysis. Cells that contain calculations and must remain unchanged are marked grey. On the supplementary and result sheets, this code is followed where necessary for a better readability or comprehension.

Due to the large number of variable parameters in the model, a list of input parameters for a base case is given in Appendix B. The values listed there are the default settings of the model, which will be discussed in more detail in the following sections.

To ensure that the model can be easily used for different types of bridges, the calculations are based on measurable, transferable units. Unless otherwise stated, times are calculated in hours, lengths in metres and mass in kg or metric tonnes. Costs are calculated in Norwegian kroner [NOK]. If cost information is available in other currency units, the exchange rate valid at the time of writing this thesis is used for conversion. The exchange rates used in the model are specified in the design generator, which is described in 4.1. The data on the exchange rates used are provided in the base case in Appendix B. According to the needs of the Langenuen project group, the costs in the model are stated in total costs and in NOK/kg, although the costs for bridges are usually stated per square meter [42].

In accordance with the specifications made in section 3, the calculations of the cost model are carried out for a top deck module of the Langenuen bridge which is defined in 2.2. All total values calculated in the model refer to one module, unless otherwise stated. The total length of the bridge and the number of modules is only included in the model to demonstrate that the module is a part of a larger entity. It can also be used, if desired, to estimate the total cost of the upper deck of a bridge, not including joining of the modules. For the tests with the cost model, these figures are not relevant, as they are simple multipliers that do not change the cost dynamics and relationships. The input values used in the model are derived from the reference contacts in the Langenuen project, unless otherwise stated and explained in the following sections.

4.1 Design generator

In the design generator, entries are made for the design of the bridge and its individual components. For a number of these entries, minimum and maximum values are set, which are used as auxiliary values for equations and for the application of logical tests that check the reasonableness of the calculation results.

The parameters to be entered into the model are the length and width of the bridge deck and the orientation of the panels. Also, the length of the buffer at the end of the profiles. The extra length is included to avoid scrap due to e.g., transport damage to the part. The specified length is sawn off at both ends in preparation for MIG welding. Furthermore, information is required on the bottom and top wall thickness, the truss, and the end thickness, as well as the width and height of the profiles. The remaining parameters of the bridge design are calculated from this information. Figure 8 shows the cross section of a profile for the Langenuen bridge, including specifications on the above-mentioned dimensions.

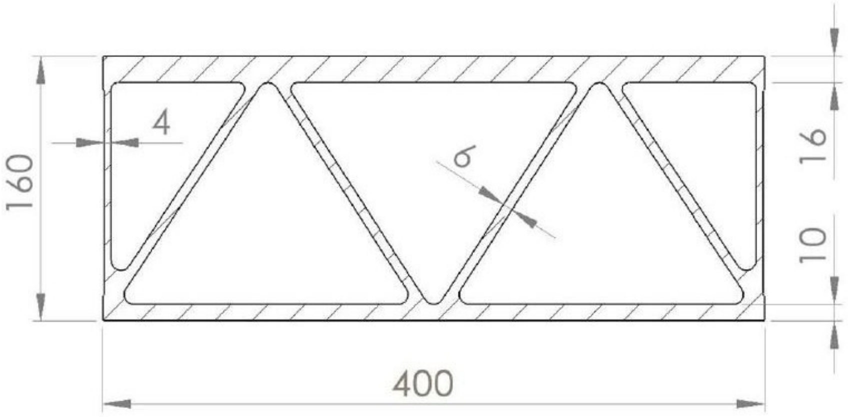


Figure 8: Cross section of a profile for the Langenuen bridge [4]

As visible in Figure 8, a 400 mm wide profile has three trusses. For reasons of stability, changes in the profile width come with changes in the number of trusses. For the model it is specified that the profile width can be varied in steps of 100 from 100-600 mm. Figure 9 shows the profile cross sections and number of trusses for all profile widths that can be set in the model. These are assumptions for modelling purposes that are not based on structural calculations.

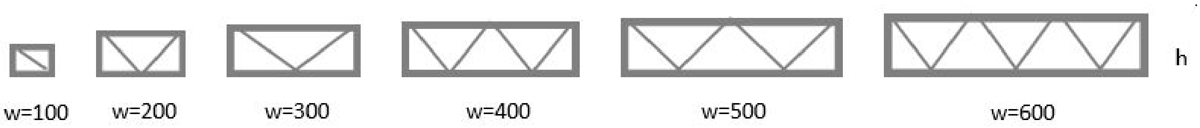


Figure 9: Cross sections and number of trusses for different profile widths

The number of panels required lengthwise and crosswise depends on the orientation of the panels. For the longitudinal concept, the length of the panels is calculated by dividing the length of the bridge deck by the maximum length of the panels. The maximum length of the panels is one of the auxiliary values mentioned earlier in this section. The width of the panels is calculated by dividing the width of the deck by the auxiliary value of the maximum width of the panels. The calculations for the transverse concept follow the same principle, except that deck length is divided by panel width and deck width by panel length. A built-in Excel function, the IFS function, outputs the corresponding result, depending on whether the user specifies "L" for longitudinal or "T" for transverse as the orientation. The IFS function checks for the fulfilment of defined conditions and returns a value corresponding to the first condition that is met. This function is also used in the calculation of width and length of the panels which is done from the respective dimensions of the deck divided by the corresponding number of panels. The IFS function is also used to determine the number of trusses in a profile depending on the profile width.

In addition, the design generator includes the calculation of the mass of primary material (Mpm) used in a top deck module in tonnes. Its calculation is done as described in equation (1).

$$Mpm = \left(\left(\frac{Af}{1000^2} * Lprt\right) * Ncav * \rho\right) \div 1000 \tag{1}$$

where: Af = Area extrusion cross section [mm^2]

Lprt = Profile length total [m]

Ncav = Number of die cavities

ρ = Density of input material [kg/m^3]

Other parameters calculated in the design generator are the number of panels in the bridge deck, the bridge deck area, number of profiles per panel, profile length per panel incl. and excl. buffer, and profile length total incl. and excl. buffer. The calculations in the design generator provide important inputs for the process related calculations. The profile geometry, for example, is decisive for the circumscribing circle diameter and the form factor for extrusion, and it determines the dimensions of the welding groove in MIG welding.

4.2 Extrusion cost

The costs for the extrusion process are comprised of costs for labour, energy, tooling, material, depreciation and overhead. For many cost calculations, information about the mass of the extrusions is needed at some point. For example, for the calculation of labour time and material demand, which are important variables for the calculation of labour and material costs. Information is needed about how long the extrusions from one billet are, how many billets are used per bridge deck, what the yield is, etc.

The extruded length in meters of one billet (Plb) is calculated as show in the following equation.

$$Plb = \left(\frac{A0}{Af}\right) * \left(1 - \frac{Bds}{100}\right) * \left(\frac{L0}{1000}\right) \tag{2}$$

where: A0 = Area billet [mm^2]

Bds = Butt discard [%]

L0 = Billet length [mm]

To calculate the number of parts per runout extrusion (Npe) Excels ROUNDDOWN function is used on equation (3). Through this function an integer result is arrived at.

$$Npe = (Lt - Ls) \div \left(\frac{Lp + (Bu * 2)}{1000}\right) \tag{3}$$

where: Lt = Runout table length [m]

Ls = Length scrapped per continuous extrusion [m]

Lp = Panel length [mm]

Bu = Buffer length on profile ends [mm]

From these two variables, and the input and calculations from the design generator, the following can be calculated: length of continuous extrusion, number of billets per runout, number of parts per billet, and eventually number of billets per top deck module, which is needed to calculate the yield. The calculation of the yield (Ye) is expressed with equation (4)

$$Ye = \frac{(Af \div 1000^2) * Ncav * Lprtb}{Nbm * (A0 \div 1000^2) * (L0 \div 1000)} \tag{4}$$

where: Lprtb = Profile length total incl. buffer [m]

Nbm = Number of billets per top deck module

Equation (5) shows the basic principle of calculating labour costs (Lcost), which is valid for all production processes in the model of this thesis.

$$Lcost = \left((Dlc + Od) * \left(\frac{12}{1750}\right)\right) * No * occ \tag{5}$$

where: Dlc = Direct labour cost per month [NOK]

Od = Overhead direct per month [NOK]

No = Number of Operators

occ = occupancy of production line [hrs]

The model's input values for direct labour costs, i.e. wages for machine operators, as well as direct overhead are based on data from Statistics Norge [46, 47]. For the calculation it is assumed that a machine operator works 1750 hours in 12 months. The number of workers depends on the production process and the size of the production plant. For extrusion, a number of 6 workers is assumed. The occupancy of the production line is calculated from cycle time, set-up time and downtime, with set-up time and downtime being fixed values. The set-up time is estimated at 10 minutes, the unplanned downtime at 5%. The planned downtime is assumed to be one shift every week, in a three-shift system. The occupancy time of the production line is arrived at through equations (6)-(8).

$$occ = \left(ct + \left(\frac{st}{60}\right)\right) \div \left(1 - \left(\frac{ud + pd}{100}\right)\right) \tag{6}$$

$$ct = (Etb + ra + dct) * \left(\frac{Nbm}{3600}\right) \tag{7}$$

$$Etb = \left(\frac{Plb}{vf}\right) * 60 \tag{8}$$

where: ct = Cycle time [hrs]

st = Set-up time [min]

ud = Unplanned downtime [%]

pd = Planned downtime [%]

Etb = Extrusion time per billet [sec]

ra = Ram acceleration time per billet [sec]

dtc = Dead cycle time per billet [sec]

vf = Exit speed [meter/min]

In order to calculate the energy costs (Ecost) for the extrusion process, the energy demand must first be determined. The model calculates the energy demand per billet for homogenisation, pre-heating, extrusion, cooling, and ageing. The sum of these calculations gives the total energy requirement for processing a billet. This value is multiplied by the number of billets per top deck module to obtain the total energy demand for a top deck module before applying equation (9) to calculate the energy cost.

$$Ecost = Et * (Ec + Ed) \tag{9}$$

where: Et = Energy total [kwh]

Ec = Energy cost per kwh [NOK/kwh]

Ed = Energy distribution cost per kwh [NOK/kwh]

Norwegian energy price data are used to calculate energy costs. The cost of electric energy consists of the price of electricity, taxes and grid charges. According to Statistics Norway, the average electricity price paid by energy-intensive industries in 2020 was 28.4 øre/kwh [48]. Manufacturing industry in Norway pays a reduced tax rate for the consumption electricity, which is set at 0.546 øre/kwh for 2021 [49]. In addition, business customers must pay 25% value-added tax (VAT). These two taxes are added to the grid fee. The grid fee depends on the size of the business, the required voltage, as well as monthly peak voltages and is therefore individual for each business [50]. In the cost model of this thesis grid fee, consumption tax and VAT are summarised under the term energy distribution costs and assumed to be 0.26 NOK/kwh. This assumption is based on the information provided by the Norwegian electricity suppliers Elvia [50] and Nordlandsnett [51] on the price of grid charges for commercial clients in 2021.

The tooling cost (Tcost) for the extrusion process are the costs incurred due to wear and tear on the die and bolster. It is calculated, as shown in equation (10), from the cost of the tool, the durability of the tool, and the usage time of the tool to produce a top deck module. It is assumed that the size of the extrusion die influences the price of the die and that larger dies are more expensive. This dependency is greatly simplified in the model, using the profile width as a multiplier on an assumed value.

$$Tcost = \left(\frac{Tco}{Ded}\right) * \left(\left(\frac{Etb}{3600}\right) * Nbm\right) \tag{10}$$

where: Tco = Cost of tool [NOK]

Ded = Durability of extrusion die [hrs]

The material costs for the top deck module result from the costs for aluminium for the module minus the income from the recovery of scrap metal. During extrusion, metal scrap is generated, e.g., in the form of cut-offs from extruded profiles. Such manufacturing scrap, just like scrap from primary aluminium production, is referred to as in-house, new, or internal scrap [8]. It usually consists of an alloy with a known composition and has no coatings or adhesions. In this case, the metal can be recycled directly back into the same alloy. Adulterated metals must first be brought to a certain purity suitable for recycling. The scrap that accumulates in manufacturing can be used to produce primary as well as secondary aluminium [8]. Despite its good recyclability, the price for aluminium scrap is significantly lower than the price for primary aluminium. The model uses a price of 2200 USD/tonne of primary aluminium, which is based on the London Metal Exchange (LME) aluminium data for March 2021 [52]. In the model, and in the remainder of this thesis, the price for primary aluminium is referred to as LME. High quality aluminium scrap trades for 750 GBP/tonne [53], which is equivalent to about 1042 USD/tonne according to the exchange rate in May 2021. The calculation of the costs for aluminium per module, the income from internal scrap, and finally the material costs including recovery (Mcost) for one module is shown in equations (11)-(13).

$$Mcost = Mcm - Vrec \tag{11}$$

$$Mcm = \left(\left(\left(\frac{A0}{1000^2}\right) * \left(\frac{L0}{1000}\right) * \ \rho\right) \div 1000\right) * Nbm * Mct \tag{12}$$

$$Vrec = \left(\left(\left(\frac{A0}{1000^2}\right) * \left(\frac{L0}{1000}\right) * \ \rho\right) \div 1000\right) * Nbm * (1 - Ye) * Vsc \tag{13}$$

where: Mcm = Material cost per module [NOK]

Mct = Material cost per tonne [NOK/t]

Vrec = Income of internal scrap (recovery) [NOK]

Vsc = Value of internal scrap [NOK/t]

The cost for the equipment required for the manufacturing process is expressed as depreciation in the cost model of this thesis. The cost of depreciation (Dost) per top deck module is calculated from the investment cost in machinery, the depreciation time in years, the theoretically available operating time in hours per year and the actual time of use of the equipment. The investment cost for an extrusion press is linked to the force of the press, which depends on the dimensions of the extrusion and the billet and is calculated on the extrusion parameters sheet. The formula for calculating the investment costs is taken from a study [54], that examined the investment costs for a greenfield plant in connection with the Langenuen suspension bridge project. In this study, a linearly increasing relationship was found between press force and investment costs for extrusion presses [54]. The depreciation period is set at 10 years, and it is assumed that the depreciation is linear. The conversion from years to theoretically available operating time in hours is made based on Norwegian laws and regulations. In Norway there is a legal right to 25 days of holiday per year [55] and there are 13 public holidays in a year. This results in 45 working weeks per year, each of which has 5 working days. Based on these specifications and assumptions, equation (14) is derived for the calculation of the depreciation costs. This approach to calculating depreciation costs is adapted from the unit-of-production method, where the amount of depreciation is based on the number of production units produced by the equipment [56]. Instead of a total number of production units produced over the life of the equipment, the model uses hours of use. This enables a calculation that considers the possible variations in the design of the production units and the resulting variations in equipment use.

$$Dcost = \left(\left(\frac{Ic}{Dp} \right) \div (24 * 5 * 45) \right) * occ \tag{14}$$

where: Ic = Investment cost [NOK]

Dp = Depreciation period [years]

According to the definition of manufacturing overheads in [56], depreciation costs can be considered part of manufacturing overheads. For reasons of clarity and comprehensibility, however, they are listed separately in this model.

The costs of production that are not directly attributable to the product or cost object are called manufacturing overheads. This term includes, for example, rent for the plant and operating costs, cleaning materials and maintenance costs [56]. The overhead costs (Ocost) in the model are the sum of costs for indirect labour, i.e., management, R&D, sales, quality, HES etc, costs for maintenance, housing and utility, insurance, IT, fixed consumables, logistics and others. For the calculation of the building costs, a depreciation period of 10 years is assumed. How much an industrial building costs depends largely on its size and is taken from [54] for all production processes. Equation (15) describes the calculation of the overhead costs of the extrusion process. The principle of the calculation is the same for all production processes.

$$Ocost = Oc * occ \tag{15}$$

where: Oc = Overhead cost per hour [NOK/hrs]

In addition to the total costs for labour, energy, tools etc., the costs per kg of material used are also calculated for each individual cost unit of each production process. This is done by dividing the total costs by the mass of primary material in the top deck module, which is calculated in the design generator and described in 4.1.

4.3 FSW cost

The costs for the FSW process are comprised of costs for labour, energy, tooling, consumables, depreciation and overhead. An important parameter for calculating the costs for friction stir welding is the length of FSW weld seam per module. As mentioned in 2.2, FSW is used to weld profiles together into panels. The profiles are welded together at the long edge, so the length of a single weld is equal to the length of a profile. Welding is carried out from both sides. The total length of FSW weld per module is calculated from the values listed in the design generator for panel length, which is equal to the profile length, number of profiles per panel and number of panels per module.

The calculation of labour costs is done in the same way as previously described for the extrusion process. However, set-up and cycle time, which are needed to calculate the occupancy of the production line, are based on process-specific variables that do not occur in extrusion. The equations used to calculate the cycle time for FSW are equations (16) and (17).

$$ct = \frac{arc * 100}{ar} \tag{16}$$

$$arc = \left(\left(\frac{Lw}{ws}\right) \div Nh\right) \div 60 \tag{17}$$

where: arc = Arc time per top deck module [hrs]

ar = Arc rate [%]

Lw = (FSW) weld length per module [m]

ws = Welding speed [m/min]

Nh = Number of welding heads

The arc time refers to the hours during which productive welding takes place. The arc rate indicates what percentage of the total execution time of the welding job is arc time. These terms are used even if there is no arc in the FSW in order to keep the terms in the model consistent and their number limited. The arc rate in the model is set at 65%, which is an estimate based on manufacturer's data [16] and expert knowledge. A welding speed of 0,5 m/min [16] is used in the model and the number of welding heads is set to two.

The set-up time for FSW consists of in-house transport and cleaning of the parts to be welded. Cleaning the parts with alcohol takes 0,5 minutes per meter [16]. For transport it is assumed that the number of profiles forming a panel are transported as one load and 10 minutes are needed per load transport. After calculating the set-up and cycle time, equations (5) and (6), described in 4.2, are used to calculate the labour costs for FSW. Adjustments of the formulas to differing units, if any, are made in the model, but are not further explained here.

The calculation of energy costs for FSW follows the same principle as for extrusion and uses equation (9), described 4.2. An energy consumption of 0,2 kwh is assumed per meter that is welded [16]. Furthermore, it is assumed that welding accounts for 75% of the energy consumption for the FSW process and 25% of the energy is used for additional activities such as lifting and clamping.

Just like for the extrusion process, the tooling costs for FSW are calculated from the cost of the tool, its durability, and time of use to produce one top deck module. For FSW, equation (18) results for the calculation of tooling costs.

$$Tcost = \left(\frac{Lw}{Dt}\right) * Tco \tag{18}$$

where: Dt = Durability of tool [m]

According to a manufacturer of welding equipment, the cost of a FSW tool is 1000 € [16]. The useful lifetime of this tool, called durability in the model, is given as 2000 m per tool [16, 17]. These are the values specified in the model for Tco and Dt.

The consumable used in friction stir welding is alcohol for cleaning the parts to be joined. The price of isopropyl alcohol in Norwegian retail shops averages NOK 189,00 per litre [57, 58]. It is assumed that 0,1 litres of cleaning alcohol are used per metre of parts to be joined. Based on these values and the calculated weld length per module, the consumables cost (Ccost) for FSW is calculated.

The calculation of the depreciation costs for FSW is carried out as described in 4.2, the same applies to the calculation of the overhead costs. Equations (14) and (15) are used, respectively. Unlike extrusion, the investment costs for FSW are assumed to be largely independent of design changes and resulting minor process changes and therefore constant. A value of USD 4000000 is used in the model [54].

4.4 MIG cost

The costs for MIG welding are comprised of costs for labour, energy, consumables, material, depreciation and overhead. There is no tool in MIG welding that wears out and needs to be replaced [15], therefore tooling costs are not involved in this part of the model. Before MIG welding, the buffer length is cut off from the panels. This length was added to both sides of the profiles, as mentioned in 4.1, to avoid transport damage and to create a run-out length for friction stir welding to exclude the hole left by the FSW tool from the final panel. The sale of the sections of the buffer length leads to income from recovery. Since in the extrusion process the recovery is included in the material costs, this cost unit occurs for MIG welding, even though no further primary material is added to the production process.

As with friction stir welding, the length of the weld per module is an important factor in many calculations of the cost of MIG welding. Unlike FSW, where all welding seams are parallel and of the same length, MIG welding is carried out on longitudinal and transverse edges of the rectangular panels. The total number of meters to be welded depends not only on how many panels are in a top deck module, but also on the orientation of the panels. For this reason, two formulas for calculating the weld length are defined in the model, which are selected with Excels IFS formula depending on the panel orientation. Equation (19) is used for the longitudinal concept, i.e., when "L" is specified for the orientation in the design generator. Equation (20) is used for the transverse concept, i.e., when "T" is specified for the orientation in the design generator.

“L” $$Lw = \left(\left(\frac{Lp}{1000}\right) * Npl * (Npw - 1)\right) + \left(\left(\frac{Wp}{1000}\right) * Npw * (Npl - 1)\right) \tag{19}$$

“T” $$Lw = \left(\left(\frac{Lp}{1000}\right) * Npw * (Npl - 1)\right) + \left(\left(\frac{Wp}{1000}\right) * Npl * (Npw - 1)\right) \tag{20}$$

where: Lw = (MIG) weld length per module [m]

Lp = Panel length [mm]

Wp = Panel width [mm]

Npl = Number of panels length direction

Npw = Number of panels width direction

The MIG welding process depends on many parameters, most of which have to be adjusted to each other in order to achieve a good welding performance [18]. Because of this, not all welding parameters are queried or listed in the model, but only those that directly influence the costs. It is expected that when manufacturing the bridge, the other parameters are adjusted to the values specified in the model. The number of welding passes is a factor used in many calculations and has a significant influence on various cost units in MIG welding. It largely depends on the cross-sectional area of the weld groove and the filler wire diameter. The model assumes a V-groove, the cross-section of which is shown in Figure 10.

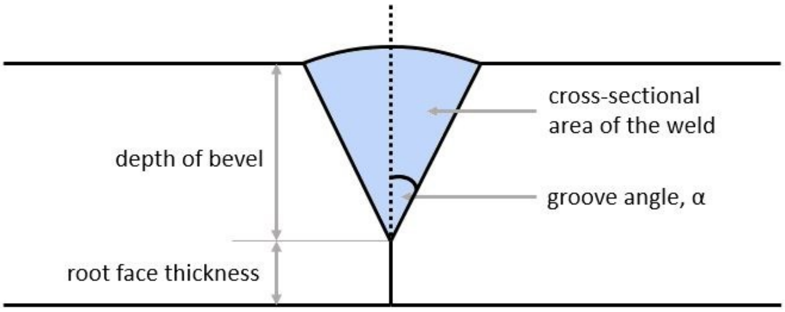


Figure 10: Cross-sectional area of a V-groove

For the calculation of the cross-sectional area of the weld according to equation (21), a root face thickness of 0 is assumed in the model. This means that the depth of the bevel is equal to the thickness of the panel. For the groove angle a value of 27,5° is used. Equation (22) is applied to calculate the number of MIG passes, and Excel's ROUNDUP function is used to round up the result to a number without decimal places.

$$Aw = \left(\frac{2 * \alpha * \pi}{360}\right) * \left(\frac{db}{\cos \alpha}\right)^2 \tag{21}$$

$$Np = Aw \div \left(\left(\left(\frac{\pi}{4}\right) * dfw^2\right) * \left(\left(wfr * \frac{De}{100}\right) \div (ws * 1000)\right)\right) \tag{22}$$

where: Aw = Cross-sectional area of the weld groove [mm²]

α = Groove angle [deg]

db = Depth of bevel [mm]

Np = Number of passes [N]

dfw = Filler Wire diameter [mm]

wfr = Wire feed rate [mm/min]

De = Deposition efficiency [%]

It is assumed that the MIG welding process for the assembly of the Langenuen bridge panels is automated. Based on this, a welding wire diameter of 1,6 mm is assumed, the wire feed rate is set at 15000 mm/min and the welding speed is set at 0.75 m/min. Due to possible speed differences, the inclusion of the wire feed-to-weld speed ratio in the calculation of the MIG passes is essential to obtain an accurate result. The deposition efficiency is used to account for losses of filler material due to slag or spatter. A value of 0,95 is a typical deposition efficiency for MIG welding with a solid wire [18]. This means that during MIG welding with solid wire, about 5 % of the material ends up as spatter and slag and not as weld metal in the weld seam.

As with extrusion and friction stir welding, the labour costs for MIG welding are calculated from the direct labour costs, direct overhead, number of workers and occupancy time of the corresponding equipment. Equation (5) is used to do so. The occupancy time of the production line is the sum of cycle time and set-up time. The cycle time is calculated in the same way as explained in 4.3 for FSW and with equation (16), involving arc rate and arc time. The arc rate for automated MIG welding is assumed at 50%. The calculation of the arc time for MIG Welding is slightly different from that for FSW. The difference is that in MIG welding the welding length is multiplied by the number of passes and not divided by the number of welding heads as in FSW. The set-up time for MIG welding is calculated in the cost model as a percentage from the cycle time and is representative of the times required to carry out all the process steps that prepare and accompany the actual welding. Some of the corresponding process steps in MIG welding are joint preparation by mechanical cutting or milling [18], oxide removal, welding personnel protection, clamping and lifting [15]. According to a reference contact, the set-up time for welding large and complex structures is about as long as three quarters of the cycle time. However, for the assembly of the upper deck only, due to the high degree of repetition, it is realistic that the set-up time is only one quarter of the cycle time.

As there is no data available on how much energy is consumed when welding a certain length, the energy consumption for MIG welding is calculated from the input power of a welding gun, as shown in equation (23). The input power of a welding gun is assumed to be 6 kW [16] with an energy efficiency estimated at 80% [15]. Just as for FSW, it is assumed for MIG welding that welding accounts for 75 % of the total energy consumption and 25 % of the energy is used for additional activities such as lifting and clamping. Finally, the energy costs for MIG welding are calculated according to equation (9), described in 4.2.

$$Eg = \frac{Pg * arc}{(Eeg \div 100)} \tag{23}$$

where: Eg = Energy consumption welding gun [kwh]

Pg = Input power welding gun [kW]

Eeg = Energy efficiency welding gun [%]

As already mentioned in 2.2.3, the consumables used in MIG welding are filler wire and shielding gas. The sum of the costs for these materials is the total cost of consumables. The weight of weld metal per meter of weld is calculated from the theoretical volume and density of the material of the filler wire [18]. The theoretical volume of the welding material is calculated by multiplying the cross-sectional area of the weld by one meter. The density of aluminium is 2710 kg/m^3. The density of aluminium alloys does not deviate much from this value, at around 2600 kg/m^3 to 2800 kg/m^3 [10]. To limit the complexity of the cost model, the value 2710 kg/m^3 is set and used for calculations. Since not all the filler metal is actually transformed into usable welding material, the deposition efficiency must be included in the calculation of the filler wire consumption. The calculations in the model are based on the use of argon as the shielding gas, which has a density of 1.784 kg/m^3 [59]. A shielding gas consumption of 20 L/min is assumed and the price for the shielding gas is estimated at 7,69 NOK/kg. The calculation of the costs for the inert gas are shown in detail in equation (24). It is important to note that the gas consumption is not calculated for the entire occupation time of the production line, but only for the arc time, as gas only flows while the arc is struck. Multiplying the volume of the shielding gas by 1000 is used to convert m^3 to litres, as 1m^3 is equivalent to 1000 litres.

$$Gcost = (arc * Gc * 60) * \left(\frac{Gp}{Vg * 1000}\right) \tag{24}$$

where: Gcost = Cost of shielding gas per module [NOK]

Gc = Shielding gas consumption [L/min]

Gp = Price of shielding gas [NOK/kg]

Vg = Volume of 1 kg shielding gas [m^3]

The calculation of the depreciation costs for MIG welding is carried out as described in 4.2, using equation (14). In [54], the investment cost for a fully equipped welding robot is estimated between USD 75000-175000. It is assumed that 8 welding robots are used in an automated production line for the assembly of bridge parts. The investment costs for MIG in the model are therefore defined at USD 1000000.

The calculation of the overhead costs for MIG welding is carried out as described in 4.2, using equation (15).

5 Results

As mentioned in section 3, the model is used to perform two types of tests, one that focuses on changes in parameters that are related directly to the product and one that examines the consequences of changes in parameters that are related to the process. The results of these tests are presented below.

5.1 Feature based tests

The parameters adjusted in the course of this test are the profile width and the orientation of the panels in the top deck. The parameters are adjusted one at a time, resulting in two main tests with six runs each. Calculations are made using different profile widths for the case of transverse panels, and the same is done for the case of longitudinal panels. The other parameters correspond to those of the base case mentioned in 4, whose complete list of input parameters can be found in Appendix B. The input values for parameters concerning the profile geometry and the panel orientation are shown in Table 2 and Table 3. The corresponding cells in the model are marked in yellow in accordance with the colour code explained in 3. The information on the geometry of the profiles is taken from the Langenuen project report [4], the possible profile widths are suggested by the reference contacts.

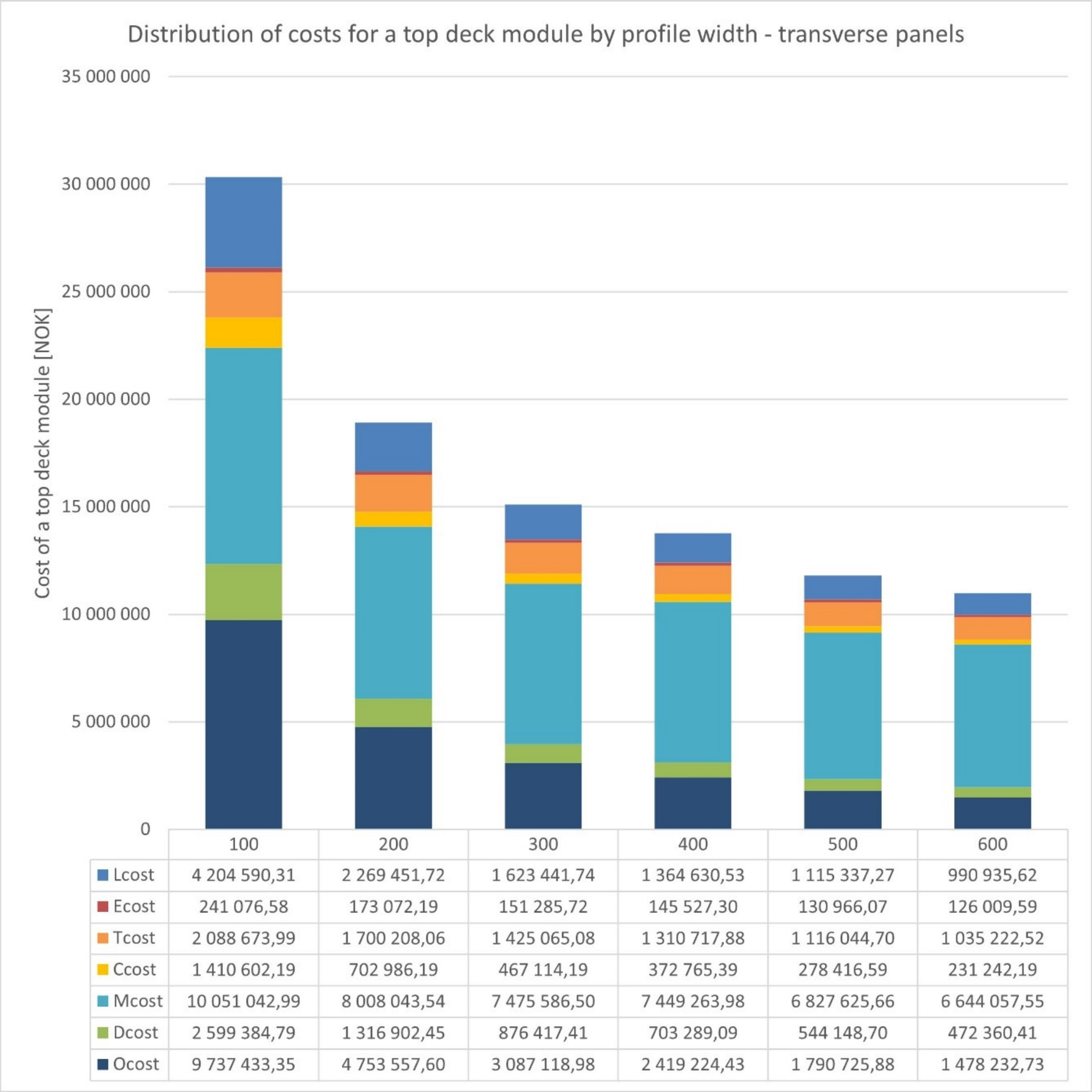
Table 2: Input values for varying profile width and transverse panel orientation

Design parameters	Input					
Longitudinal [L] vs Transverse [T] orientation	T					
Profile wall thickness bottom [mm]	12					
Profile wall thickness top [mm]	16					
Profile truss thickness [mm]	6					
Profile end thickness [mm]	4					
Profile width (steps 100) [mm]	100	200	300	400	500	600
Profile height [mm]	150					

Table 3: Input values for varying profile width and longitudinal panel orientation

Design parameters	Input					
Longitudinal [L] vs Transverse [T] orientation	L					
Profile wall thickness bottom [mm]	12					
Profile wall thickness top [mm]	16					
Profile truss thickness [mm]	6					
Profile end thickness [mm]	4					
Profile width (steps 100) [mm]	100	200	300	400	500	600
Profile height [mm]	150					

Figure 11 shows the amount and distribution of costs by profile width for transverse panels. The total costs for a top deck module with a profile width of 100 mm are the highest and those for a top deck module with a profile width of 600 mm the lowest. Not only are the total costs decreasing, but it can also be seen that all the cost units that make up the total costs are decreasing. The chart shows that costs for tooling, consumables and energy play a minor role. These costs decrease with increasing profile width, but their level is very low compared to the other cost centres. While all costs decrease, including the material costs, the share of the latter in the total costs increases from approximately 33% at 100 mm profile width to approximately 61% at 600 mm profile width. This suggests that the reduction in material consumption responsible for the reduction in material costs is beginning to stagnate, while other costs continue to fall. This behaviour seems logical, as the reduction of material consumption is in fact only possible to a limited extent. In the list of costs included in Figure 11, it can also be observed that the material costs hardly change from profile width 300 to 400 and profile width 500 to 600. This is due to the fact that from 300 to 400 and from 500 to 600 the number of trusses in the profile is increased by 2 each. This compensates for any material reduction due to fewer side walls in respect of a whole panel.



	100	200	300	400	500	600
🟦 Lcost	4 204 590,31	2 269 451,72	1 623 441,74	1 364 630,53	1 115 337,27	990 935,62
🟥 Ecost	241 076,58	173 072,19	151 285,72	145 527,30	130 966,07	126 009,59
🟧 Tcost	2 088 673,99	1 700 208,06	1 425 065,08	1 310 717,88	1 116 044,70	1 035 222,52
🟨 Ccost	1 410 602,19	702 986,19	467 114,19	372 765,39	278 416,59	231 242,19
🟦 Mcost	10 051 042,99	8 008 043,54	7 475 586,50	7 449 263,98	6 827 625,66	6 644 057,55
🟩 Dcost	2 599 384,79	1 316 902,45	876 417,41	703 289,09	544 148,70	472 360,41
■ Ocost	9 737 433,35	4 753 557,60	3 087 118,98	2 419 224,43	1 790 725,88	1 478 232,73

Figure 11: Distribution of costs for a top deck module by profile width - transverse panels

The greatest change in the costs displayed in Figure 11 can be seen between 100 mm and 200 mm profile width, with the most significant change in overhead costs. The overhead costs for a top deck module made of 100 mm wide profiles are NOK 9.737.433,35, which is the second highest cost centre after the material costs. The overhead costs for a top deck module made from 200 mm wide profiles are NOK 4.753.557,60. The overhead costs consist of costs that are mostly independent of other parameters in the model. The sum of these costs is converted to costs per hour as described in 4.2 and then multiplied by the time for occupying the production line. This dependence of overhead costs on production line occupancy time indicates a drastic reduction in production time from the manufacture of a top deck module with 100 mm profiles to one with 200 mm profiles. Similar dependencies exist for labour costs and depreciation costs, which also show about a halving from the 100 mm profile case to the 200 mm profile case. Figure 12, with the red line illustrating the total occupancy time of the production lines for the manufacture of a top deck module, confirms this assumption.

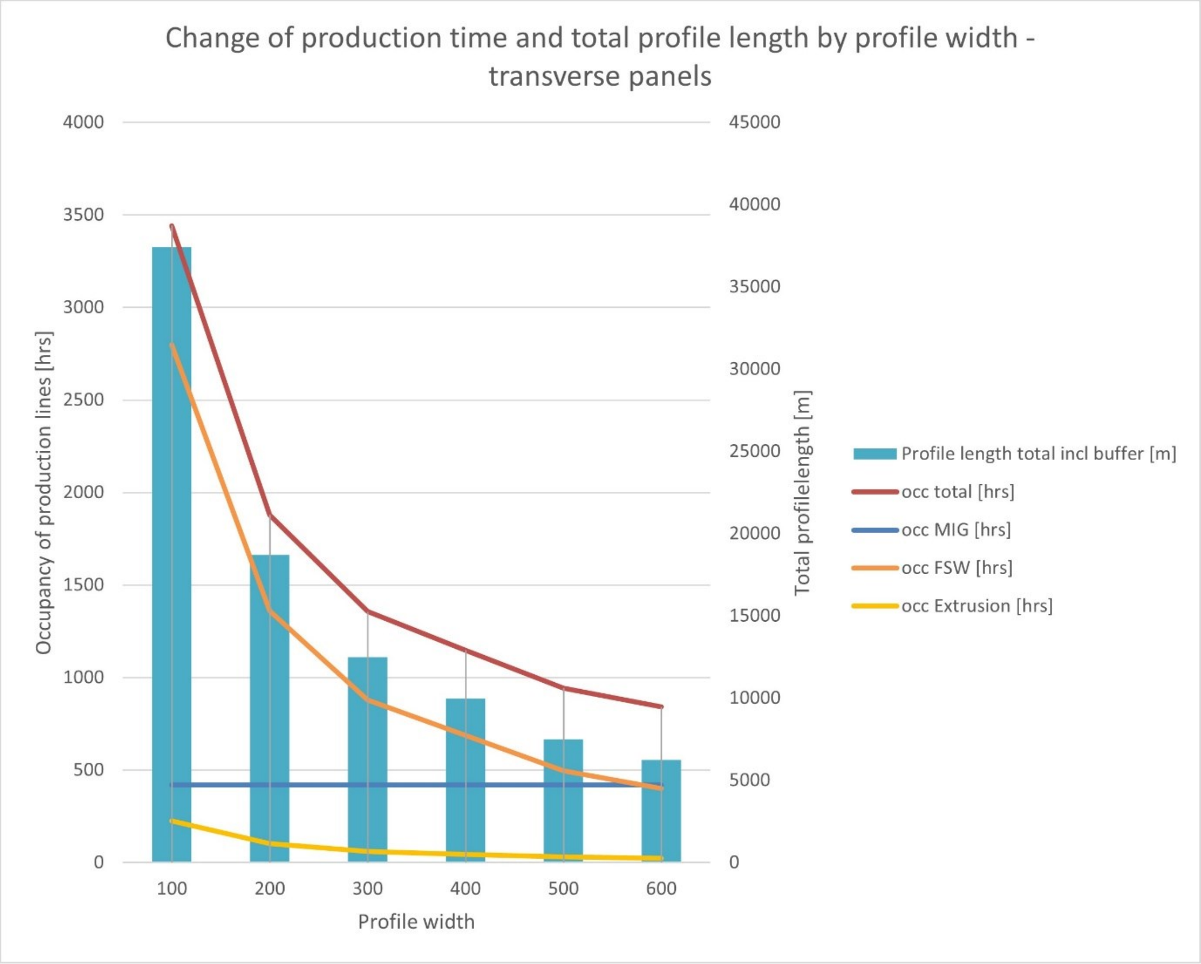
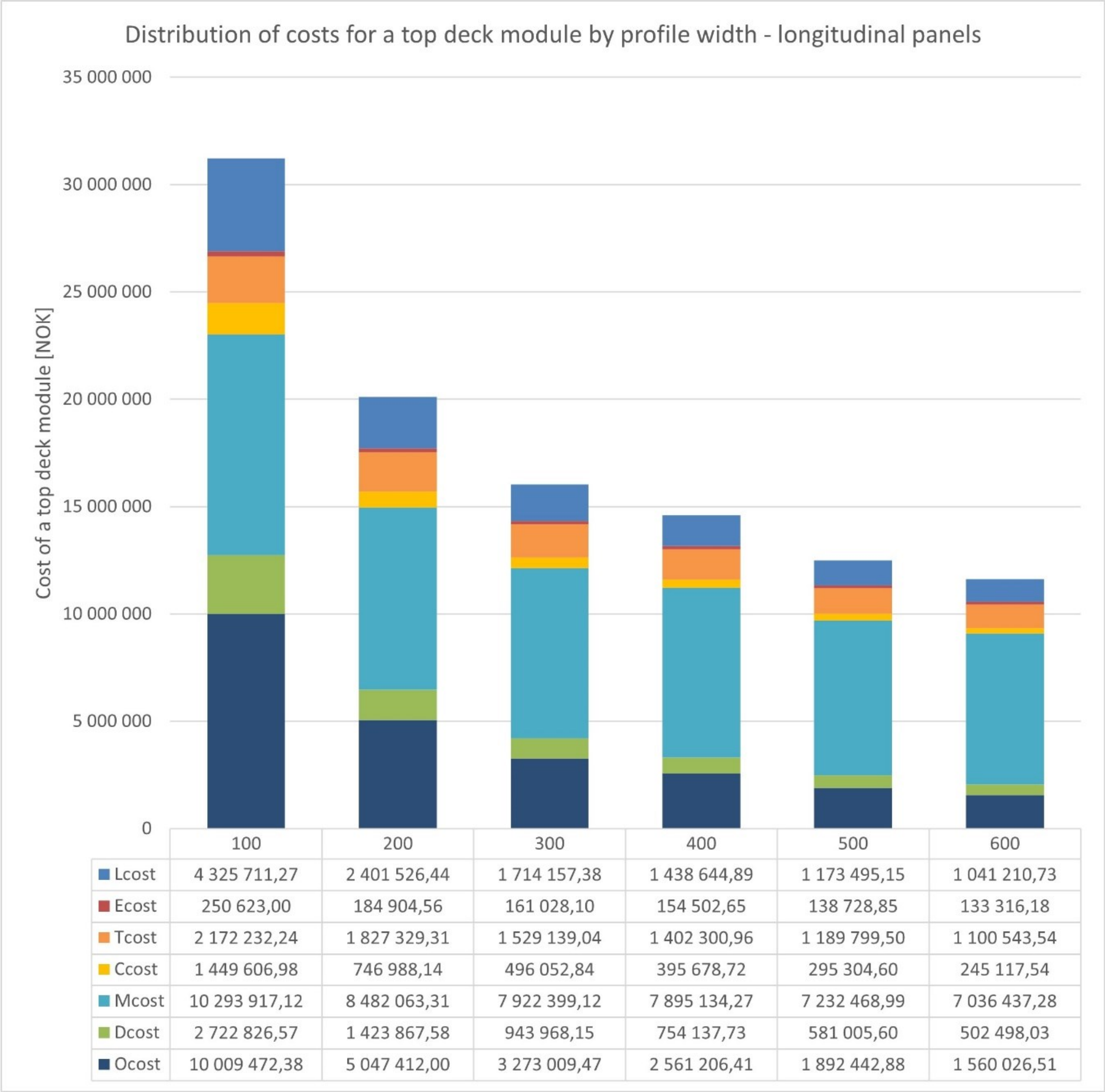


Figure 12: Change of production time and total profile length for a top deck module by profile width - transverse panels

Figure 12 further shows that the reduction in the time required to produce a top deck module is largely due to a reduction in the time required for friction stir welding. The curve of the friction stir welding production line occupancy shows an identical trend to the changing height of the bars indicating the total profile length in a top deck module. This behaviour is in line with expectations, as reduced profile length means less length welded with FSW. This in turn means a reduction in the time required for this production process. Figure 12 shows that the occupancy of the production line for MIG welding is independent of the profile width. The corresponding line does not show any change, which is because the panel width remains constant even if the width of the profiles from which the panels are made up changes. The production process that takes the least time is extrusion. For this process, too, the occupation time of the production line decreases with increasing profile width. This is due to the circumstance that the total profile length is synonymous with total the length of parts to be extruded. Even though wider extrusions require more force and possibly run slower, this cannot outweigh a reduction in the length of extruded parts from 37440 m for 100 mm profiles, to 6240 m for 600 mm profiles.

The dynamics of the costs depending on the profile width for longitudinal panels correspond for the most part to the dynamics just explained for transverse panels, as the diagrams in Figure 13 and Figure 14 show. However, from the list of costs in Figure 13, it can be seen that the amount of the costs differs slightly. The production of a top deck module with longitudinal panels results in higher costs than the production of a top deck module with transversal panels. In the specific case of the module with 300 mm wide profiles, the total cost of NOK 16.039.754,11 for longitudinal alignment compared to NOK 15.106.029,62 for transversal alignment corresponds to a cost increase of about 6%. The increased costs are not concentrated on one particular cost element but are distributed equally across all cost elements. The smallest difference in costs occurs in labour costs, with about 5,6% higher costs for the longitudinal scenario. The largest difference in costs occurs in depreciation costs, with approximately 7,7% higher costs for the longitudinal scenario. These figures are based on the example of the module with 300 mm wide profiles.



	100	200	300	400	500	600
🟦 Lcost	4 325 711,27	2 401 526,44	1 714 157,38	1 438 644,89	1 173 495,15	1 041 210,73
🟥 Ecost	250 623,00	184 904,56	161 028,10	154 502,65	138 728,85	133 316,18
🟧 Tcost	2 172 232,24	1 827 329,31	1 529 139,04	1 402 300,96	1 189 799,50	1 100 543,54
🟨 Ccost	1 449 606,98	746 988,14	496 052,84	395 678,72	295 304,60	245 117,54
🟦 Mcost	10 293 917,12	8 482 063,31	7 922 399,12	7 895 134,27	7 232 468,99	7 036 437,28
🟩 Dcost	2 722 826,57	1 423 867,58	943 968,15	754 137,73	581 005,60	502 498,03
🟦 Ocost	10 009 472,38	5 047 412,00	3 273 009,47	2 561 206,41	1 892 442,88	1 560 026,51

Figure 13: Distribution of costs for a top deck module by profile width - longitudinal panels

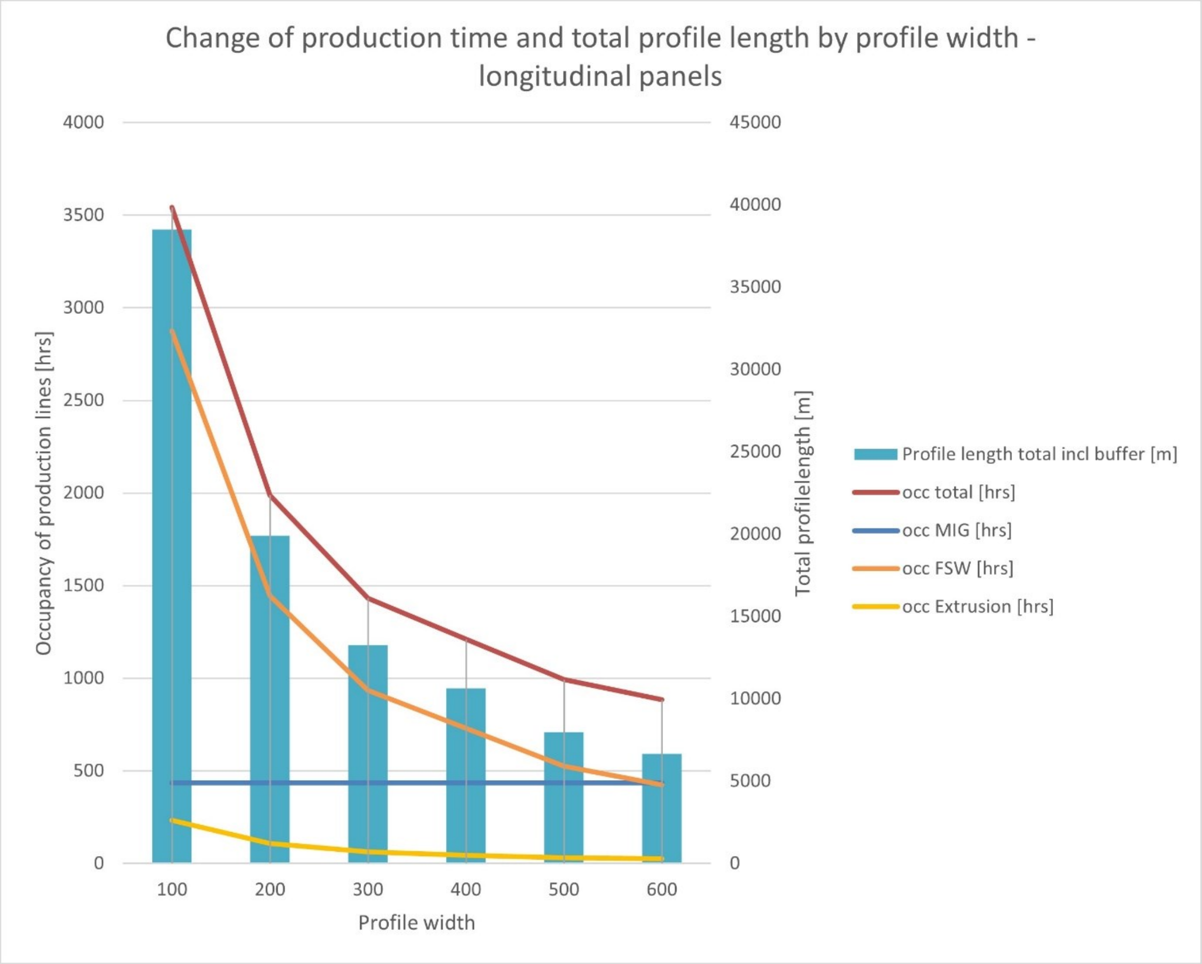


Figure 14: Change of production time and total profile length for a top deck module by profile width – longitudinal panels

The differences in costs between transverse and longitudinal panel orientation, however, only become as clear as described above when looking at the absolute costs. The costs per kg of material are almost identical between the two options, as can be seen in Table 4 on the following page, where "T" marks the transverse panel orientation and "L" the longitudinal orientation. Table 4 also shows how much material is contained in a finished top deck module according to panel orientation and profile width.

The reason that the cost per kg of material used does not show a significant difference, while the absolute cost of a top deck module with longitudinal panels is 7% higher than that of a module with transversal panels, is that more material is used for the former. On average, a top deck module with longitudinal panels is 20,76 tonnes heavier than one with transversal panels. The module in which the panels are assembled from 100 mm profiles has the highest material consumption in both module configurations. In this module version, the difference in material consumption between transverse and longitudinal panel orientation is the smallest at 13,77 tonnes.

Table 4: Cost and material use of a top deck module by profile width

	Profile width	Extrusion cost [NOK/kg]	FSW cost [NOK/kg]	MIG cost [NOK/kg]	Sum cost [NOK/kg]	Mass of used Material [t]
T	100	32,75	29,62	1,58	63,95	474,33
	200	30,05	18,05	2,00	50,10	377,78
	300	28,19	12,49	2,14	42,82	352,75
	400	27,22	9,79	2,15	39,16	351,47
	500	26,62	7,70	2,35	36,67	321,89
	600	26,24	6,37	2,42	35,03	313,41
L	100	32,80	29,56	1,61	63,97	488,10
	200	30,04	18,02	1,96	50,02	402,15
	300	28,15	12,47	2,10	42,72	375,51
	400	27,15	9,77	2,11	39,03	374,15
	500	26,51	7,67	2,31	36,49	342,66
	600	26,11	6,34	2,37	34,82	333,63

The diagrams in Figure 15 and Figure 16 show the data from Table 4 graphically. The graphs clearly show that the response of the costs to the changes in profile width is the same between modules with transverse panels and those with longitudinal panels. This observation was made earlier for the sum of the costs, but Figure 15 and Figure 16 show that this is also true for the costs of the individual production steps. The curve progressions for extrusion, FSW and MIG, as well as the total costs, are similar between the two diagrams.

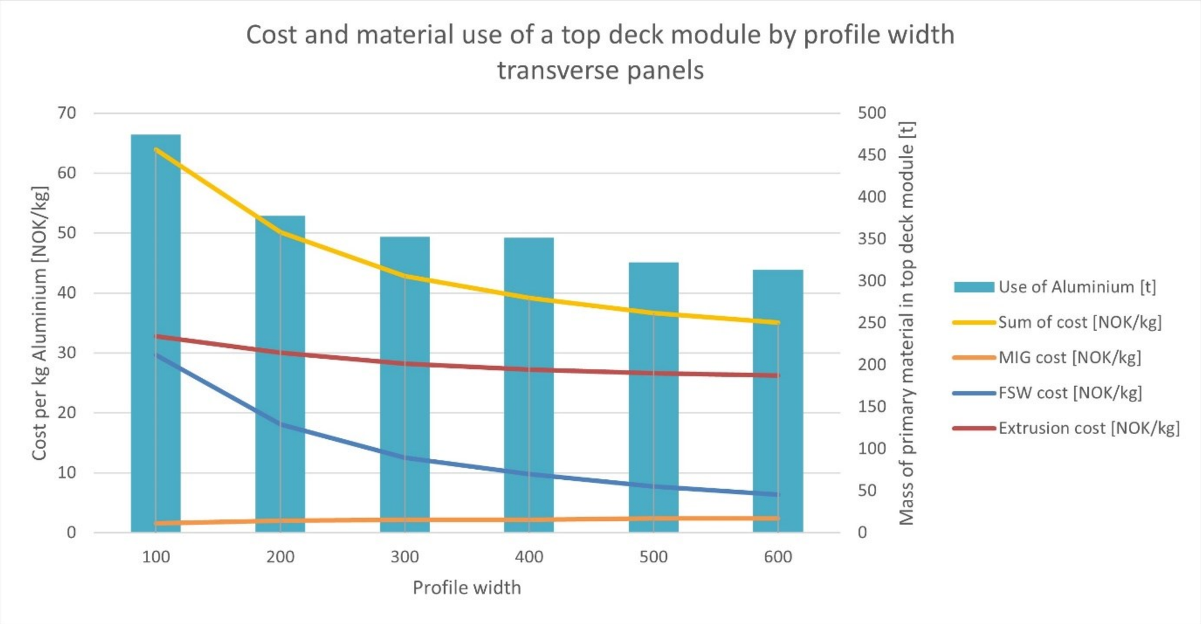


Figure 15: Cost and material use of a top deck module by profile width - transverse panels

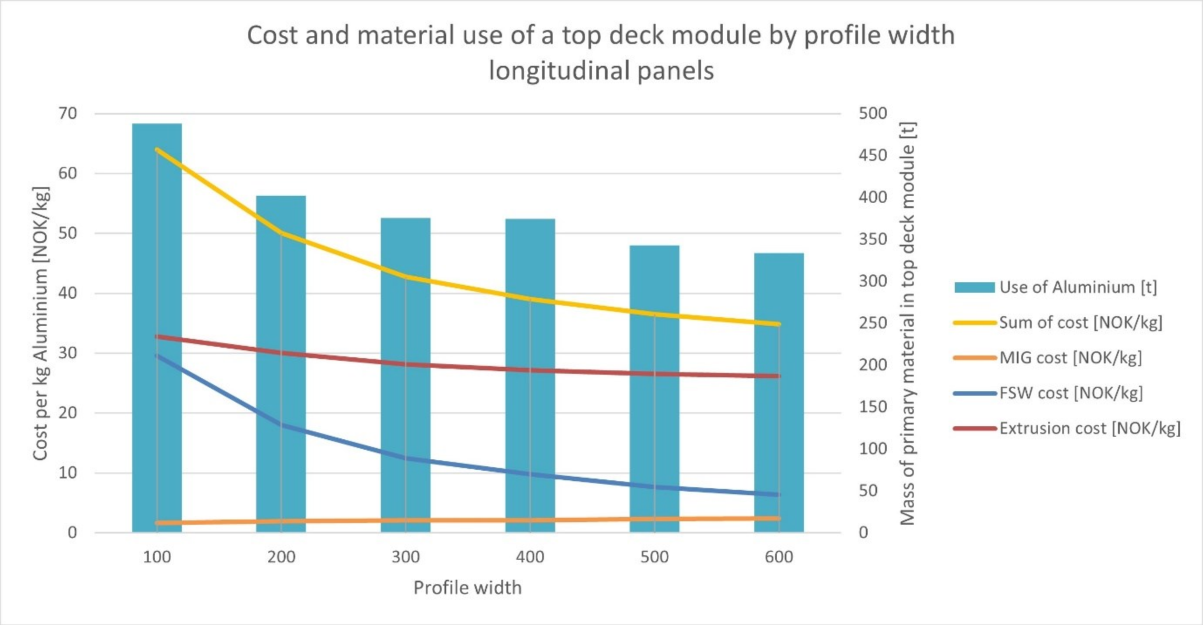


Figure 16: Cost and material use of a top deck module by profile width - longitudinal panels

The curves for the costs per kg of material in Figure 15 and Figure 16 show a trend similar to that of the curves for the occupancy time of the production lines in Figure 12 and Figure 14. This confirms the previously expressed assumption of a strong correlation between costs and production time. However, while the occupation time of the production lines for MIG welding is the same for each profile width, the costs for MIG welding increase slightly with increasing profile width. This change is hardly visible in the diagrams in Figure 15 and Figure 16, but can be seen in Table 4. The reason for this slight increase in costs is the reduced number of profiles and the lower material usage, which leads to less cut-off in MIG welding and thus less income from recovery.

The complete numerical test results can be viewed on the result sheets exported from the cost model and attached to the thesis in Appendix C.

A discussion of the above results with the Langenuen project group showed that the presented diagrams represent dynamics that are largely in line with the experience-based expectations of the experts from the project group. This is particularly the case for the two welding processes. The fact that the extrusion costs decrease with increasing profile width is considered unexpected, since larger presses with more force are needed for larger extrusions. This means, as explained in 4.2, a considerable increase in investment costs. In view of the reduced time needed for the extrusion process due to the increase in profile width, and the dependence of depreciation costs on the occupancy time of the production line explained in 4.2, it is reasonable that extrusion costs decrease. The experts note that expectations of costs, especially for large extrusions, are partly based on quotations from suppliers. Since the model outputs the production costs and not the price estimated for a profile of a certain width, discrepancies can arise.

5.2 Sensitivity analysis

The sensitivity analysis tests how the costs react to fluctuations in parameters that are not assigned to the design but to the process. The results of the previous test already indicate that material and occupancy time of the production lines are important factors in the costs of manufacturing the top deck module. Material and overhead costs account for the largest share of total costs, followed by labour costs. Costs for tooling, consumables and depreciation have a medium to small share of the total costs and energy plays the smallest role. Given these findings, parameters are chosen which are expected to have a considerable influence on the costs and which are reduced and increased by 10% and 20% respectively to determine their actual impact. The parameters adjusted in the course of the sensitivity analysis are the scrap metal price, LME, depreciation period, welding speed for FSW, arc rate for FSW, arc rate for MIG, and the filler wire diameter. An overview of these parameters, their default values, and the values for the test scenarios is given in Table 5. The values used in the model otherwise correspond to the base case (Appendix B), which provides for a profile width of 300 mm and a transverse orientation of the panels in the top deck module.

Table 5: Test parameters, default values and test scenarios for the sensitivity analysis

Test parameter	-20%	-10%	Default value	+10%	+20%
Scrap metal price [GBP/kg]	0,68	0,77	0,85	0,94	1,02
LME [USD / ton]	1760	1980	2200	2420	2640
Depreciation period [years]	8	9	10	11	12
Welding speed [m/min] FSW	0,40	0,45	0,50	0,55	0,60
Arc rate [%] FSW	52	58,5	65	71,5	78
Arc rate [%] MIG	40	45	50	55	60
Filler Wire diameter [mm]	1,28	1,44	1,60	1,76	1,92

The results of the sensitivity analysis are shown in Figure 17. The diagram shows the cost of a top deck module in NOK/kg for the 5 different test scenarios, where 0 describes the test scenario with initial values. For this reason, all curves intersect in the initial value scenario which, as only one parameter at a time is changed, always corresponds to the base case.

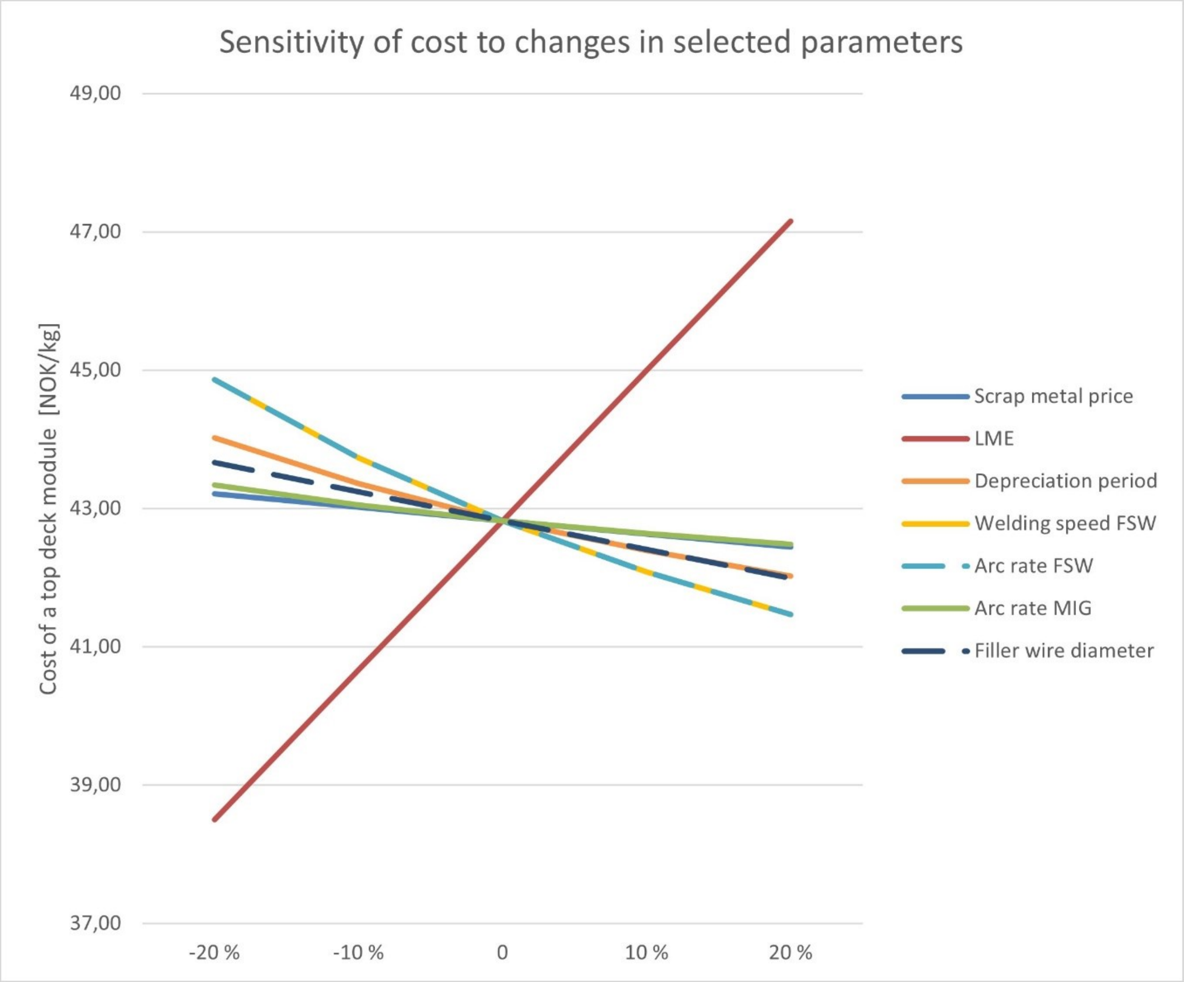


Figure 17: Results, sensitivity analysis

The results of the sensitivity analysis show that for all factors selected for testing, fluctuations have an influence on the costs of a top deck module. Among the selected parameters, the costs are most sensitive to fluctuations in the material price. A 20% reduction in the material price leads to a reduction in the cost of the Top Deck module from NOK 42,82/kg to NOK 38,5/kg. An increase of 20% in the material price leads to an increase in the cost of the Top Deck module from NOK 42,82/kg to NOK 47,15/kg. The diagram in Figure 17 shows that material price and top deck module cost have a linear relationship. While it is not clearly visible in the graph, the figures from the tests show that this also applies to the relationship between the price of scrap metal and the cost of a top deck module. The test scenarios -20%, -10%, 0, +10%, +20% for this parameter lead to the following costs of the top deck: 43,21; 43,02; 42,82; 42,63 and 42,44 NOK/kg. This translates to a change in costs of 0,19 NOK/kg from test scenario to test scenario. Only between scenario -10% and scenario 0 the cost of a top deck module changes by 0,2 NOK/kg, which may be due to rounding in preceding calculations. The results for these two parameters are as expected since prices are directly related to costs.

The other parameters on which the sensitivity analysis is performed have a less direct relationship to costs. The depreciation period determines over how many years of useful life the investment costs in equipment are spread, but also in building costs that are part of the overhead. The depreciation period thus influences the level of depreciation costs and overhead costs for all three production processes. Figure 17 shows that the total cost of a top deck module changes to a greater extent when the depreciation period is reduced than when it is extended. Overall, however, the impact of variations in this parameter is moderate, especially given that this parameter affects cost centres in all production processes. However, since the affected cost centres, depreciation costs and overhead costs depend on the occupancy time of the production lines, as explained earlier, it can be assumed that the parameter depreciation period becomes more relevant with higher occupancy times.

As with the depreciation period, the curves for welding speed for FSW and arc rate for FSW show that the total cost of a top deck module increases more when these parameters are decreased than it decreases when the parameters are increased by an equivalent amount. Variations in welding speed for FSW or arc rate for FSW cause identical changes in the cost of a top deck module, and in fact the second most significant among the selected parameters. Both parameters, through their influence on the cycle time, affect the occupancy time of the FSW line, which, according to the results of the previous test, is the busiest of the three production lines. The fact that variations in the parameters FSW welding speed and FSW arc rate have a comparatively high influence on the cost of a top deck module supports the assumption that the occupancy time of the production lines, or production time, is one of the cost drivers.

The MIG welding rate and the filler wire diameter also influence the production time and compared to the FSW parameters, their influence on the costs is rather small. However, these parameters only influence the occupancy time of the MIG production line, while the FSW parameters only influence that of the FSW production line. From the calculations of the model and from Figure 12 in 5.1. it can be seen that, for the case of 300 mm profiles, MIG has a share of about 30,8% of the total production time, while the share of FSW is about 64,8%. Examining the curves in this context reveals that the influence of the two MIG parameters on the cost of a top deck module is analogous to that of the two FSW parameters discussed earlier.

The complete numerical test results can be viewed on the result sheets exported from the cost model and attached to the thesis in Appendix C.

6 Discussion

6.1 Evaluation of the developed model

The results presented in the previous section from the tests conducted with the cost model show that the developed model is capable of producing cost estimates and responding to varying inputs in different parameters. In a discussion with the Langenuen project group, in which the results of the feature-based test were presented, the behaviour of the model was assessed as logical, but not free from inaccuracies and uncertainties. As already mentioned in 3, the model is based on several basic assumptions. The assumptions do not necessarily correspond to a realistic production scenario. For example, it is questionable whether all production steps would be carried out in one factory, or whether parts would be bought from suppliers, or certain processes outsourced. The isolation of the production system in the sense that only the top deck modules for the bridge are produced in the factory, or at least that these have first priority, is also debatable. However, making such assumptions is essential to establish a starting point for the modelling process, especially when modelling a system that is not fixed. The same applies to the production processes involved in the model. While extrusion is a fairly standardized process, welding is highly variable. Especially in MIG welding, as described in 2.2.3, there are several parameters that have to be adjusted and coordinated to achieve a good welding result. For reasons of practicability, it is necessary to simplify processes. For the cost model of this thesis, this means, as mentioned in 4.4, to include only those parameters in the model that directly influence the costs. However, this requires that in the case of actual production, the other parameters have to be adjusted to those in the model. The degree of uncertainty thus influences how much detail is included in the model. Although detailing and specification can reduce uncertainty, it can only do so if details of the processes to be modelled are known. A high level of detail would moreover be outside the scope of this thesis, which is why trade-offs had to be made. However, this leads to inaccuracies, for example in the calculation of the mass of scrap generated. In the monthly meeting with the Langenuen project group, in which the results were presented and discussed, it was pointed out that the proportion of metal scrap generated increases with the size of the extrusions and that this is not sufficiently reflected in the results.

The uncertainties and trade-offs result in the model developed providing cost estimates that are quantitatively not robust enough to base budget plans on. However, the results of the tests carried out, as well as the overall positive feedback from the Langenuen project group, allow the conclusion that the model provides valuable insights into the interrelationships and drivers of production costs of large infrastructure elements as in the Langenuen case. Further substantiation of this conclusion through additional steps to validate this model is desirable. However, validating a model such as the one developed is difficult as there are no known cases of similar construction projects carried out from which data can be obtained for comparison. Testing and expert opinions are therefore the main methods of validation. Further tests and experiments with different scenarios would increase the validity of the model. For example, the feature-based test could be run with a different profile cross-section to check if the dependencies on profile width change. Running the sensitivity analysis with more than one parameter at a time could also be considered. Running tests with the developed cost model is very time consuming as the spreadsheet does not allow for results from multiple runs to be cached. It is necessary to manually copy all results out of the calculation and transfer them to a separate sheet, which can then be used to create summaries and graphs. This process is laborious and prone to errors. The most common errors that have occurred are transfer errors and accidental changing of cells when alternating between worksheets. The one parameter at a time testing strategy allows such errors to be detected at the latest when graphing the results. It can therefore be stated with certainty that errors of this kind are not contained in the results. However, for the execution of further and particularly more complex tests, a coupling of the spreadsheet with a simulation programme is imperative. Further meaningful tests, though, are also limited by the current configuration of the model. Tests to change features of the design or assemblies are only worthwhile to a limited extent. It is expected that changes in the design or construction features will alter the performance of the bridge girder. For this reason, options such as changing the cross-section of the profiles, or choosing a different weld seam geometry in MIG welding, are not included in the model. This could be overcome by linking to appropriate databases or CAD programmes. As far as the process part of the model is concerned, it is possible to manually change process parameters, for instance the welding speed. However, the reduction of e.g., set-up time as a result of modifying the workflow is not feasible with the model. This could be achieved by means of simulations, which provide a way to execute models over time [60]. Different ways to overcome the identified limitations of the model and to build comprehensive cost models for large infrastructure elements are further elaborated in the following section.

6.2 Cost models for large infrastructure elements

As frequently mentioned in the literature and referred to in 2.3.1, cost modelling is a time-consuming process. In cost modelling, the need for data of different types from different sources is high [24, 43], especially in a complex project like the Langenuen suspension bridge, which includes several production processes. Collecting data for the model took a lot of time, but so did getting familiar with the production processes and relationships, understanding the system both as a manufacturing system and also as an economic system. Time constraints, but also the lack of strong expertise and information on the economics of the manufacturing processes, as well as the lack of available documentation on similar projects and cost models, resulted in many assumptions and trade-offs having to be made. In the case of this thesis, therefore, Eriksson's [41] comment mentioned in the literature review that interdisciplinary teams are necessary to produce early and accurate cost estimates seems particularly valid.

Nevertheless, this thesis shows that important insights can be gained even with simpler cost models. The developed cost model may not produce accurate cost estimates, but it has proven that it can produce reasonable results that stimulate discussion. And providing a basis for discussion on how product and process decisions affect costs is an important purpose of cost models [24]. In the creation of an understanding of the causes and drivers of costs, which is repeatedly mentioned in the literature review in 2.3.1 as being important, the developed model has also proved useful. However, as mentioned in the previous paragraph, the spreadsheet-based cost model has limitations, firstly due to its static nature and dependence on manual testing, and secondly due to the restricted changeability of features. Dynamic process simulation models are needed to conduct experiments for effective product and process design [38]. However, a computer-aided simulation is not only necessary for conducting experiments, but it would also enable the modelling of a realistic production scenario, giving insights on the performance of the overall system [60]. This would primarily affect the process part of the model by allowing performance factors to be included in the cost calculation that have so far been omitted, for example bottlenecks and delays in production. Computer-aided simulations make it possible to visualise system behaviour over time, which is why they are often used to understand complex systems and to support decision-making [60, 61]. The aspect of decision support is also addressed in the articles presented in the literature review, mainly in connection with cost optimisation. Since the aim of creating a cost model for large infrastructure elements made of aluminium, such as bridge girders, is not just to determine the costs, but to find out how the product and production system can be designed as cost-effectively as possible, computer-aided simulations are indispensable for this.

Solutions to the limitations of the developed cost model through restricted changeability of product and production features have already been mentioned briefly in 6.1. In this context, the linking of the model to databases and CAD programmes was mentioned. Most costs are determined by decisions made early in the design phase, whether for product or process [30, 33, 62]. A cost model should therefore start at this point and provide the opportunity to make informed decisions that can reduce costs before they occur.

However, bridges are designed to meet safety and performance objectives for their intended function under the expected operating conditions and predicted service life. The fulfilment of functional requirements and safety has utmost priority [42]. This means that for infrastructure elements such as bridge girders it is not possible, for example, to simply reduce material, change component geometry or join sections with a U-weld instead of a V-weld in order to improve economic efficiency. All changes of features must be controlled and approved with regard to the fulfilment of safety and performance requirements. Doing this for a complex construction project like a bridge, but also for a single bridge girder, is not feasible manually with a spreadsheet. A linkage of the cost calculation with CAD programs or databases, as proposed by Philpott, et al. [30], Caprace and Rigo [21], or Chayoukhi, et al. [34] is therefore necessary. The need to meet safety and performance requirements also means that the model must consider the whole bridge and not just individual components as in this thesis. Otherwise, appropriate verification values would also have to be defined for smaller elements of a bridge, such as a bridge girder, or even a profile of a panel. Linking the cost model to CAD models and databases cannot and is not meant to replace an accurate calculation of performance parameters and an assessment of safety. The suggested approach presumes that a bridge design exists that meets all requirements and that, based on this design, a cost optimisation is carried out by means of a cost model. The intention is similar to Nieto's [11] proposal to include manufacturability constraints and a feedback mechanism as an improvement to his cost model for extrusions. The ability of the model to check performance and safety constraints and to inform the user via a feedback mechanism whether the design meets the requirements and if not, where the problem is (load, stability, etc.), would increase the usefulness of a cost model for large infrastructure elements considerably.

In view of the capabilities and limitations of the developed model and the findings from the literature, a cost model for large infrastructure elements should be developed by an interdisciplinary team and meet the following requirements:

- Robust cost calculation based on real data
- Linking the model to a CAD programme or databases containing information on product-based features
- Linking the model to databases containing information on process-based features
- Support of process and cost analysis by simulation software
- Support for manufacturing system design by simulation software

A model that meets these requirements is predicted to have many applications. Cost models with different objectives have already been presented in the literature review in 2.3.1. With cost models for large infrastructure elements, developed according to the previous recommendations, it is conceivable that not only the costs for a project can be optimised, but also the costs of achieving a certain goal can be estimated. Especially if the cost model is based on a robust process model and linked to simulation, time or capacity-based goals could be tested for their financial consequences. For example, if it is known that FSW is usually a bottleneck, it could be tested how costs change when the use of FSW is reduced as much as possible. In the case of the top deck module of the Langenuen suspension bridge, such a reduction of FSW is reflected in the change of the profile width. But also, the use of alternative joining methods and their financial consequences could be analysed in an adequate cost model.

Another possible application for the cost model is meeting a cost target. The literature review in 2.3.1 outlines the principle of target costing and points out that early cost estimates are necessary to achieve a cost target [26]. A model as described should not only be able to provide these cost estimates, but rather assist in determining the necessary product and process configurations to achieve the target. Cost and value would then drive the design process, which is precisely what defines target costing [25].

The work by Orji and Wei [37] presented in the literature review deals with the implementation of sustainable production by means of a cost model. The link between sustainability and costs in this case is a carbon tax, which is to be avoided through energy-saving activities. Even without a carbon tax, energy conservation is an objective whose financial impact might be of interest for sustainable projects and where a cost model can help. Especially when energy is only a small part of the total cost, as in the Langenuen case, and there is almost no cost benefit from saving it, knowing whether there is an additional financial cost is important for project planning. Additional financial cost can occur e.g., due to switching to a more energy-efficient but labour-intensive process. The use of recycled materials might also be a sustainability goal, and it is particularly conceivable in connection with aluminium, due to the high quality of the secondary material [8]. Particularly when, as in the Langenuen case, the material represents a significant part of the total cost, the use of recycled material can have a big impact. A cost model could quantify the cost impact of price differences between primary and secondary aluminium.

In the context of sustainability related goals, it would be reasonable to extend the model to include the calculation of CO_2 emissions or other relevant sustainability indicators. This would help to put costs in perspective, to justify any additional costs for sustainable solutions and to evaluate benefits against costs. In response to the European Green Deal, an EU taxonomy for sustainable activities was recently elaborated, which is to govern preferential financial support for sustainable projects and businesses [63]. It is expected that such undertakings and regulations will increase in the future. Accordingly, a cost model with a sustainability dimension could play a major role in obtaining funding.

All previously described applications for a cost model, which was developed according to the recommendations made, are conceivable for the development of new bridges as well as for replacement and renewal projects. The latter, according to Siwowski [3], quoted in 1.1, could play an important role in the future use of aluminium in bridges.

In the results presented in 5.1, it was observed that absolute costs and costs per kilogram of material give a different impression of which top deck module is most favourable in terms of cost. Even if both cost calculations are correct, the model must not give the impression that it is preferable to use more material to make the cost per kg look more attractive, for example compared to an alternative design concept using steel. This would not only be misleading, when e.g., applying for funding, it would also be highly unsustainable.

For cost models for bridges, consideration should be given to providing only the total cost and the typical cost per square meter bridge deck area [42] as financial outputs. In contrast to material consumption, length and width of a bridge can be expected to vary little or not at all in different bridge designs for the same project. In this way, more consistency in the results would be achieved. If it is an important factor for comparison, e.g., because of a comparison of different materials, the price per kg can be calculated manually from the other outputs of the model.

However, for material comparisons, such as with steel, a model estimating costs from raw material to final product may not be satisfactory and lifecycle cost models should be considered instead. As mentioned in 2.3, lifecycle approaches also consider costs that arise after production and up to the end of a product's life [15]. With the integration of all necessary operations and related expenses over the service life of a bridge, it is possible to obtain a holistic assessment of the costs of a bridge on which conclusive comparisons can be made between, for example, steel and aluminium. As mentioned in section 1 and 2.1, aluminium is resistant to corrosion and therefore aluminium bridges are less maintenance intensive than steel and concrete bridges. This characteristic, and its financial implications, would be reflected in a life cycle cost model, whereas it is not reflected in either the developed model or the suggested model. The good recyclability of aluminium, which has been mentioned repeatedly in this thesis, can also strongly influence the comparison of material alternatives. At the end of life, the sale of the aluminium scrap is conceivable which would be accounted for as income in the life cycle cost model and thus considerably reduce the total life cycle costs of an aluminium bridge.

7 Conclusion

In this thesis the possibilities for the development of cost models for large infrastructure elements, based on the specific case of the Langenuen suspension bridge, have been investigated. A cost model was developed and tested, the results of which were presented and discussed in the previous sections. It was found that cost models can be valuable tools in planning infrastructure projects such as bridges. They can reduce uncertainty and risk by providing information on cost early in the product development process, offering the possibility to reduce costs before they occur. Even comparably simple cost models, such as the one developed in the context of this work, can create a better understanding of the costs of a project and stimulate discussions about costs. The bottom-up approach and the process-based method with the possibility to include features has proven to be useful. A hybrid bottom-up process and feature-based cost model, incorporating the suggestions made in 6.2, could provide robust information on the costs of various objectives in a project and contribute to their achievement. For bridge construction with aluminium, target costing could be facilitated with this model and thus competitiveness with other materials could be achieved. However, when comparing the costs of constructions made of different materials, only life cycle cost models provide the depth and comprehensiveness needed for a thorough comparison.

Although the model has been validated through testing and expert opinion, validation remains a vulnerability in this work. There is a lack of data to compare with the results of the tests and expert opinions, while valuable, are still subjective. While the model is based on literature and data where available, it cannot be avoided that it is influenced by the author's assumptions, understanding of the production process and choice of detail. This carries the risk that the model is built to confirm the perceptions of the modeller. This problem has a negligible impact on the answers to the research questions of this thesis but becomes very relevant when the objective is to make robust estimates with a cost model. For this reason, further research should be conducted by research groups rather than individual researchers to avoid bias.

7.1 Future work

In subsequent studies, the difficulty of validating cost models for projects where there is no comparative data, as mentioned above, should be addressed. Furthermore, research on cost models for large infrastructure elements is needed, examining the feasibility of the recommendations mentioned in 6.2. Concrete approaches to integration with CAD programmes and databases need to be developed and tested. Another area for further research is simulations. DES and SD are approaches to computer simulations which have been applied in the studies discussed in the literature review. However, there are further simulation approaches, as well as the possibility for combinations of these. Research is needed to determine which type of simulation is best suited for the purposes of a cost model as proposed.

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Appendices

Appendix A: List of Reference contacts

Appendix B: List of input parameters to the base case

Appendix C: Results sheets exported from the cost model

Appendix A: List of Reference contacts

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Appendix B: List of input parameters to the base case

Exchange rates	
NOK/USD	8,21
NOK/EURO	9,94
NOK/GBP	11,43
Design generator	
Total bridge length [m]	1775
Length of top deck module [m]	120
Width of top deck module [m]	31
Longitudinal [L] vs Transverse [T] orientation	T
Buffer length on profile ends [mm]	50
Profile wall thickness bottom [mm]	12
Profile wall thickness top [mm]	16
Profile truss thickness [mm]	6
Profile end thickness [mm]	4
Profile width (steps 100) [mm]	300
Profile height [mm]	150
Extrusion cost	
Butt discard [%]	3
Length scrapped per continuous extrusion [m]	3
Quality Scrap [%]	5
Saw blade width [mm]	5
Runout table length [m]	45
Ram acceleration time per billet [sec]	7
Dead cycle time per billet [sec]	30
Set-up time [min]	10
Unplanned downtime [%]	5
Planned downtime [%]	6,7
N operators	6
Direct labour cost per month [NOK]	41 280
Energy efficiency homogenization furnace [%]	40,00
Energy efficiency preheating [%]	80
Press efficiency hydraulics [%]	85
Energy to cool one billet runout [kwh]	1
Energy cost per kwh [NOK/kwh]	0,30
Energy distribution cost per kwh [NOK/kwh]	0,26
Durability of die [hrs]	10
LME [USD / ton]	2200,00
LME premium	150
Scrap metal price [GBP/kg]	0,85
Depreciation period [years]	10,00
Management, R&D, Sales, Quality, HES etc [NOK / year]	18 000 000
Maintenance [NOK / year]	8 100 000
Housing and utility [NOK / year]	9 127 588
IT [NOK / year]	200 000
Fixed consumables [NOK / year]	2 000 000
Logistics [NOK / year]	5 000 000

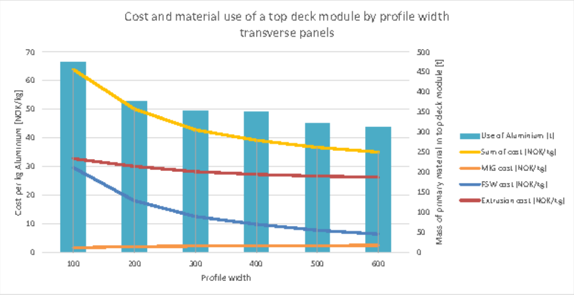
Other [NOK / year]	7 000 000
FSW cost	
Arc rate [%]	65
Welding speed [m/min]	0,50
Number of welding heads [N]	2
Transport inhouse [min/Panels]	10
Cleaning with alcohol [min/m]	0,50
Unplanned downtime [%]	5
Planned downtime [%]	6,7
N operators	3
Direct labour cost per month [NOK]	41 280
Energy consumption per welded meter [kwh]	0,2
Energy cost per kwh [NOK/kwh]	0,30
Energy distribution cost per kwh [NOK/kwh]	0,26
Durability of tool [m]	2 000
Alcohol for cleaning [L/m]	0,10
Prize of alcohol for cleaning [NOK/L]	189
Investment [NOK]	32 840 000
Depreciation period [years]	10,00
Management, R&D, Sales, Quality, HES etc [NOK / year]	2 700 000
Maintenance [NOK / year]	1 822 500
Housing and utility [NOK / year]	4 056 704
Insurance cost per year [NOK / year]	675 000
IT [NOK / year]	9 000
Fixed consumables [NOK / year]	90 000
License [NOK/year]	427 420
Logistics [NOK / year]	2 250 000
Other [NOK / year]	2 250 000
MIG cost	
Deposition efficiency [%]	95
Filler Wire diameter [mm]	1,6
Wire feed rate [mm/min]	15000
Welding speed [m/min]	0,75
Arc rate [%]	50,00
groove angle [deg]	27,5
root face thickness [mm]	0
Saw blade width [mm]	5
Unplanned downtime [%]	5
Planned downtime [%]	6,7
N operators	3
Direct labour cost per month [NOK]	41 280
Input power welding gun [kW]	6
Energy Efficiency welding gun [%]	80
Energy cost per kwh [NOK/kwh]	0,29
Energy distribution cost per kwh [NOK/kwh]	0,26
Shielding gas consumption [L/min]	20,00
Prize of shielding gas [NOK/kg]	7,69
Volume of 1 kg shielding gas [m³]	0,56

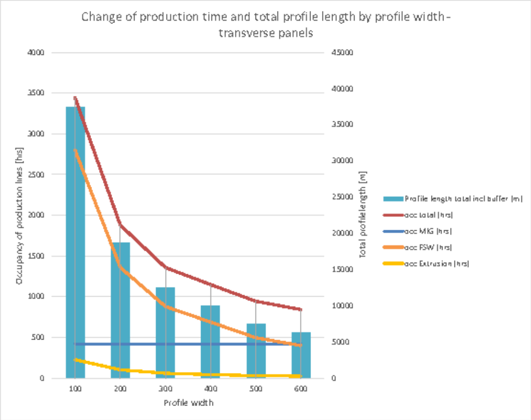
Prize for filler wire [NOK/kg]	68,00
Investment [NOK]	8 210 000
Depreciation period [years]	10,00
Management, R&D, Sales, Quality, HES etc. [NOK / year]	2 700 000
Maintenance [NOK / year]	1 822 500
Housing and utility [NOK / year]	4 056 704
Insurance cost per year [NOK / year]	675 000
IT [NOK / year]	9 000
Fixed consumables [NOK / year]	90 000
Logistics [NOK / year]	2 250 000
Other [NOK / year]	2 250 000

Appendix C: Results sheets exported from the cost model

Profile width - transverse panel

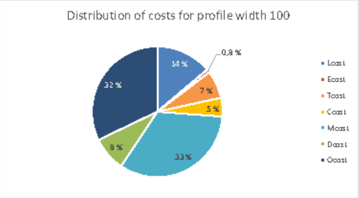
Design parameters	Input					
Longitudinal [L] vs Transverse [T] orientation	T					
Profile wall thickness bottom [mm]	12					
Profile wall thickness top [mm]	16					
Profile truss thickness [mm]	6					
Profile end thickness [mm]	4					
Profile width (steps 100) [mm]	100	200	300	400	500	600
Profile height [mm]	150					





Profile width: 100

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	516 585,17	3 208 894,55	479 110,59	4 204 590,31
Energy cost	Ecost	230 181,41	10 133,76	761,41	241 076,58
Tooling	Tcost	1 728 925,51	359 748,48	X	2 088 673,99
Consumables cost	Ccost	X	1 368 057,60	42 544,59	1 410 602,19
Material cost inclusive recovery	Mcost	10 077 629,41	X	-26 586,42	10 051 042,99
Depreciation	Dcost	833 580,74	1 702 264,04	63 540,01	2 599 384,79
Overhead/In-direct	Ocost	2 145 647,87	7 402 372,85	189 412,63	9 737 433,35
Sum cost per module		15 532 550,12	14 051 471,28	748 782,80	30 332 804,20
Sum cost per kg material		**32,75**	**29,62**	**1,58**	**63,95**
Occupancy of production line [hrs]	occ	225,31	2 799,09	417,92	**3 442,32**
Profile length total incl buffer [m]	Lprtb				37 440,00
Mass of primary material in top deck module [t]	Mpm				474,33



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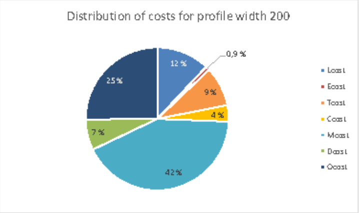
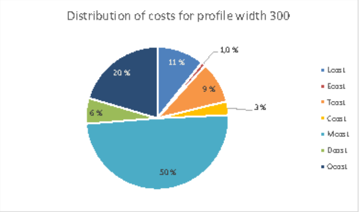
Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	232 269,17	1 558 071,96	479 110,59	2 269 451,72
Energy cost	Ecost	167 418,62	4 892,16	761,41	173 072,19
Tooling	Tcost	1 526 536,38	173 671,68	X	1 700 208,06
Consumables cost	Ccost	X	660 441,60	42 544,59	702 986,19
Material cost inclusive recovery	Mcost	8 029 218,41	X	-21 174,87	8 008 043,54
Depreciation	Dcost	426 831,73	826 530,71	63 540,01	1 316 902,45
Overhead/In-direct	Ocost	969 938,48	3 594 206,49	189 412,63	4 753 557,60
Sum cost per module		11 352 212,80	6 817 814,60	754 194,35	18 924 221,75
Sum cost per kg material		**30,05**	**18,05**	**2,00**	**50,10**
Occupancy of production line [hrs]	occ	101,30	1 359,09	417,92	**1 878,31**
Profile length total incl buffer [m]	Lprtb				18 720,00
Mass of primary material in top deck module [t]	Mpm				377,78



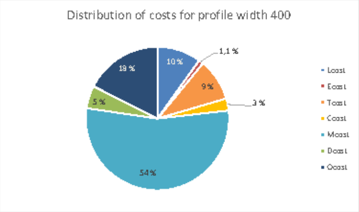
Profile width: 300

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	136 533,38	1 007 797,77	479 110,59	1 623 441,74
Energy cost	Ecost	147 379,35	3 144,96	761,41	151 285,72
Tooling	Tcost	1 313 419,00	111 646,08	X	1 425 065,08
Consumables cost	Ccost	X	424 569,60	42 544,59	467 114,19
Material cost inclusive recovery	Mcost	7 495 358,39	X	-19 771,89	7 475 586,50
Depreciation	Dcost	278 257,81	534 619,59	63 540,01	876 417,41
Overhead/In-direct	Ocost	572 888,65	2 324 817,70	189 412,63	3 087 118,98
Sum cost per module		9 943 836,58	4 406 595,71	755 597,33	15 106 029,62
Sum cost per kg material		**28,19**	**12,49**	**2,14**	**42,82**
Occupancy of production line [hrs]	occ	59,55	879,09	417,92	**1 356,56**
Profile length total incl buffer [m]	Lprtb				12 480,00
Mass of primary material in top deck module [t]	Mpm				352,75



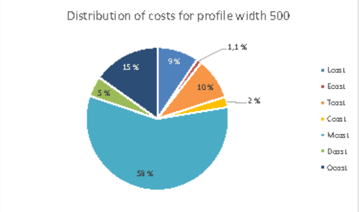
Profile width: 400

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	97 831,85	787 688,09	479 110,59	1 364 630,53
Energy cost	Ecost	142 319,81	2 446,08	761,41	145 527,30
Tooling	Tcost	1 223 882,04	86 835,84	X	1 310 717,88
Consumables cost	Ccost	X	330 220,80	42 544,59	372 765,39
Material cost inclusive recovery	Mcost	7 468 964,35	X	-19 700,37	7 449 263,98
Depreciation	Dcost	221 893,93	417 855,15	63 540,01	703 289,09
Overhead/In-direct	Ocost	412 749,61	1 817 062,19	189 412,63	2 419 224,43
Sum cost per module		9 567 641,59	3 442 108,15	755 668,85	13 765 418,59
Sum cost per kg material		**27,22**	**9,79**	**2,15**	**39,16**
Occupancy of production line [hrs]	occ	42,67	687,09	417,92	**1 147,68**
Profile length total incl buffer [m]	Lprtb				9 984,00
Mass of primary material in top deck module [t]	Mpm				351,47



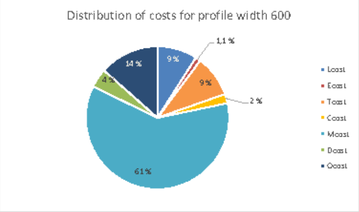
Profile width: 500

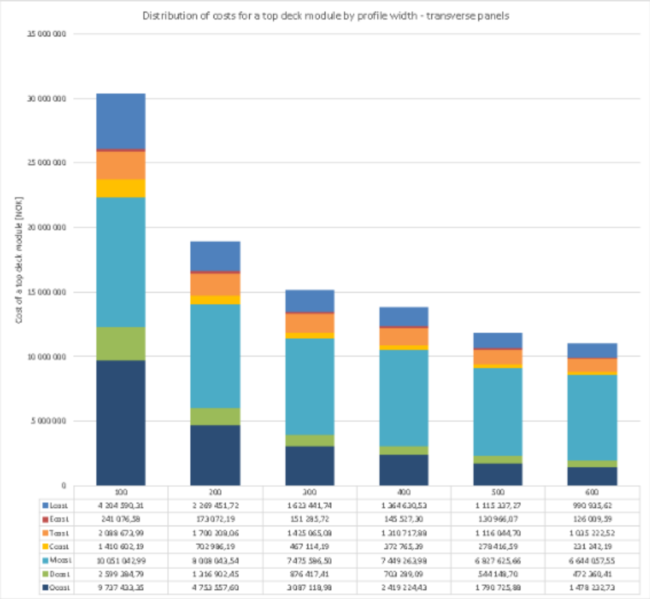
Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	68 648,27	567 578,41	479 110,59	1 115 337,27
Energy cost	Ecost	128 457,46	1 747,20	761,41	130 966,07
Tooling	Tcost	1 054 019,10	62 025,60	X	1 116 044,70
Consumables cost	Ccost	X	235 872,00	42 544,59	278 416,59
Material cost inclusive recovery	Mcost	6 845 667,92	X	-18 042,26	6 827 625,66
Depreciation	Dcost	179 517,98	301 090,71	63 540,01	544 148,70
Overhead/In-direct	Ocost	292 006,58	1 309 306,67	189 412,63	1 790 725,88
Sum cost per module		8 568 317,30	2 477 620,59	757 326,96	11 803 264,85
Sum cost per kg material		**26,62**	**7,70**	**2,35**	**36,67**
Occupancy of production line [hrs]	occ	29,94	495,09	417,92	**942,95**
Profile length total incl buffer [m]	Lprtb				7 488,00
Mass of primary material in top deck module [t]	Mpm				321,89



Profile width: 600

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	54 301,45	457 523,58	479 110,59	990 935,62
Energy cost	Ecost	123 850,42	1 397,76	761,41	126 009,59
Tooling	Tcost	985 602,04	49 620,48	X	1 035 222,52
Consumables cost	Ccost	X	188 697,60	42 544,59	231 242,19
Material cost inclusive recovery	Mcost	6 661 624,72	X	-17 567,17	6 644 057,55
Depreciation	Dcost	166 111,92	242 708,48	63 540,01	472 360,41
Overhead/In-direct	Ocost	233 391,18	1 055 428,92	189 412,63	1 478 232,73
Sum cost per module		8 224 881,74	1 995 376,81	757 802,05	10 978 060,60
Sum cost per kg material		**26,24**	**6,37**	**2,42**	**35,03**
Occupancy of production line [hrs]	occ	23,68	399,09	417,92	**840,69**
Profile length total incl buffer [m]	Lprtb				6 240,00
Mass of primary material in top deck module [t]	Mpm				313,41

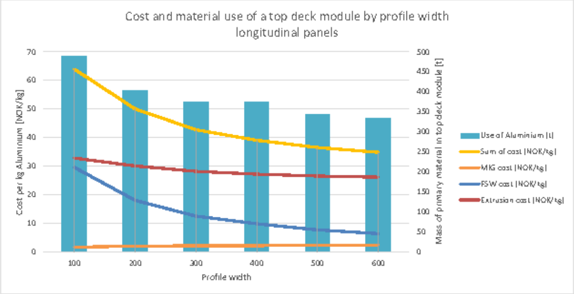


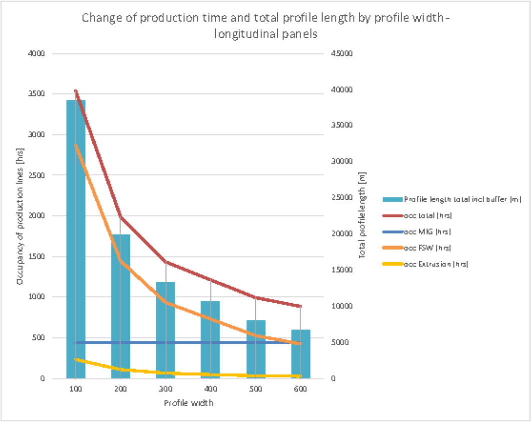


	100	200	300	400	500	600
🟦 Lcost	4 204 590,31	2 269 451,72	1 623 441,74	1 364 630,53	1 115 337,27	990 935,62
🟥 Ecost	241 076,58	173 072,19	151 285,72	145 527,30	130 966,07	126 009,59
🟧 Tcost	2 088 673,99	1 700 208,06	1 425 065,08	1 210 717,88	1 116 044,70	1 035 222,52
🟨 Ccost	1 410 602,19	702 986,19	467 114,19	372 765,39	278 416,59	231 242,19
🟦 Mcost	10 051 042,99	8 008 043,54	7 475 586,50	7 449 263,98	6 827 625,66	6 644 057,55
🟩 Dcost	2 599 384,79	1 316 902,45	876 417,41	703 289,09	544 148,70	472 360,41
🟦 Qcost	9 737 433,35	4 753 557,60	3 087 118,98	2 419 224,43	1 790 725,88	1 478 232,73

Profile width - longitudinal panel

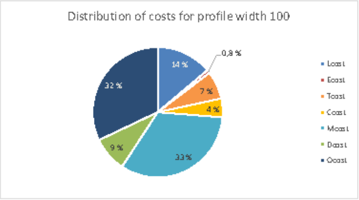
Design parameters	Input					
Longitudinal [L] vs Transverse [T] orientation	L					
Profile wall thickness bottom [mm]	12					
Profile wall thickness top [mm]	16					
Profile truss thickness [mm]	6					
Profile end thickness [mm]	4					
Profile width (steps 100) [mm]	100	200	300	400	500	600
Profile heigth [mm]	150					





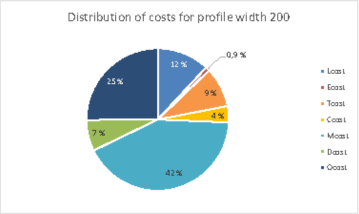
Profile width: 100

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	531 067,55	3 294 984,37	499 659,35	4 325 711,27
Energy cost	Ecost	239 419,77	10 409,17	794,06	250 623,00
Tooling	Tcost	1 802 706,78	369 525,46	X	2 172 232,24
Consumables cost	Ccost	X	1 405 237,68	44 369,30	1 449 606,98
Material cost inclusive recovery	Mcost	10 318 668,77	X	-24 751,65	10 293 917,12
Depreciation	Dcost	908 628,14	1 747 933,23	66 265,20	2 722 826,57
Overhead/In-direct	Ocost	2 210 968,54	7 600 967,41	197 536,43	10 009 472,38
Sum cost per module		16 011 459,56	14 429 057,32	783 872,68	31 224 389,56
Sum cost per kg material		**32,80**	**29,56**	**1,61**	**63,97**
Occupancy of production line [hrs]	occ	231,62	2 874,19	435,85	**3 541,66**
Profile length total incl buffer [m]	Lprtb				38 503,30
Mass of primary material in top deck module [t]	Mpm				488,10



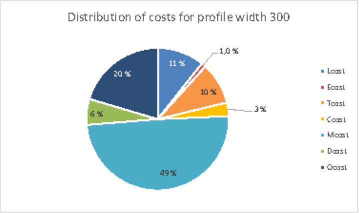
Profile width: 200

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	246 047,25	1 655 819,84	499 659,35	2 401 526,44
Energy cost	Ecost	178 905,92	5 204,58	794,06	184 904,56
Tooling	Tcost	1 642 566,58	184 762,73	X	1 827 329,31
Consumables cost	Ccost	X	702 618,84	44 369,30	746 988,14
Material cost inclusive recovery	Mcost	8 502 456,65	X	-20 393,34	8 482 063,31
Depreciation	Dcost	479 218,09	878 384,29	66 265,20	1 423 867,58
Overhead/In-direct	Ocost	1 030 181,38	3 819 694,19	197 536,43	5 047 412,00
Sum cost per module		12 079 375,88	7 246 484,48	788 231,00	20 114 091,36
Sum cost per kg material		**30,04**	**18,02**	**1,96**	50,02
Occupancy of production line [hrs]	occ	107,31	1 444,36	435,85	**1 987,52**
Profile length total incl buffer [m]	Lprtb				19 915,50
Mass of primary material in top deck module [t]	Mpm				402,15



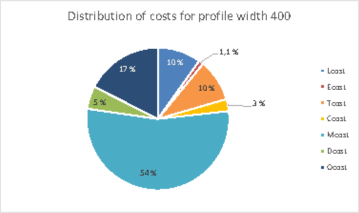
Profile width: 300

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	144 094,09	1 070 403,94	499 659,35	1 714 157,38
Energy cost	Ecost	156 888,24	3 345,80	794,06	161 028,10
Tooling	Tcost	1 410 363,00	118 776,04	X	1 529 139,04
Consumables cost	Ccost	X	451 683,54	44 369,30	496 052,84
Material cost inclusive recovery	Mcost	7 941 441,27	X	-19 042,15	7 922 399,12
Depreciation	Dcost	309 871,85	567 831,10	66 265,20	943 968,15
Overhead/In-direct	Ocost	606 233,58	2 469 239,46	197 536,43	3 273 009,47
Sum cost per module		10 568 892,03	4 681 279,89	789 582,19	16 039 754,11
Sum cost per kg material		**28,15**	**12,47**	**2,10**	**42,72**
Occupancy of production line [hrs]	occ	62,85	933,71	435,85	**1 432,41**
Profile length total incl buffer [m]	Lprtb				13 277,00
Mass of primary material in top deck module [t]	Mpm				375,51



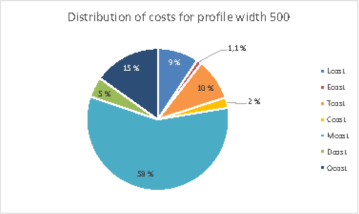
Profile width: 400

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	102 747,96	836 237,58	499 659,35	1 438 644,89
Energy cost	Ecost	151 106,30	2 602,29	794,06	154 502,65
Tooling	Tcost	1 309 919,59	92 381,37	X	1 402 300,96
Consumables cost	Ccost	X	351 309,42	44 369,30	395 678,72
Material cost inclusive recovery	Mcost	7 914 107,53	X	-18 973,26	7 895 134,27
Depreciation	Dcost	244 262,70	443 609,83	66 265,20	754 137,73
Overhead/In-direct	Ocost	434 612,40	1 929 057,58	197 536,43	2 561 206,41
Sum cost per module		10 156 756,49	3 655 198,06	789 651,08	14 601 605,63
Sum cost per kg material		**27,15**	**9,77**	**2,11**	**39,03**
Occupancy of production line [hrs]	occ	44,81	729,44	435,85	**1 210,10**
Profile length total incl buffer [m]	Lprtb				10 621,60
Mass of primary material in top deck module [t]	Mpm				374,15



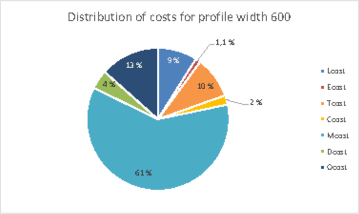
Profile width: 500

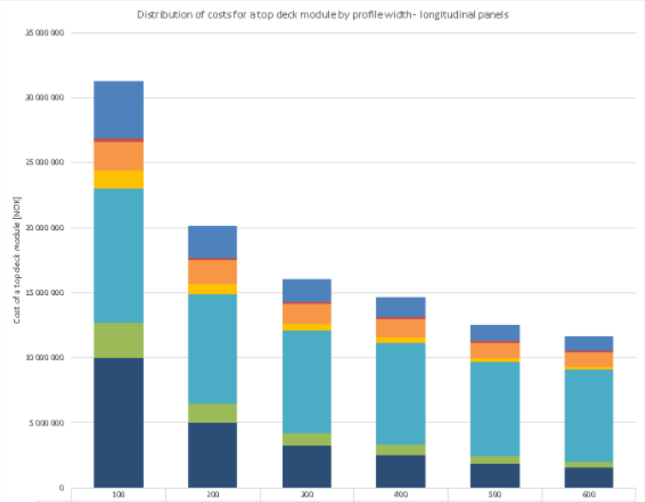
Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	71 764,58	602 071,22	499 659,35	1 173 495,15
Energy cost	Ecost	136 076,01	1 858,78	794,06	138 728,85
Tooling	Tcost	1 123 812,81	65 986,69	X	1 189 799,50
Consumables cost	Ccost	X	250 935,30	44 369,30	295 304,60
Material cost inclusive recovery	Mcost	7 249 845,34	X	-17 376,35	7 232 468,99
Depreciation	Dcost	195 351,85	319 388,55	66 265,20	581 005,60
Overhead/In-direct	Ocost	306 030,76	1 388 875,69	197 536,43	1 892 442,88
Sum cost per module		9 082 881,36	2 629 116,22	791 247,99	12 503 245,57
Sum cost per kg material		**26,51**	**7,67**	**2,31**	**36,49**
Occupancy of production line [hrs]	occ	31,30	525,18	435,85	**992,33**
Profile length total incl buffer [m]	Lprtb				7 966,20
Mass of primary material in top deck module [t]	Mpm				342,66



Profile width: 600

Cost summary	Abbr	Extrusion	FSW	MIG	Sum
Direct labour	Lcost	56 563,35	484 988,03	499 659,35	1 041 210,73
Energy cost	Ecost	131 035,10	1 487,02	794,06	133 316,18
Tooling	Tcost	1 047 754,19	52 789,35	X	1 100 543,54
Consumables cost	Ccost	X	200 748,24	44 369,30	245 117,54
Material cost inclusive recovery	Mcost	7 053 356,08	X	-16 918,80	7 036 437,28
Depreciation	Dcost	178 954,92	257 277,91	66 265,20	502 498,03
Overhead/In-direct	Ocost	243 705,34	1 118 784,74	197 536,43	1 560 026,51
Sum cost per module		8 711 368,98	2 116 075,31	791 705,54	11 619 149,83
Sum cost per kg material		**26,11**	**6,34**	**2,37**	**34,82**
Occupancy of production line [hrs]	occ	24,67	423,05	435,85	**883,57**
Profile length total incl buffer [m]	Lprtb				6 638,50
Mass of primary material in top deck module [t]	Mpm				333,63





	100	200	300	400	500	600
■ Lcost	4 325 711,27	2 401 526,44	1 714 157,38	1 438 644,89	1 173 495,15	1 041 210,73
■ Ecost	250 623,00	184 904,56	161 028,10	154 502,65	138 728,85	133 316,18
■ Tcost	2 172 232,24	1 827 329,31	1 529 139,04	1 402 300,96	1 189 799,50	1 100 543,54
■ Ccost	1 449 606,98	746 988,14	496 052,84	395 678,72	295 304,60	245 117,54
■ Mcost	10 293 917,12	8 482 063,31	7 922 399,12	7 895 134,27	7 232 468,99	7 036 437,28
■ Dcost	2 722 926,57	1 423 867,58	943 968,15	754 137,73	591 005,60	502 498,03
■ Ocost	10 009 472,38	5 047 412,00	3 273 009,47	2 561 206,41	1 892 442,88	1 560 026,51

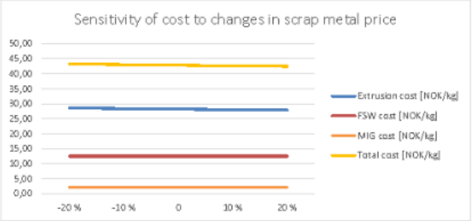
Sensitivity analysis

Design parameters	Input
Longitudinal [L] vs Transverse [T] orientation	T
Profile wall thickness bottom [mm]	12
Profile wall thickness top [mm]	16
Profile truss thickness [mm]	6
Profile end thickness [mm]	4
Profile width (steps 100) [mm]	300
Profile heigth [mm]	150

Test parameter	Decrease		Default value	Increase	
Scrap metal price [GBP/kg]	-20 %	-10 %	0,85	10 %	20 %
LME [USD / ton]			2200		
Depreciation period [years]			10		
Welding speed [m/min] FSW			0,5		
Arc rate [%] FSW			65		
Arc rate [%] MIG			50		
Filler Wire diameter [mm]			1,6		

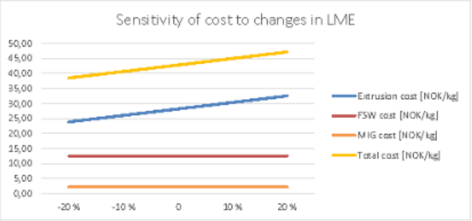
Scrap metal price [GBP/kg]

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	0,68	28,56	12,49	2,15	43,21
-10 %	0,77	28,38	12,49	2,15	43,02
0	0,85	28,19	12,49	2,14	42,82
10 %	0,94	28,00	12,49	2,14	42,63
20 %	1,02	27,82	12,49	2,13	42,44



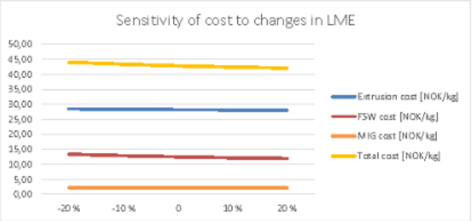
LME [USD / ton]

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	1760,00	23,86	12,49	2,14	38,50
-10 %	1980,00	26,03	12,49	2,14	40,66
0	2200,00	28,19	12,49	2,14	42,82
10 %	2420,00	30,35	12,49	2,14	44,99
20 %	2640,00	32,52	12,49	2,14	47,15



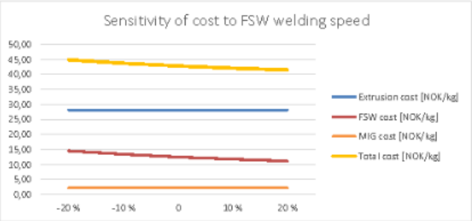
Depreciation period [years]

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	8,00	28,46	13,34	2,23	44,02
-10 %	9,00	28,31	12,87	2,18	43,36
0	10,00	28,19	12,49	2,14	42,82
10 %	11,00	28,09	12,18	2,11	42,39
20 %	12,00	28,01	11,93	2,09	42,02



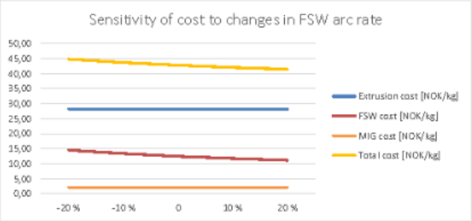
Welding speed [m/min] FSW

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	0,40	28,19	14,53	2,14	44,86
-10 %	0,45	28,19	13,40	2,14	43,73
0	0,50	28,19	12,49	2,14	42,82
10 %	0,55	28,19	11,75	2,14	42,08
20 %	0,60	28,19	11,14	2,14	41,47



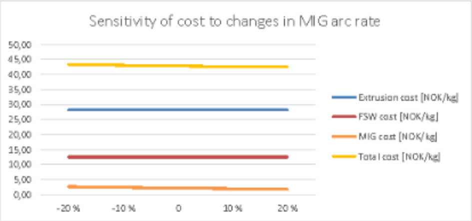
Arc rate [%] FSW

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	52,00	28,19	14,53	2,14	44,86
-10 %	58,50	28,19	13,40	2,14	43,73
0	65,00	28,19	12,49	2,14	42,82
10 %	71,50	28,19	11,75	2,14	42,08
20 %	78,00	28,19	11,14	2,14	41,47



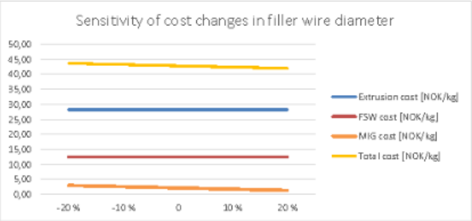
Arc rate [%] MIG

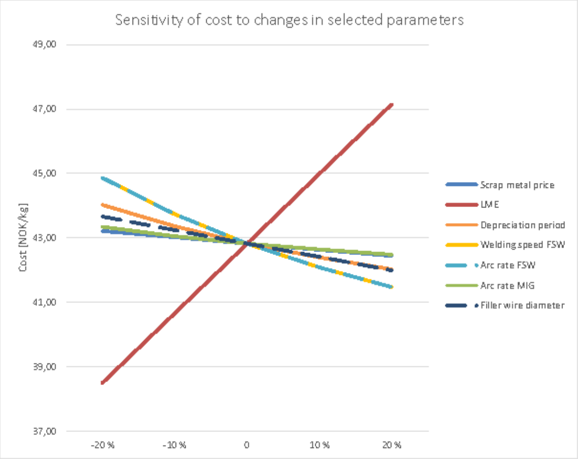
Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	40,00	28,19	12,49	2,66	43,34
-10 %	45,00	28,19	12,49	2,37	43,05
0	50,00	28,19	12,49	2,14	42,82
10 %	55,00	28,19	12,49	1,95	42,64
20 %	60,00	28,19	12,49	1,80	42,48



Filler Wire diameter [mm]

Test scenario		Cost [NOK/kg]			
		Extrusion	FSW	MIG	Total
-20 %	1,28	28,19	12,49	2,98	43,66
-10 %	1,44	28,19	12,49	2,56	43,24
0	1,60	28,19	12,49	2,14	42,82
10 %	1,76	28,19	12,49	1,73	42,41
20 %	1,92	28,19	12,49	1,31	41,99




Sensitivity of cost to changes in selected parameters
Cost [NOK/kg]
49,00
47,00
45,00
43,00
41,00
39,00
37,00
-20 %
-10 %
0
10 %
20 %
Scrap metal price
LME
Depreciation period
Welding speed FSW
Arc rate FSW
Arc rate MIG
Filler wire diameter

NTNU

Kunnskap for en bedre verden