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Feature-Based Costing Method for Skeletal Steel Structures based on the Process Approach

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Abstract

This thesis presents a new method for costing the skeletal steel structures used in industrial, commercial or office buildings or constructions. Furthermore it proposes a design concept that takes the joint details into account in dimensioning assemblies. Thereby the designer can compare the costs of not only members but also joints and choose a suitable construction both structurally and economically.

The fabrication processes required to complete the assembly in a workshop as well as the processes involved in transporting it to the site and erecting it are presented. The majority of fabrication processes are assumed to be carried out using NC equipments, each executing one process in its own cost centre in the workshop. A feature-based costing method consisting of the functions developed for individual processes is created. For erection a complete new approach is presented. The cost functions have components for material, labour, equipment investment and maintenance, real estate investment and maintenance, consumables and energy. Cost functions include both pre-set values for parameters of the process environment, based on literature and observations, and variables originating from features. Variables are defined by the designer during the structural design process.

In this context the word ‘feature’ is used to refer to attributes which affect the costs of the assembly during the manufacturing, transportation or erection processes. For example, paint thickness is a feature, but the colour of a paint is a feature only if there are differences between the costs of different colours.

The reliability of the method is proved by calculating the costs of eight assemblies of varying features. The results produced by the proposed method are compared with offers received from five European workshops and results produced by a method developed in Australia and using a similar approach.

The practicality of the method is illustrated by two examples where the rotational stiffness of joints was varied.

The final conclusion is that the proposed method provides a reliable and practical tool for the designer to evaluate her/his structural decisions from the economic viewpoint already at an early design stage, as well as allows optimising a structure aimed to minimise the total cost.

Tiivistelmä

Tässä tutkimuksessa esitellään uusi menetelmä teollisten, toimisto- ja kaupallisten rakennusten ja rakenteiden teräsrunkojen kustannusten arviointiin. Lisäksi ehdotetaan, että suunnitteluprosessissa otetaan liitosten jäykkyys huomioon jo runkoa mitoitettaessa. Tällöin suunnittelija voi verrata sekä kantavan profiilin, että liitoksen kustannuksia eri vaihtoehtojen välillä valitakseen sekä rakenteellisesti, että taloudellisesti sopivimman ratkaisun.

Tutkimuksessa esitellään konepajavalmistuksessa, kuljetuksessa ja työmaa-asennuksessa tarvittavat prosessit. Konepajavalmistus on oletettu tehtävän pääosin numeerisesti ohjatuilla työstökoneilla, kukin osavalmistusprosessi omassa tilassaan. Näille osavalmistusprosesseille on kehitetty kustannuskaavat, joissa huomioidaan valmistettavan osan ominaisuudet. Lisäksi asennuskustannusten laskentaan on kehitetty uusi lähestymistapa. Kustannuskaavat sisältävät komponentit materiaalille, työlle, laite- ja kiinteistöinvestoinneille sekä –ylläpidolle, lisäaineille, kulutusosille ja laitteiden käyttämälle energialle. Kustannuskaavoissa on sekä havainnoista, että kirjallisuudesta saadut esiasetetut vakiot ympäristötekijöille, ja muuttujat valmistettavan kappaleen ominaisuuksille. Suunnittelija määrittelee arvot muuttujille suunnittelutyön yhteydessä.

Tässä yhteydessä ominaisuus-termiä on käytetty silloin, jos ominaisuus aiheuttaa kustannuksia valmistus-, kuljetus- tai asennusprosessin aikana. Esimerkiksi maalikalvon paksuus on ominaisuus, mutta maalin väri on ominaisuus vain, jos se aiheuttaa lisäkustannuksia.

Menetelmän luotettavuus on osoitettu vertaamalla sillä laskettujen kahdeksan testiasennusosan kustannuksia viideltä eurooppalaiselta konepajalta saatuihin tarjouksiin, sekä kirjallisuudesta saadun australialaiseen laskentamenetelmän tuloksiin.

Menetelmän käytännöllisyyttä on havainnollistettu kahdella laskentaesimerkillä, joissa liitosten jäykkyyttä on muuteltu.

Loppupäätelmänä on, että menetelmä tarjoaa luotettavan ja käytännöllisen työkalun suunnittelijalle jo suunnittelun varhaisessa vaiheessa hänen arvioidessaan tekemiensä suunnitteluratkaisujen taloudellisuutta. Menetelmä tarjoaa työkalun myös kustannusten minimointiin pyrkivään rakenteiden kokonaisoptimointiin.

Preface

My work with the topic started in 1998 during the national technology project FINNSTEEL. Within its subproject “Intelligent Joints” I started to investigate the manufacturing processes and their cost structures. The idea of the project was to create a tool to calculate costs of pre-designed joints with dimensions as variables. A report was published (in Finnish) to partners of the project. Still a wish to continue with the topic remained. The kick-off was not until 2005 when Professor Teuvo Tolonen from Tampere University of Technology (TUT) invited me to participate two years doctoral seminar organized by him. That seminar gave me the impulse to carry on with the research work, and we decided with Professor Markku Heinisuo, also from TUT, to expand the target to costs of the entire delivery process of skeletal steel structures, including erection.

The reviewers of the thesis, Professor Hartmut Pasternak from Brandenburg University of Technology Cottbus and Professor Mikko Malaska from University of Oulu, are kindly acknowledged for their comments and suggestions to improve the manuscript.

I am also grateful for Professor Hartmut Pasternak and Professor Pentti Mäkeläinen from Aalto University for agreeing to act as opponents during the defense of the thesis.

My tutor, interlocutor and activator since 90’s has been Professor Markku Heinisuo from Research Centre of Metal Structures. I will denote my sincere thanks to him for his support and patience.

I wish to give my acknowledge to Professor Teuvo Tolonen of his interest to my work.

My thanks goes also to Olli Knuutila, who made a great job in investigating and reporting the erection times at actual site.

I thank my employer Metso Power Oy, particularly my boss Risto Hokajärvi, giving me a possibility to concentrate on writing during autumn 2009.

Thanks goes also to Jorma Tianen for his professional checkup of the manuscript’s spelling.

And ultimately, warmest thanks to my family, my wife Tuula and our children Hanna, Olli and Maija, for indicating interest on my work with a very positive attitude.

This thesis is dedicated to my mother Kaarina and father Erkki.

Tampere, March 2012

Jaakko Haapio

Contents

List of definitions, symbols and abbreviations

Definitions:

Feature	Attribute which affects the costs of the structure during the project
Assembly	An entity put together in a workshop
Main profile	Main part of the assembly, here a welded or rolled profile
Part	Additional component connected to the main profile to create a joint or stiffener
Manufacturing	Complete set of processes carried out in workshop
Fabricating	Work done to accomplish a feature
Cost centre	Space in the workshop where a specific process is executed. Includes required equipment and has a defined floor area [m2]

Symbols:

L	[mm]	length of assembly in the direction of process

Material:

W_m	[kg]	weight of material
u_m	[€/kg]	unit cost of material
W_{SMPl}	[kg]	weight of plate material
c_{SMBPl}	[€/kg]	basic steel price
c_{SMBG}	[€/kg]	steel grade add-on price
c_{SMT}	[€/kg]	thickness add-on price
c_{SMQ}	[€/kg]	quantity add-on price
c_{SMTQ}	[€/kg]	quantity per thickness add-on price
c_{SMUT}	[€/kg]	ultrasonic inspection add-on price
W_{SMP}	[kg]	weight of profile
c_{SMBP}	[€/kg]	unit price of profile
dl	[pcs]	number of bolts of different diameter and length
c_{Bi}	[€/pcs]	unit price of bolt i
c_{Ni}	[€/pcs]	unit price of nut i
c_{Wi}	[€/pcs]	unit price of washer i

Investment:

A	[€/a]	uniform series end-of-period installment
P	[€]	a sum of money invested in the initial year
I	[%]	interest rate (cost of capital)
n	[pcs]	time, the number of units (years) on which interest accumulates

Cost functions:

C_T	[€]	total cost
C_{SM}	[€]	material cost

The following cost centre symbols are used in place of index $_k$:

$_B$	blasting
$_{Cu}$	cutting
$_{BW}$	beam welding
$_S$	sawing

$_{D}$	drilling	
$_{Co}$	coping	
$_{PF}$	part fabricating	
$_{PA}$	part assembling	
$_{W}$	welding	
$_{Pu}$	punching-shearing	
$_{Bo}$	bolting	
$_{P}$	painting	
$_{T}$	transporting	
$_{E}$	erecting	

T_{Nk}	[min]	non-productive time of cost centre k
T_{Pk}	[min]	productive time of cost centre k
c_{Lk}	[€/min]	unit labour cost of cost centre k
n_k	[pcs]	number of workers
c_{Eqk}	[€/min]	equipment installment unit cost of cost centre k
c_{Mk}	[€/min]	unit cost of equipment maintenance of cost centre k
c_{REk}	[€/min]	unit cost of real estate of cost centre k
c_{Sek}	[€/min]	unit cost of real estate maintenance of cost centre k
c_{Ck}	[€/min]	unit cost of time related consumables needed in processing of cost centre k
c_{Enk}	[€/min]	unit cost of energy needed in processing of cost centre k
C_{Ck}	[€/min]	total cost of non-time-related consumables used in cost centre k
u_k	[€/min]	utilization ratio of cost centre k [decimal, ≤1]

Cutting:

v_c	[mm/min]	conveyor speed
v_{Cu}	[mm/min]	speed of cutting

Beam welding:

L_w	[mm]	length of weld
b	[mm]	depth of weld
α	[deg]	bevel angle
W_w	[kg]	weight of a single weld
n_{wh}	[pcs]	number of simultaneously welded seams

Sawing:

h	[mm]	sawing height of profile
S	[mm/min]	vertical feeding speed of blade
S_m		material factor
A_h	[mm^2]	sum of areas of horizontal parts of profile
Q	[mm^2/min]	sawing efficiency of blade for solid material
t_{mv}	[mm]	thickness while sawing
t_m	[mm]	thickness of thickest vertical plate in sawing position
α	[deg]	sawing angle zero when sawing perpendicular to main profile's longitudinal axis
S_t	[mm^2]	total area a blade can saw before it has to be replaced
F_s		parameter depending on equipment type
F_{sp}		parameter depending on thickness of material
p_{SB}	[€]	price of saw blade

Drilling:

n_{ri}	[pcs]	amount of holes of row *r* in direction *i*
r_f	[pcs]	total number of rows of first run
r_s	[pcs]	amount of rows of second run
V_f	[mm/min]	feeding speed
f_n	[mm/round]	feeding speed
r	[round/min]	rotating speed
d	[mm]	drill bit diameter
V_c	[m/min]	recommended cutting speed for drill bit
n_{ij}	[pcs]	amount of holes of row *i* in direction *j*
t_j	[mm]	plate thickness in direction *j*
d_{ij}	[mm]	hole diameter in row *i* in direction *j*. Index *4* refers to the second run.
p_{DB}	[€]	price of drill bit
n_{dd}	[pcs]	number of different drill bit sizes
T_{PDk}	[min]	drilling time with drill bit size $_k$, subtotal
p_{DBk}	[€/min]	unit cost of drill bit $_k$

Coping:

n_{Co}	[pcs]	total number of coped individual tracks
L_{Co}	[mm]	length of each individual coping track
v_{Co}	[mm/min]	speed of coping based on plate thickness

Fabrication of parts:

v_f	[mm/min]	feeding speed of punching equipment
u_{ca}	[€/m]	unit price of angle
T_f	[min]	total feeding time
n_z	[pcs]	number of different sizes of holes
n_n	[pcs]	total number of holes

Part assembling

N_{tack}	[pcs]	number of tacks/part
L_{fw}	[mm]	length of fillet weld
a	[mm]	size of fillet weld
L_{bw}	[mm]	length of single-bevel butt weld
b	[mm]	depth of weld
n_b	[pcs]	total number of bolts

Post-treatment:

L_{PT}	[mm]	total length of edges to be deburred
L_{UT}	[mm]	total length of *UT*-tested welds
$\mathrm{L_{MT}}$	[mm]	total length of MT-tested welds

Painting:

n_f		number of films
v_{si}	[decimal, ≤1]	volume solids of paint of film *i*
DFT_i	[mm]	dry thickness of film *i*
t_{iloss}	[mm]	total loss of film *i*

f_{pg}	[mm^3/min]	flow through spray gun
A	[mm^2]	total area of assembly to be painted
$_{Al}$		alkyd system
$_{Ep}$		epoxy system
$_{Pu}$		polyurethane system
$_{Ac}$		acryl system

Drying:

T_{Dyi}	[min]	drying time of film *i*
A_{Dy}	[m^2]	area required for drying of assembly
L_A	[m]	length of assembly
W_{Amin}	[m]	narrowest width of assembly

Transportation:

L	[m]	length of assembly
W	[m]	width of assembly
H	[m]	height of assembly
W_A	[kg]	weight of assembly
V_A	[m3]	volume of assembly
d_{ws}	[km]	tranpertation distance

Erection:

T_E	[min]	calculated duration of erecting cycle of an assembly
T_{El}	[min]	Lifting time
T_{Ej}	[min]	Joining time
T_{Em}	[min]	time required to move man lift
T_{Er}	[min]	time required for hook to return
T_{Eb}	[min]	time required for joining with bolts
n_{bi}	[pcs]	amount of bolts in joint *i*
L_A	[mm]	length of assembly
l_s	[m]	direct distance between lifting area and final assembly point.
n_{b1}		number of bolts per Joint 1
n_{b2}		number of bolts per Joint 2
N_c	[tonnes]	nominal capacity of crane
h_s	[m]	height of the final assembly location above man lift location

Abbreviations:

FBCM	Feature-based costing method
AVWS	Average workshop price
WDK	Cost method presented by Watson et al. (1996)
DFT	dry film thickness
WFT	wet film thickness
UPG	unit price group

1. Introduction

1.1 Context of the study

This study deals with skeletal steel structures used for industrial, commercial or office buildings or constructions such as those shown in Fig. 1. The skeletons consist of assemblies produced in a workshop, which are transported to the site and erected there.

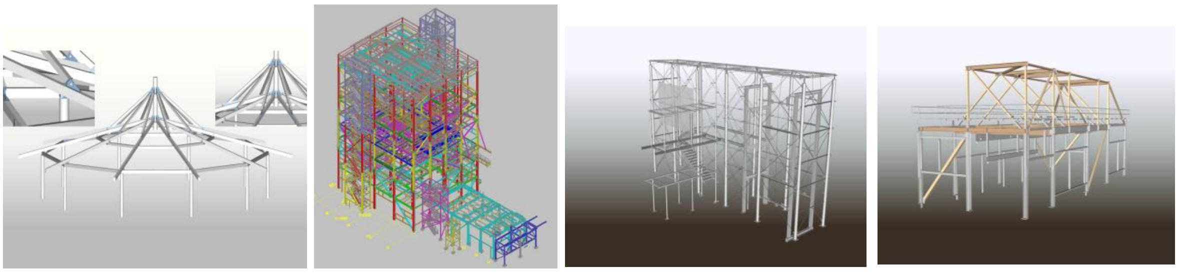


Fig. 1. Typical skeletal steel structures

Assemblies for the above-mentioned buildings and constructions are nowadays manufactured in workshops equipped with numeric-controlled tools such as saws, drills, cutting and beam welding equipment.

To maintain the competitiveness of steel against materials such as wood and concrete, and to enable workshops and constructors to operate profitably, the cost of the skeleton must be considered during production.

According to Evers & Maatje (2000), the cost breakdown of steel structures is roughly as shown in Fig. 2.

1) Design 13%
2) Material 38%
3) Production 27%
4) Coating 10%
5) Erection 12%

Fig. 2. Cost breakdown of steel structure. Evers & Maatje (2000)

Material, production, coating and erection costs depend on the country in question. The designer seldom has control over the source of the material and the place of production, which makes them input data, not a variable from the viewpoint of the designer.

It is a widely accepted fact (e.g. Evers & Maatje, 2000, p.17) that the designer plays a significant role in determining the costs of structures. As the design phase determines 88% of the costs (see Fig. 3), the designer needs to know the breakdown of the costs of structures to be able to make economical decisions.

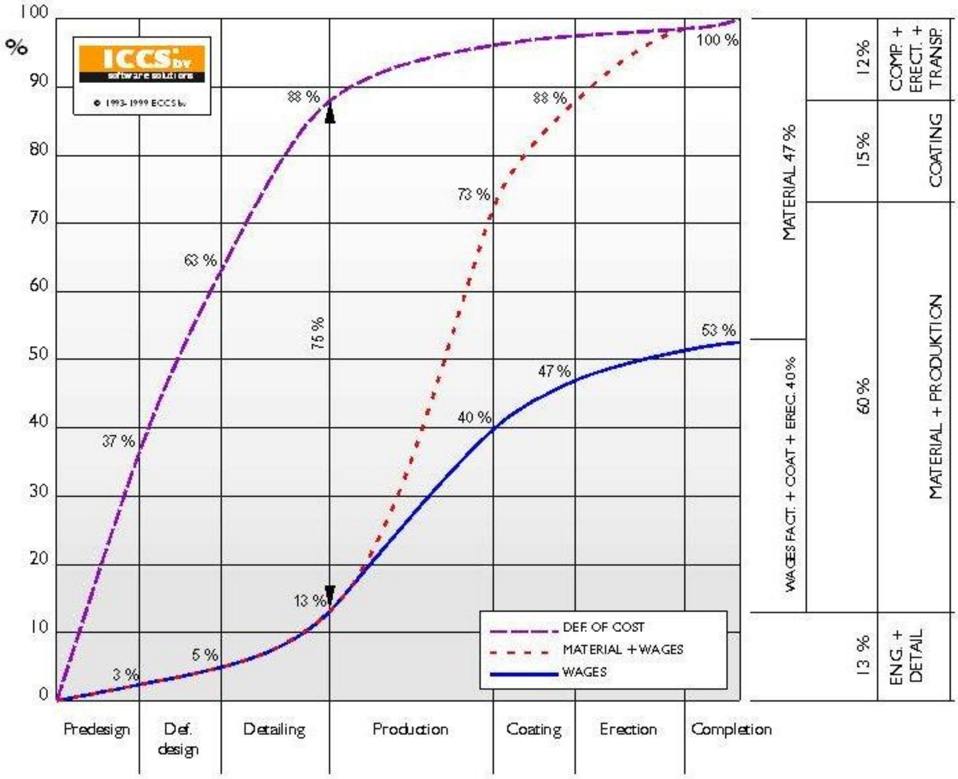


Fig. 3. Definition and accumulation of costs of steel structures during delivery process. Evers & Maatje (2000)

In Fig. 3 the progress of the project is shown on the horizontal axis, while the vertical axis presents the percentage of defined and accumulated costs. The long-dashed line presents the definition percentage of total costs, the solid line presents the accumulation of wages, and the short-dashed line the accumulated total costs. It can be clearly seen that most of the costs are defined during the design phase.

The next paragraph discusses the significance of costs. That will be followed by a literature review and presentation of the research problem and the aim of the study. Then, the research method will be explained and the new costing method introduced. The results will be verified by project case study and two examples followed by a summary and discussion.

1.2 Background of the research problem

Design is not only fundamental to stable structures, it is also the key to a stable industry (Girardier, 1995, p.467).

Evers & Maatje (2000, p.17) state that 88% of the total costs of a structural steel element are already determined by the end of the detail design stage. They divided design into three stages: predesign, define design and detailing, see Fig. 3. Decisions made during predesign, when e.g. the material of the structural elements and the dimensions of the building frame are decided, lock in 37% of the costs, while define design (also called basic design) when sizes of the load carrying structures are determined, locks in 63% of the costs. The last design stage (also called detail design) involves detailing of the connections from the viewpoint of production. Evers & Maatje include design, material, production, coating and erecting in the total costs.

Thus, the designer bears a great responsibility for the economy of the structure built according to her/his designs. At the start of the design process the designer has many alternatives to choose from, but the number alternative designs decreases as the design process proceeds. The designer may initially be asked only to design a building of a certain volume or floor area. The material of the building frame can be, for example, concrete, brick, wood or steel. When the material has been decided, the number of design parameters decreases drastically.

It seems obvious that creation of more economical solutions in the design stage improves the overall economy of the project and benefits also the end user (Schreve & al. 1999, p.731). That requires improving the ability of the designer to design less costly solutions. Designers need to know more about cost build-up and have appropriate tools for analysing the economy of the designed structure.

The design of an economical structure requires a lot of knowledge about the nature of the costs of the building process. The designer has to have an understanding of the consequences of the selections she/he makes during each design phase. The designer may acquire knowledge through experience and praxis or from other people. Information for dimensioning structures by stress calculations is not as readily available as cost and economic information. According to Tizani et al. (1996, p.12), that is due its dependence on factors such as particular practices, layout, equipment and space available in a workshop as well as the current state of the economy. In addition, the collection of explicit knowledge about the costs of fabrication is hindered by the reluctance of fabricators to provide commercially sensitive information about their costs, fearing that it might affect their competitiveness (Tizani & al. 1996, p.12).

Li et al. (1997, p.52) state that labour costs are difficult to obtain since real costs are affected by many parameters, most of which are uncertain at the design stage (e.g. cutting equipment, welding equipment, crane, etc.), and they also vary between construction companies and workshops.

The methods and tools of cost estimating vary depending on the stage of design. Before the basic design stage, cost estimating may be based on the volume or area of the building. When the frame material has been selected, i.e. basic design starts, the estimating has typically been based on weight or volume of the material. Recent studies have focussed on this stage by creating tools for more accurate estimation while the details of the design are still unknown. This has led to the use of different kinds of empirical coefficients derived from measurements or historical data. The cost functions of these tools aim to combine two features: usability and accuracy. According to Heinisuo & Jalkanen (2009, pp. 1-2), if the cost estimator has enough historical data on the costs of a certain type of structure she/he is currently working with, cost estimation may be rather accurate also on weight basis. But if the structure is of new type, there is the risk that its cost structure is not consistent with the old one and the unit cost per kilogramme is different thus leading to a false estimate. In such cases it is important to know what the real cause of the cost is.

Traditionally the economy of a designed structure has been estimated based on the weight of the steel used to manufacture and erect the structure (Watson et al. 1996 p.2). Depending on the author, material cost represents from 26% (Carter et al., 2000, p.16) to 38% (Evers & Maatje, 2000, p.14) or 40% (Girardier, 1995, p.467) of the total cost of the erected structure. Carter et al. (2000, pp.16-17) state that the percentage share of material cost has dropped during 15 years from 40% (1983) to 26% (1998). Salokangas (2009, p. 5) found material cost to be from 18% to 53% of total cost depending on the type of structure – a service platform support structure and a series of high wind columns, respectively. These examples indicate that the total cost of the structure cannot be estimated directly on the basis of material cost, unless the estimator is well aware of the nature of the structure.

The role of joints (material, manufacturing and erecting) is very easily underestimated when discussing costs. According to Nethercot (1998, p.2), material cost accounts for 50% of total cost, and 60% of the remaining 50% (=30% of total cost) is directly influenced by the number of joints that need to be made, while according to Girardier 50% of the total cost comes from making joints (1995, p.467). Compared with the share of the cost of frame materials (18%- 53%), joints should be given at least as much attention when striving for cost effective structures.

According to Gibbons, the labour cost to material cost ratio increased from 1.00 in 1960 to 2.88 in 1990, which means that the steel frame requiring the smallest labour input costs the least (1995, pp.250). On the other hand, according to Evers & Maatje (2000, p.14), steel construction companies in Northern Europe have invested into production equipment, which decreases the amount of labour-intensive work. This investment trend is evident all over the world.

During the last two decades, the research and development on cost estimation has concentrated on finding more detailed cost functions, even if they are complicated and impossible to compute manually. One reason for this trend is the parallel development of optimisation tools along with the increasing capacity of computers. New optimisation applications, namely heuristic algorithms, do not require solving exactly the objective function, but only finding the best local solution by iteration. Use of a heuristic algorithm allows finding a good or correct solution to the problem, which does not necessarily fulfill all the strict logical requirements of a mathematical optimum (Jalkanen 2007, p.29).

The wide use of building information modelling (BIM) nowadays also gives more opportunities to use detailed and complicated cost functions requiring lot of input data. The data needed for cost estimation can be obtained directly from the structural model (Heinisuo et al. 2010).

1.3 Review of cost estimation models and methods for steel structures presented in literature

Literature includes many steel-structure cost estimation models and methods. Here, model refers to an approach, which incorporates a concept that allows estimating costs, and method refers to a function with defined parameters. Some methods include total delivery process costs of a steel building frame, i.e. design, manufacturing, transporting and erecting costs, whereas some methods concentrate on manufacturing costs and possibly limited fabrication tasks. As welding is a labour-intensive process including many design variations, it is no surprise that welding cost estimation methods particularly are the subject of great interest.

Tizani et al. (1996) present a Knowledge-based System (KBS) design model, which also includes an economic appraisal module. The model has been developed for tubular steel trusses. It is classified as object oriented as it divides the truss into its main components of joints, members and sections, and further into sub-components like RHS/CHS, fabrication costs, material costs, welding equipment, welds, paints, etc. However, the authors do not present their cost functions in this paper.

Li et al. (1997) introduce a prototype of an Integrated Design System (IDS), which is based on the above mentioned KBS. An IDS contains modules for joint & member design, analysis, cost appraisal and check & advice. This system allows the designer to make use of the possible economic advantages of semi-rigid joints.

A knowledge-based system is also presented by Shehab & Abdulla (2002). They concentrate on machining and injection moulding, but their basic concept could be adopted by the construction manufacturing industry. They have already written software which allows the designer to compare manufacturing costs with different manufacturing processes.

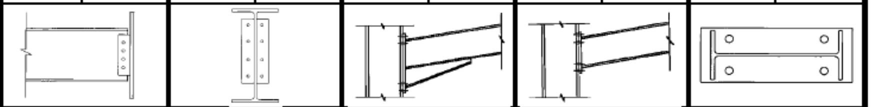
Watson et al. (1996) have developed a costing method aimed at:

- Being a more reliable and accurate method,
- Providing a continuous approach from initial project costing to fabricator's detailed costing,
- Providing a clearer focus on the elements that will have a significant effect on the final cost,
- Enabling reliable determination of the cost of contract variations,
- Providing a methodology that is easy to understand.

The second bullet is very important and provides a new approach to estimating. It is obvious that even if weight is used as the cost unit in the contract, the fabricator will in any case calculate his costs based on actual cost elements, and convert them afterwards to weight-based unit prices. This negates the relationship between cost-causing actions and the cost unit used by the designer. Watson et al. divided costs in four categories: steel supply, fabrication, surface treatment and erecting. Material cost is based on section length or plate area. Fabrication cost covers detail design, workshop fabrication and transporting. Estimation of design and fabrication costs is done on work-hour basis, while transporting cost estimates are done on member basis. Surface treatment estimation takes place on area basis while erecting is also done on member basis. The method covers the complete delivery project from detail design through workshop to erected structure. Predesign and basic design are excluded. Unit costs are presented on spreadsheets, and no cost functions are given. Costs of beam–to-column joints, base plate joints and splice connections are divided into three categories depending on the section mass of the connected member (Watson et al. p. 16).

The costs given in the tables were received from fabricators. Therefore, no thorough analysis of the cost basis is presented. The tables in Appendix A by Watson et al. (1996) are based on a project value greater than AUD 150,000 and the hourly labour rate is AUD 40.

TABLE A2.1.1 CONNECTIONS COSTS

Connections	Web Side Plate		Flexible End Plate		Moment Haunch		Moment		Base Plate	
Section mass (kg/m)	Hours	$	Hours	$	Hours	$	Hours	$	Hours	$
<60.5 60.6 to 160 160.1 to 455	0.8 1.6 3.0	32 64 120	1.0 1.8 3.3	40 72 132	6.2 9.5 11.4	248 380 456	1.6 2.7 5.4	64 108 216	1.5 2.0 3.0	60 80 120
Diagram										
Comments	Cut beam & WSP drill/punch holes CFW to WSP *		Cut beam & FEP drill/punch holes CFW to FEP *		Doubler plate (200x100x16mm) extra $20ea Cut haunch, beam & end plate, drill/punch holes & weld CPBW to Flange & CFW to Web*				Cut, beam & plate drill & weld CFW*	

*Note: For further details refer AISC (28)

Fig. 4. Connections costs, Watson et al. (1996) Table A2.1.1

Fig. 4. shows an example of a table in the report by Watson et al. (1996). It gives the complete cost of a chosen connection. The user has to choose the connection type and section mass [kg/m]. Three different section mass categories are presented: <60.5 kg/m, 60.6 to 160 kg/m and 160.1 to 455 kg/m. If no suitable connection or work done along member is found from the tables, the fabrication costs can be combined from individual element costs of section end cut, welding, cropping, hole drilling, etc.

TABLE A2.3.8 DRILLING & PUNCHING HOLES

Plate Thickness	Punching		Drilling	
mm	Hours/unit	$/unit	Hours/unit	$/unit
<16.5	0.02	0.8	0.05	2.0
16.6 to 32	-	-	0.10	4.0
32.5 to 50	-	-	0.15	6.0

Fig. 5. Drilling and punching costs, Watson et al. (1996) Table A2.3.8

Fig. 5. shows punching and drilling costs according to plate thickness.

As can be seen from Figs. 4 and 5, the steps of variables, here section mass and plate thickness, are discrete.

Pavlovčič et al. (2004) present a very detailed cost estimation method. It takes into account material, fabrication, transporting and erecting. Two types of joints are implemented in the optimisation system for joint cost estimation: a field weld joint and a bolted end- plate joint. Fabrication cost functions for welding (material, assembly and tack welding, and welding work), cutting (cutting, gas consumption and plate handling), painting (work, material), surface preparation, flange aligning, joints, and hole forming are given. All functions are given in quadratic parabola format, the parameters being weld thickness, material volume, plate thickness and hole diameter. Labour cost, equipment cost and depreciation (loss in value) costs are represented by with cost factor k_i[€/h], specified separately for each fabrication process *i*. Transporting and erecting depend on the mass of structures.

Klanšek & Kravanja (2005) present a detailed swarm of time-based manufacturing cost functions for a composite floor system supported by steel I-beams or trusses (rolled channel sections or cold formed hollow sections). The costs are divided into material, power consumption and labour costs. Material costs are given for structural steel, concrete, reinforcement, shear connections, welding electrodes, anti-corrosion, fire protection and top-coat paints, formwork floor-slab panels and cutting gas. Power consumptions are given for sawing of steel sections, edge grinding, drilling, welding, stud welding and concrete vibration. Labour costs are given for metal cutting (sawing and steel-sheet cutting), edge grinding, preparation, assembly and tacking, welding, welding of shear connectors, drilling, placing the formwork, cutting, placing and connecting the reinforcement, concreting, consolidating and cutting the concrete. No costs for equipment, design, transporting or erecting are included in the functions.

Farkas & Jármai (2003) base their cost calculations on two terms: material cost and fabrication cost. Material cost includes only steel structure material, no consumptions. The manufacturing unit cost, k_f [$/min], is common for all fabrication processes and constant for a given manufacturer. Fabrication cost functions are given for preparation, assembly and tacking, continuous welding, additional fabrication (welding) actions, arc spot welding, post-welding treatments, flattening plates, surface preparation, painting, plate cutting and edge grinding, and hand cutting and equipment grinding of strut ends. Design, transporting and erecting costs are excluded. The functions typically include a difficulty parameter which takes into account the complexity of the structure varying between 1 and 4.

Sarma & Adeli (2000) present a different type of cost estimation approach. In the USA, where hot rolled I-shapes are widely used, unit price of shapes ($/100 lbs) is not always unique or even linearly proportional to the weight of the shape. Thus, the minimum weight solution is not always the minimum cost solution, even when considering only the cost of the material (Sarma & Adeli 2000, p.1339). Their report presents a multicriteria method, which minimises the weight, the cost and the number of different shapes used in the complete structure. The last criterion is important for manufacturers (Templeman 1988, see Sarma & Adeli 2000, p. 1340), but the mathematical function for estimating the influence of the number of different members and shapes is not explicit. The authors created a function where the user may choose parameters that take into account the effect of the number of different shapes. The cost estimation method takes into account only member material costs.

Vartiainen (2000) developed functions for determining welding costs by means of regression analysis. He obtained welding times from four companies, and studied the relationships between welding time and five different parameters, i.e. weld volume, number of welds, mass of welded parts, length of the welds and number of parts.

Schreve et al. (1999) created a detailed cost function for tack welding in a jig. They took into account the set up time per batch, jig cleaning, fastening and unfastening the part, inserting and removing a part from the jig, tacking, electrode changing, deburring parts before assembly, flame cutting the parts with fit-up problems, measuring parts, operator repositioning, and finally removing and putting down the assembly (Schreve et al. p. 733).

Ou-Yang, C. & Lin, T.S. (1997) present a framework for cost estimation of a blank to be machined. The initial input consists of the features of the part, such as requirements for surface quality and geometry. The estimating process starts with the construction of a model of the part, and continues with surface tolerance specification, retrieving feature geometry and estimation of manufacturability of the part. If the part passes the test, the next step involves estimating manufacturing times with selected processes that provide the desired features. The cost is calculated by summing up the unit costs of fabricating processes and multiplying them by the time needed for each process.

Sawada et al. (2008) developed a cost estimation function for a specific beam-to-column joint used in Japan for rigid-frame structures. The cost function includes terms that represent the preparatory process, assembly, welding and preparation of shop drawings. The coefficients of the function were derived from three manufacturing companies in Japan. The variables of the function consist of the total number of parts of the joints and all joined section areas between the column and diaphragm and the joined area between columns and brackets (Sawada et al. pp.136-137).

Summary of the review

If the delivery process is considered to consist of providing shop drawing design, material, fabrication, surface treatment, transporting and erecting, then a single method to determine the cost of the entire delivery process exists (Watson et al. 1996). The following method has been presented by Pavlovčič et al. (2004), which does not, however, consider the shop drawing cost.

Another group of methods considers only manufacturing costs: those by Klanšek & Kravanja (2006) and Farkas & Jármai (2003). The former method does not include equipment cost, while the latter does not account for sawing and drilling costs.

The third group consists of the method by Sarma & Adeli (2000). It includes only member material cost and is used for the optimisation of a large number of structure members.

The fourth group includes methods or models for specific manufacturing processes or specific structures. Vartiainen (2000) presents a method for estimate welding costs, Schreve et al. (1999) present a method for determining tack welding cost, Ou-Yang, C. & Lin, T.S. (1997) developed a costs model for machining a solid part, and Sawada et al. (2008) a cost method for a specific rigid beam-to-column joint.

The fifth group consists of models, which incorporate the concept of cost estimating, but do not yet include information for designers. Such models have been introduced by Tizani et al. (1996) and Li et al. (1997). These models are precise and give a good opportunity to utilise computer technology to solve economic questions. However, they are only prototypes, and the writer did not find any further information about the development of these models.

In the late 90's a commercial software application for steel building structure cost estimating became available. It was launched by ICCS bv (Evers & Maatje (2000)), and came with a brochure (ICCS-TVC 1998). The author could no longer find links on the Internet to that application.
AceCad has a cost estimating application called StruM.I.S Estimating. In it material and labour costs are separated, and fittings have their own cost calculation module.
Graphisoft announced in 2004 their application of a cost estimating tool named Virtual Construction™.
The Finnish Tocoman has TCM Pro-software, which creates a cost estimate using the designer's structure model and Tocoman's own cost database.

At least two conclusions can be made based on the literature review. Firstly, the economy of design results cannot be determined on the basis of the weight of a structure (Watson & Buchhorn 1992 p. 437, Sharma & Adeli 2000 p. 1339, Steel construction institute 1992, see Tizani et al. 1998 p. 11, Maatje & Evers 2004 p. 27). Secondly, the designer's knowledge of manufacturing and erecting costs, and particularly manufacturing costs of the joints, is a key factor in achieving cost savings (Nethercot 1998, p. 2, Gibbons 1995 p. 250, Girardier 1995 p. 468).

The costs of individual steel fabrication processes have been studied widely, and some of the studies present the cost functions in parametric form (Farkas & Jármai (2003), Pavlovčič et al (2004), Klanšek & Kravanja (2006)). However, these studies are focussed only on a few types of structures and processes, and the parameters of the functions do not provide complete information about the origin of the costs. Nor do the functions in these studies include investment and maintenance costs of equipment and/or real estate. Thus no parametric cost method covering various types of structures and the whole delivery process was found in literature.

The method presented by Watson et al (1996), even though it covers the entire production process from detail design to erection, is not parametric, but discrete, and does not give enough information about the origin of the costs. In other words, it does not allow the designer to update or change the parameters, such as labour and investment costs affecting the final product costs, as needed.

Often the designer must decide between a simple but heavier and a lighter but more complex structure requiring more fabrication processes (such as the adding of stiffeners). Or she/he wants to compare the costs of different types of joints. In both instances, the designer needs a sophisticated tool to be able to determine the cost differences between detailed solutions. Furthermore, the cost components must be at comparable level to allow comparing material cost against manufacturing cost. As the material cost is final for the workshop, also the manufacturing cost must include all possible components. Otherwise, the comparison favours manufacturing. The workshop cost components consist of labour, investment, maintenance, consumables and energy costs. None of the reviewed methods included all of these components.

Based on the literature review, and considering the economy of steel structures, there is a clear need for a costing method, which is transparent, parametric, covers the whole delivery chain and which can be integrated with existing design tools. In the case of industrial, commercial or office buildings or constructions it is often possible to use either a concrete or a steel skeleton. Also therefore, it is essential for steel structure manufacturers that the design decisions made by the designer strive to the economical ones. So far, a method has not been created which would enable the designer to evaluate the entire cost impacts of her/his decisions.

1.4 Research problem

The research problem is formulated as follows:
Based on what was concluded above, the research problem is to develop a costing method for skeletal steel structures, which enables the designer to take into account the cost effects of a structure's features under her/his control, and which covers the delivery chain from the workshop to the erection site. The method should include all essential cost components of the workshop and erection site and be transparent to allow updating parameters that affect costs.

1.5 Aim of this thesis

This thesis aims to develop a method, which gives the designer detailed information of the cost structure of the manufacturing, transportation and erecting processes. The method should take into consideration those features of the structures that affect costs. It should be suitable for different process environments as it uses pre-set parameters that can be altered according to the actual environment, and variables that can be obtained from the structural model.

The method should be targeted to the early stage design, as the potential for finding the most economical solutions is largest at that stage (Evers & Maatje (2000)). Therefore it should include, as a default, all needed environmental parameters, to enable the designer to concentrate on structural solutions.

The thesis is limited to the beam-to-column structures used in industrial, commercial or office buildings or constructions. The dimensions of an assembly are limited to 15 by 2 metres (LxW). Manufacturing is carried out mainly with NC equipment, and joining at the site is by bolting. The assemblies are coated with paint.

2. Method for solving the research problem

The following approach is selected to solve the research problem:
The delivery chain of a steel structure is simulated and modelled based on the different processes needed to produce an erected steel skeleton with specified features. The modelling uses mathematical functions describing the costs, which include process variables that the designer can alter to determine their effect on total cost, and pre-set environment-based, but changeable parameters that define those attributes of the process environment, which affect the costs.

The research method is a mixture of empirical and theoretical. Lots of visits to different workshops and sites have been made in connection with measurements, discussions and interviews, while theoretical research has mainly involved calculations on the productivity of equipments.

The selected method simulates the real delivery process. It includes configurable parameters, which determine the process environment from the economical point of view, such as labour, equipment and real estate, material and consumables unit costs. Therefore, it is easy to adjust the method to suite the actual situation in the workshop and at the site. There are neither rules of thumb nor constants whose origin and definition are unclear. If a process not included in the method needs to be added, that can be done easily using the same principle as when creating one of the process functions presented in the method. As the method is based on a simulated delivery chain and its environment, its reliability can be made as accurate as necessary by fine-tuning the parameters of the method.

On the other hand, the method is complex and includes many pre-set parameters that need to be checked and updated. The complexity does not impede the calculation itself, because it is done by computer, but it may prevent the designer from noticing areas with potential for cost savings. The designer has to conduct an estimation with chosen variables and evaluate her/his selection afterwards. The complexity also means that using the method by itself is impractical – it needs to be linked to a building information model (BIM) from which the variables of the features are read directly.

Here, the word ‘feature’ is used to refer to those attributes that affect the costs of the structure during the manufacturing, transportation and erection processes. For example, paint thickness is a feature, but the colour of a paint is a feature only if there are differences between the costs of colours.

3. Design process

The design of a steel frame building has two main targets: to ensure that the structural behaviour of the frame is within allowed limits, and to produce information for the manufacture and erection of the frame. Both targets apply to members and joints. It has been common practice to conduct a structural analysis of the entire frame by consultant engineer assuming the joints to be totally rigid or fully hinged. In such cases the frame is analysed and the cross-sections of the members are chosen. Then, the joints are designed by manufacturer for the forces received from structural analysis. If the joint type and dimensions are such that it can be considered rigid or hinged, that will not cause an error in the structural analysis. But if the behaviour of the joint can be categorised as semi-rigid, there is the risk of exceeding the allowed stress or displacement limits of the member. On the other hand, Li et al. (1997 pp. 47-48) highlight the risk of an uneconomical outcome of this design process, where the designer chooses the joint type without feed-back from the manufacturer or the erector. Costly design of joints is due to a lack of extensive experience related to manufacturing and erecting costs. Li et al. (1997 p.48) came to the conclusion that the best solution is to transfer joint design from the manufacturer to the designer. In Finland this has been common practice for many years.

Fig. 6 presents the traditional design process where the main members are first dimensioned for either totally rigid or hinged joints. Although structural analysis software can handle semi-rigid connections, it is common practice to model joints into the structural analysis model either as rigid or hinged. The structural analysis model can be derived directly from the product model or it can be created separately. As joint design is executed after member size selection in the detail design phase, the actual joint structural analysis parameters are seldom updated to the structural analysis model (Li et al. 1997 p.47).

Weynand et al. (1998 p.6) concluded that using semi-rigid joints gave the most economical structure in the studied cases. To achieve the full advantage of semi-rigid joints requires including joint behaviour in the structural analysis model. This leads to the need to add initial joint parameters to the product model or structural analysis model. Li et al. (1997 pp.51, 60) presented a quasi-plastic analysis method where the moment resistance of a chosen joint is added to the analysis model thus reducing the beam span moment. This way the joint resistance is fully utilised and member stresses reduced accordingly.

Steel building structure designers nowadays frequently use product modelling software, such as Tekla Structure (2009) and StruCad (2009). The question of making use of the potential of more detailed modelling already in the early stages of design has been raised. As can be seen from Fig. 6, the inclusion of actual joints in structural analysis is often disregarded, and the frame members are designed only assuming rigid or hinged joint behaviour. The problem is how can the designer know what kind of details to include in the model when designing the frame, as she/he has to decide whether to make the joint hinged, rigid or semi-rigid. That decision has a major influence on the dimensions of the frame members. But in order to be able to rank the alternatives, the designer must have enough accurate information on the manufacturing costs of not only the members, but also the joints.

The following design process is proposed to draw possible further economic benefits from modelling the joints in the basic design stage:

1. Introduce the initial members and joints into a product model with joint spring factors/moment resistances.
2. Execute the structural analysis with initial member sections and chosen joints.
3. Check the manufacturer's profile and joint databases.
4. Check stresses of the members and shear stresses of the joints (moment check of joint is not needed as the moment of a joint is limited to full resistance).
5. Increase or decrease member and/or joint sizes according to the structural analysis.
6. When sizes are adequate, estimate the cost of the frame.
7. Vary the joint type with new joint parameters.
8. Repeat steps 1-5.
9. Choose the optimal alternative.

This process is presented in Fig. 7.

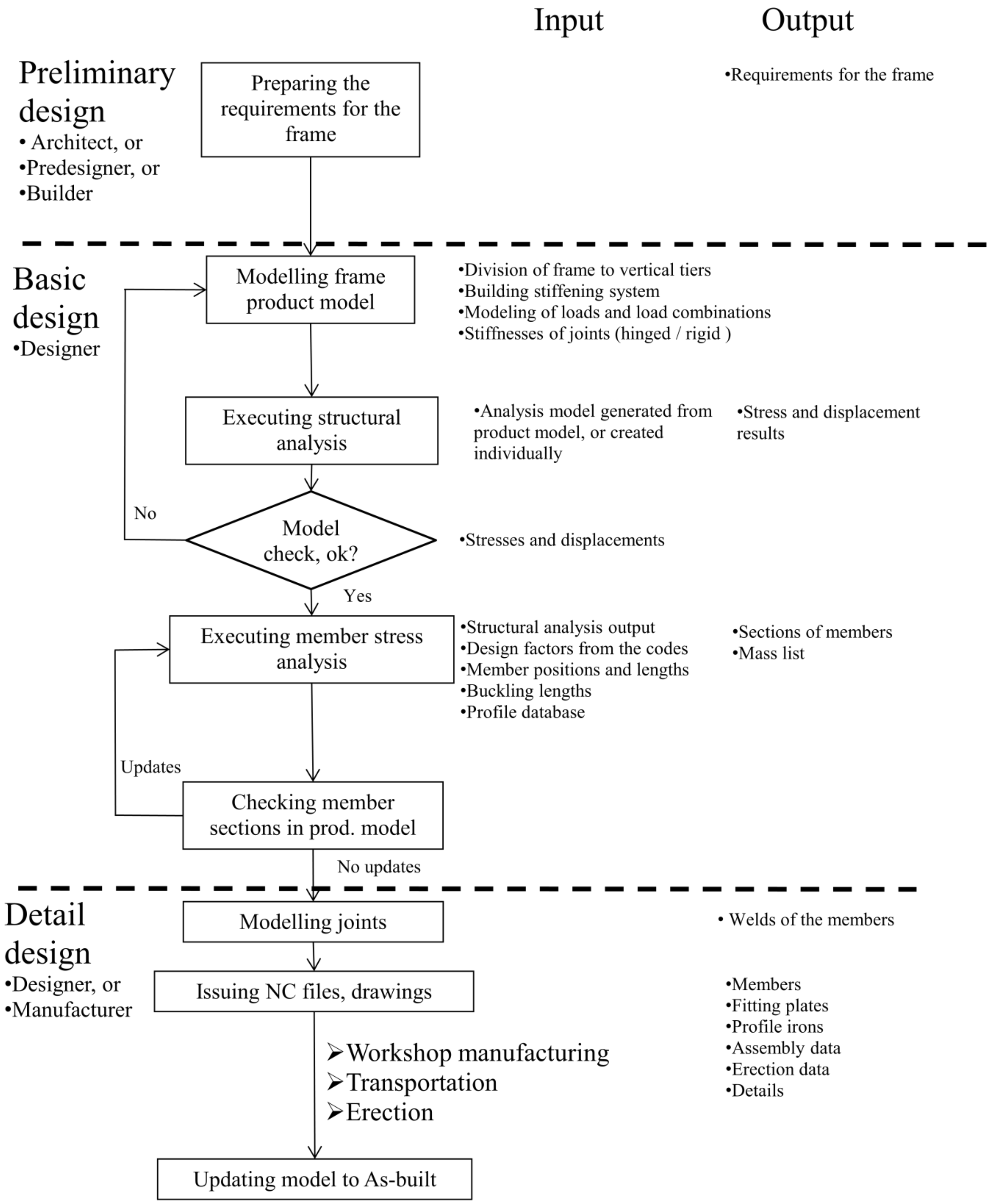


Fig. 6. Traditional design process.

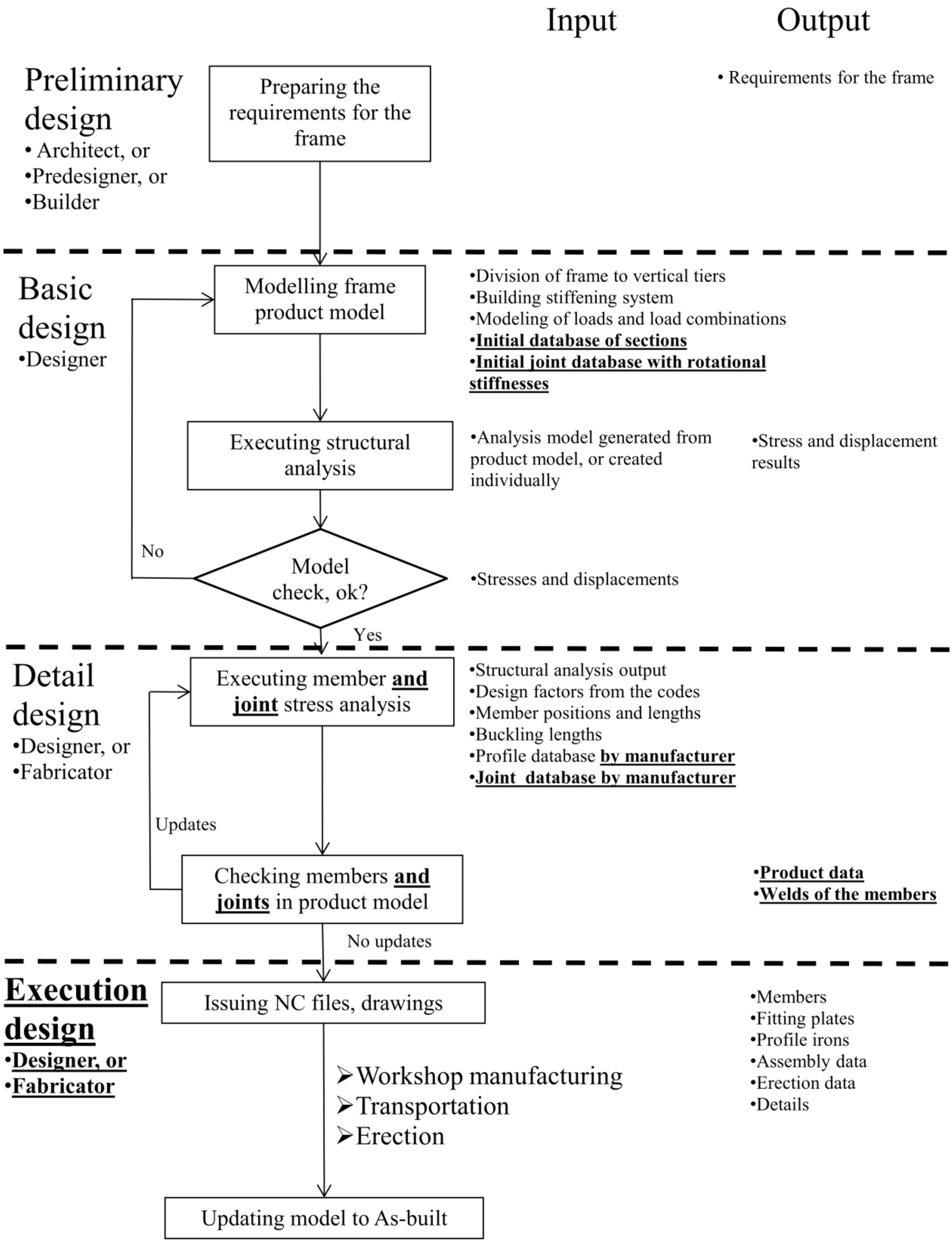


Fig. 7. Suggested design process with joint modelling at the basic design stage. Changes compared to Fig. 6 in underlined bold text.

4. Feature-based costing method

4.1 Assumptions and basis of the method

This thesis deals with a costing method based on the processes needed to produce the features of a structure. After an investment into a workshop or site facility has been made, many of the related cost factors are fixed, and the costs will run for their life time regardless of the utility rate of these factors. A fixed unit cost, €/time unit, can easily be determined for a complete workshop, or for each of its cost centres. Thus, the time used to produce a feature is essential, and a time-based approach for estimating its cost is justifiable. This approach is widely used by a number of researchers, including Farkas & Jármai (2003), Pavlovčič et al.(2004) and Ou-Yang & Lin (1997). The process consists of productive time and non-productive time. Girardier (1995, p.469) as well as Shehab & Abdalla (2002, p.1006) point out the significance of non-productive time in calculating total manufacturing time. Therefore, a virtual workshop was established to be able to estimate the non-productive time as well as the cost of real estate, see Fig. 8. Transportation between cost centres is not considered in this thesis.

The aim of the used form of cost calculation is to make use of so-called deep knowledge. By using it the components of the cost function of a cost centre represent the actual, cost-causing processes and the use of statistical factors is minimised. This approach offers the best possibility of determining the influence of different parameters on the process. It also allows using the values of manufacturer-dependent parameters most suitable for the environment in question. On the other hand, this kind of formulation is sensitive to the chosen factors, and thus requires careful checking of factors set-up before estimation. Usually, the designer does not know during the basic design phase which workshop is going to manufacture the structure, and consequently does not know which facilities will be used to manufacture it. The designer must be aware of this uncertainty and might possibly conduct a sensitivity analysis with selected parameters. However, it is believed that an educated guess about the initial parameter settings is sufficient in most cases and that the results will not be significantly affected by changing them.

This thesis looks into the costs of manufacturing, transporting and erecting steel building frames. Such frames consist of load carrying vertical columns and horizontal beams connected by joints. Assemblies, again, are joined by bolting. Columns are connected to the foundations by base bolts. Typically columns are grouted to the foundations after bolting, but this process is not dealt with here. Stiffening of the frame is effected by rigid joints, steel diagonals, wall structures or a stiffening superstructure such as a concrete tower.

The thesis does not deal with secondary structures, such as wall and roof claddings, stairs, handrails, floor slabs or plates, or cold formed profiles.

Coating is assumed to be carried out by painting, hot dip galvanising is not dealt with.

Columns and braces are hot rolled I-profiles (IPE, HEA, HEB), rectangular hollow sections (RHS), circular hollow sections (CHS), welded I-profiles (WI) or box profiles (WB). Beams are hot rolled or welded I-profiles or welded box beam profiles (WQ).

Design is presumed to be done using modelling and structural analysis software. Outputs are mainly files suitable for NC equipments, but workshop fabrication drawings are printed as necessary. Assembly drawings for the erection site will be provided.

Manufacturing is assumed to be executed with NC equipments. Only welding, parts assembly and minor works such as grinding are labour-intensive. This means that manufacturing is based on the production line, each cost centre occupying its own space in the line.

Unit costs and costs of equipment and investments are revised to correspond to the 2009 price level in Finland.

4.2 Manufacturing process and material flow

The layout of the virtual workshop and erection site shown in Fig. 8 is presented to clarify the process of delivering a steel structure project. The workshop is able to handle assembly with maximum dimensions of L x W x H = 15,000 x 2,000 x 800 mm^3,

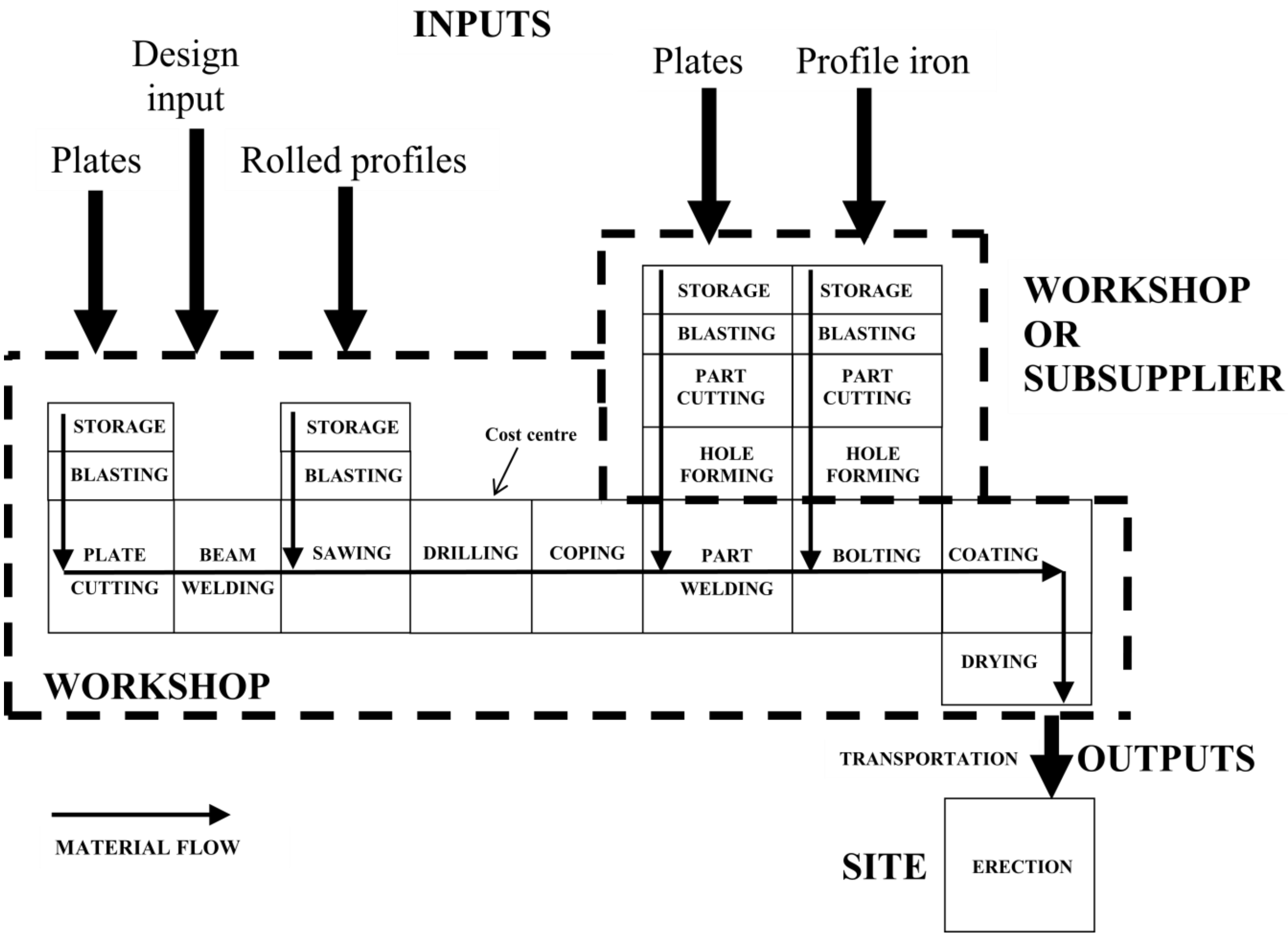


Fig. 8. Workshop's and site's material flow and cost centres.

4.3 Cost components

When calculating a cost, it is essential to use components that correspond to the purpose of the calculation. If only the manufacturing costs of two optional joints that require about the same amount of material and kind of work (say welding) are compared, only the labour cost component is needed. But when comparing totally different types of joints, say hinged versus rigid, which may also affect the dimensions of the main profile and require different fabrication processes and amount of erection work, then all available cost components must be used to get reliable results. The cost comparisons found in literature commonly include material and labour cost components, and in some cases also equipment cost, transporting cost and erecting cost (Pavlovčič et al. 2000). The real estate cost component of cost centres was not found in any of the references. If erection cost is based only on the weight of the member, that will favour a light structure even if its erection time is longer and thus probably results in a higher actual cost.

This thesis focusses on six cost components: labour, material, investments (equipment and real estate), consumables, energy, maintenance (equipment and real estate) costs. Costs are divided in two categories: time-dependent and non-time-dependent. Time-dependent costs include labour, investments, energy, maintenance, and some consumables costs, while non-time-dependent costs consist of material and some consumables costs. All costs presented in the following paragraphs are ex VAT.

4.3.1 Labour costs

Labour costs are all-in costs as described by Pilcher (1992 pp.245-248). This means that the hourly rate includes also overtime, holiday, sick leave, insurance, training and other costs that the employer must pay. These components are stipulated in law and contracts between employers and workers' unions. Different skill requirements can be taken into account in labour costs by using different hourly rates. Costs of foremen, other management and other overhead costs are not considered.

In Finland labour costs can be obtained from the statistical report published by Elinkeinoelämän Keskusliitto EK (The Confederation of Finnish Industries EK). This publication gives the average hourly cost rate. It has to be increased by 70% to get the total rate (EK, 2009 p. 17). The multiplier includes among other things costs of holidays, sick leaves, as well as retirement and social security costs, which are mandatory in Finland.

Four groups of workers are considered in this thesis. The codes, specifications and hourly rates used in the above-mentioned report are also used in Table 1.

Cost category 1		**Column I [€/h]**
20 Plate and construction work	Wage group A	16.23
Wage supplements	70 %	11.36
	Total =	**27.59**
22 Welding	Wage group A	16.13
Wage supplements	70 %	11.29
	Total =	**27.42**
33 Equipment work	Wage group A	16.28
Wage supplements	70 %	11.40
	Total =	**27.68**

63 Quality control	Wage group A	16.07
Wage supplements	70 %	11.25
	Total =	**27.32**

65 Erecting work at site	Wage group A	15.79
Wage supplements	70 %	11.05
	Total =	**26.84**

Table 1. Workers hourly rate and wage supplements (EK, 2009)

4.3.2 Material costs

Material costs consist of the costs of materials needed for manufacturing and erecting the structure. Steel material consists of plates, hot rolled sections, welded tubes, angle iron, and bolting material, i.e. bolts, nuts and washers. Material costs are based on DDP delivery terms (Incoterms) workshop or site. The size of the steel plates may vary depending on the steel mill, and according to Salokangas (2009) standard mill delivery sizes in Finland are 1,500 x 6,000 mm^2 or 2,000 x 6,000 mm^2. The minimum size of a mill delivery lot is 2,000 kg per thickness and grade. Wholesalers can deliver plates up to 2,450 x 12,000 mm^2. Standard lengths of hot rolled profiles purchased from wholesalers are 6, 12, 15 or 18 metres.

The actual cost of steel plates depends on a combination of different features of the material plus extra services provided during delivery. In this thesis the following features are considered: steel grade, steel plate thickness, amount per thickness and grade, total amount per order and ultrasonic testing. Omitted are, for example, other types of testing, sulphur removal, normalisation, and material certificate.

The material cost of steel is calculated using Function (1):

$C_{SM} = W_m \times u_m$, where (1)

C_{SM} = cost of material [€]
W_m = weight of material [kg]
u_m = unit cost of material [€/kg]

Unit cost of material consist of price of the material added with wastage. In this thesis no wastage is considered.

Personal materials for employees such as clothes, safety goggles, helmets or gloves are not considered.

4.3.3 Investment costs

Investments costs consist of two main groups: equipment and real estate. Equipment costs consists of the price of the equipment, whereas real estate costs are made up of the price of the land and the building. An alternative to investment is renting equipment and/or real estate. Typically erection site cranes are rented, as they would be costly investments and their utilisation rate during the project may be low.

According to Pilcher (2000 p. 463), the cost of owning an item of mechanical plant is influenced by the following factors:

1. Capital cost
2. Residual, resale or scrap value
3. Useful life and obsolescence of equipment
4. Tax allowances
5. Required return on capital employed
6. Cost of capital

Capital cost, tax allowances and required return on capital employed can be established with certainty, while resale value, life of equipment and cost of capital are approximations. In this thesis resale value is set to 0 for equipment and to the price of the land in case of real estate, life of the equipment is defined in the process presentations of subsequent paragraphs, tax allowances are set to 0, and cost of capital is set to 5 per cent. The required return on capital will be set during the final pricing of the production and is considered here.

The real estate cost consists of the construction cost of the workshop building which is set to €900/m^2 (Haahtela & Kiiras, 2008) and the price for raw land set to €6/m^2 (the workshop is assumed to be located in the City of Seinäjoki, Finland). Plot ratio, which tells how much one can build on the raw land, is set to 0.5. Thus, the cost of the land for the building is €12/m^2.

In the case of capital costs, the uniform series capital installment factor is used to estimate the annual cost using Function (2).

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \tag{2}$$

where

A = uniform series end-of-period installment [€/a]

P = a sum of money invested in the initial year less resale value [€]

I = the interest rate (cost of capital) [%]

n = time, the number of units (years) over which interest accumulates

4.3.4 Consumables

The cost of consumables consists of the costs of materials needed to execute the processes. Such as welding wires, flux, cutting and welding gases, blasting grains, saw blades, drill bits, paint and bolting materials. Consumption of some consumables , like flux, gases, blades and bits, is time-dependent, whereas consumption of others, like paint thickness and bolt size, is feature-based. Unit cost of consumables consists of material price added with wastage. No wastage is considered in this thesis.

4.3.5 Energy costs

Energy in this context means the electricity needed to run the equipments at the workshop. Energy for heating, cooling and lighting of the building is included in the maintenance cost. Energy costs only include the electricity consumed by processing equipments like shot blast turbines, the drilling rotator and the band saw motor. Small motors, typically connected to the conveying systems, are disregarded. The unit cost of electricity is assumed to be €0.1 /kWh. The energy cost will be calculated using nominal power of equipment, i.e. no efficiency ratio is considered.

4.3.6 Equipment and real estate maintenance costs

Equipment maintenance costs result from activities that keep equipments running. They include spares and maintenance work. It does not involve renovating the equipment, but just keeping it in running condition. The maintenance cost of each piece of equipment is presented in the corresponding paragraph.

Real estate maintenance costs accrue from the use of the space at the workshop. They include costs of heating, ventilation, cleaning, and maintenance work on the building. According to Kiinteistön ylläpito, RT-kortit KH X1-00291(2001), KH X1-00379 (2007) and KH X1-00424 (2009), these costs amount to €9.0/(m^3a). The height of the workshop is set to be 8 metres which means a real estate maintenance cost of €72/(m^2a).

4.3.6 Overhead costs

Overhead costs include indirect costs of the company, such as salaries of marketing, sales and other office staff. These costs also include costs of the office building, the canteen and the locker rooms. Although overheads are fixed costs, they are typically estimated like variable costs using the overhead rate. Overhead costs are calculated by multiplying the sum of the other direct costs of the workshop by a rate set in advance. In this thesis overhead costs are not considered, but in Finland their share is typically around 5%.

4.3.7 Profit

Even though profit is the actual result of business activity, and cannot be set beforehand, it must be included in the final price in cost calculation. In cost calculation profit can be treated as the required return on capital employed (ROCE) mentioned in Paragraph 4.3.3. Because profit is added to all costs, it makes no difference to the economical ranking order of chosen structural alternatives, hence it is not taken into account in this thesis.

4.4 Cost structure

As the aim of this thesis is to develop a method for comparing alternative structural solutions, it is appropriate to try to allocate all the costs of a single assembly according to the matching principle. To achieve this target the costs are divided into variable and fixed costs.

Variable costs

	Steel material	plates, profiles
	Wages	blue collar
	Wage supplements	social costs
	Consumables	wires, flux, gases, drills, blades, grains, etc.

Fixed costs

	Equipment	depreciation and interest on invested capital
	Real estate	depreciation and interest on invested capital
	Maintenance	of equipment, including spares
	Maintenance	of real estate, including heating, ventilation and lighting

In this thesis fixed costs are allocated to the cost centres according to the space and equipment required by each cost centre.

Variable costs depend only on the volume of production. In this thesis this means that blue collar workers are paid only for work done, not on a monthly basis. The policy of payment basis varies by workshops. Payment may also be based on a fixed wage plus variable supplements depending on the work done. Thus, it consists of both variable and fixed costs.

Treating equipment depreciation as a fixed cost means that the cost will be estimated only based on the life of the equipment. It could also be treated as a variable cost depending on the actual time of use of the equipment, but as the equipment may become technically outdated requiring replacement while it is still running and usable, the fixed cost definition was deemed appropriate.

Fixed cost per produced units varies depending on the utilisation ratio of the cost centre. Adjustment of this ratio is the task of workshop management. In this thesis it is set to 1, which means that the whole capacity of the cost centre is utilised during a work shift. However, the term ‘utilisation ratio’ is included in cost functions to allow simulating its effect on costs. The annual number of work days is assumed to be 252 consisting of week days less public holidays. Daily working hours are set to 8, which translated into 120,960 annual work minutes for a work shift. Fixed costs are allocated to this number of minutes.

4.5 Detailed cost functions

Cost functions are generated for each cost centre. The function of a cost centre consists of parameters related to the process in question and variables that describe the feature of the structural element relevant to this process. The cost originating from the cost centre is estimated based on the time needed at the cost centre. The total time needed at the cost centre refers here to the time spent processing a feature of the structure there. The processing of a feature starts when the assembly arrives to the equipment of the cost centre for processing and ends when the assembly leaves the equipment. The internal transporting time between cost centres is assumed to overlap with the time used at the cost centre and does thus not increase total time. Total time is divided into non-productive and productive time. Non-productive time covers the preparations before actual processing, such as fastening the main profile to the equipment, moving the processing tool to the surface of the profile, changing tools, releasing the profile and conveying it through the equipment. Productive time means actual processing time such as blasting, cutting, sawing, drilling, coping or welding.
The total cost function of an assembly according to Fig. 3. can be presented as follows:

$$C_T = C_{SM} + C_B + C_{Cu} + C_{BW} + C_S + C_D + C_{Co} + C_{PF} + C_{PA} + C_{PT} + C_P + C_T + C_E \quad (3)$$

where
C_T = total cost [€]
C_{SM} = material cost [€]
C_B = blasting cost [€]
C_{Cu} = cutting cost [€]
C_{BW} = beam welding cost [€]
C_S = sawing cost [€]
C_D = drilling cost [€]
C_{Co} = coping cost [€]
C_{PF} = part fabrication cost [€]
C_{PA} = part assembling cost [€]
C_{PT} = post-treatment cost [€]
C_P = painting cost [€]
C_T = transporting cost [€]
C_E = erecting cost [€]

As storage may take place in open air, in covered cold storage or in heated storage, it is not considered here.

The cost function for an assembly processed in workshop cost centre *k*, presented in generic form, is:

$$C_k = (T_{Nk} + T_{Pk}) \times \left(c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} + c_{Sek}\right)/u_k + T_{Pk} \times (c_{Ck} + c_{Enk}) + C_{Ck} \quad (4)$$

where
C_k = total cost of cost centre k [€]
T_{Nk} = non-productive time of cost centre k [min]

T_{Pk} = productive time of cost centre k [min]
c_{Lk} = unit labour cost of cost centre k [€/min]
c_{Eqk} = equipment installment unit cost of cost centre k [€/min]
c_{Mk} = unit cost of equipment maintenance of cost centre k [€/min]
c_{REk} = unit cost of real estate of cost centre k [€/min]
c_{Sek} = unit cost of real estate maintenance of cost centre k [€/min]
c_{Ck} = unit cost of time-related consumables needed in processing of cost centre k [€/min]
c_{Enk} = unit cost of energy needed in processing of cost centre k [€/min]
C_{Ck} = total cost of non-time-related consumables used in cost centre k [€]
u_k = utilisation ratio of cost centre k [decimal, ≤1]

The following cost centre identifiers are used with the cost centre functions presented below:
$_B$ = blasting
$_{Cu}$ = cutting
$_{BW}$ = beam welding
$_S$ = sawing
$_D$ = drilling
$_{Co}$ = coping
$_W$ = welding
$_{Pu}$ = punching/shearing
$_{Bo}$ = bolting
$_P$ = painting
$_T$ = transporting
$_E$ = erecting

4.5.1 Material

Cost of material includes cost of raw plates, profiles and bolting material. Materials used during workshop processes are defined as consumables, and their costs are presented in connection with process presentations.

The total cost of raw plates is calculated using Function (5) as follows:

$$C_{SM} = W_{SMPl} \times (c_{SMBP} + c_{SMG} + c_{SMT} + c_{SMQ} + c_{SMQT} + c_{SMUT}) \text{ [€]} \tag{5}$$

where

W_{SMPl} [kg] is weight of the plate

c_{SMBPl} [€/kg] is basic cost

c_{SMBG} [€/kg] is steel grade add-on

c_{SMT} [€/kg] is thickness add-on

c_{SMQ} [€/kg] is quantity add-on

c_{SMTQ} [€/kg] is quantity per thickness add-on

c_{SMUT} [€/kg] is ultrasonic inspection add-on

Unit prices used in this thesis are presented in Appendix 9.2.

Material cost of profiles is calculated with Function (6) as follows:

$$C_{SM} = W_{SMP} \times c_{SMBP} \text{ [€]} \tag{6}$$

where

W_{SMP} [kg] is weight of the profile

c_{SMBP} [€/kg] is unit cost of the profile

Unit prices of profiles are presented in Appendix 9.3.

The material cost of bolts, nuts, and washers is calculated with Function (7) as follows:

$$C_{SM} = \sum_{i=1}^{dl} n_i \times (c_{Bi} + c_{Ni} + c_{wi}) \text{ [€]} \tag{7}$$

where
dl = number of bolts of different diameter and length
c_{Bi} = unit cost of bolt i [€/pcs]
c_{Ni} = unit cost of nut i [€/pcs]
c_{Wi} = unit cost of washer i [€/pcs]

Unit prices of bolts, nuts and washers are presented in Appendix 9.4.

4.5.2 Blasting

Description of the process:

The conveyor feeds the main plate or profile into the shot blasting chamber at constant speed. No non-productive time is included.

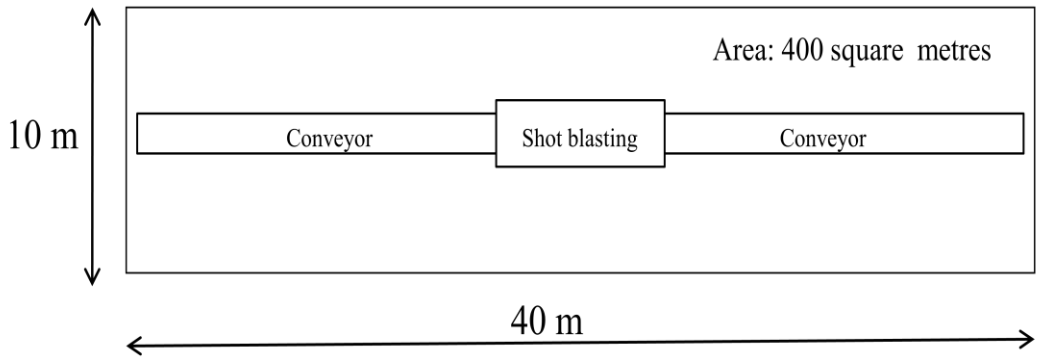


Fig. 9. Lay-out of blasting cost centre.

The blasting cost function can be expressed:

$$C_B = T_{PB} \times (c_{LB} + c_{EqB} + c_{MB} + c_{REB} + c_{SeB} + c_{CB} + c_{EnB})/u_B \quad (8)$$

Total processing time T_{TB} for blasting is determined by dividing element length L_B [mm] by conveyor speed v_c [mm/min], $T_{TB} = L_B / v_c$ [min]. Conveyor speed v_c = 3 000 mm/min is used in this thesis (Gietart). The assumption is that only one structural element is blasted at a time.

c_{LB} is the unit labour unit cost of the blasting process $c_{LB} = n_{bw} x c_l$, where n_{bw} is the number of workers and c_l is the minute rate of a worker). One machine operator is assumed to execute the process at an hourly rate of €27.68 or for €0.46/min.

c_{EqB} is equipment cost calculated according to Function (2), where P_B is the investment cost of blasting equipment and conveyors less resale value, i is investment rate (set to 5%), and n is useful life of equipment (set to 20 years). P_B is assumed to be €200,000 (Gietart) and resale value €0. These figures produce an annual equipment installment of €16,050 and c_{EqB} = €0.13/min.

c_{MB} is annual maintenance cost of equipment, set to €1,000/a, or c_{MB} =€0.01/min.

c_{REB} is real estate investment cost, calculated according to Function (2). The investment cost of the space for blasting is 400 m^2 x €912/m^2 = €364,800, resale value is 400 m^2 x €12/m^2 =€4,800, i is set to 5% and n to 50 years. These figures result in an annual real estate installment of €19,720, and c_{REB} = €0.16/min.

c_{SeB} is the real estate maintenance cost calculated according to Fig. 9 as 400 m^2 x €72/m^2 = €28,800/a or €0.24/min.

c_{CB} is cost of consumables, in this case steel shot, used during the blasting phase. The consumption of grains is typically 10 kg/8 h, when the equipment utilisation ratio is 0.5 (FredEX), which translates into consumption of 0.042 kg/min with an utilisation ratio of 1. A unit weight cost of €0.50/kg (FredEX) results in a unit cost c_{CB} of €0.02/min.

c_{EnB} is cost of the energy used by the blasting equipment during the process. When using four blasting turbines consuming 10 kW each, total power consumption is 40 kW (Gietart). With an energy unit cost of €0.1/kWh, we arrive at an energy consumption unit cost c_{EnB} = €0.07/min.

u_B is the utilisation ratio of the cost centre (set to 1).

Thus, Function (8) assumes the form:

$$C_B = L_B/_{v_c} \times (0.46 + 0.13 + 0.01 + 0.16 \ + 0.24 + 0.02 + 0.07.)/1 \qquad (9)$$

$$C_B = L_B \times 0.000363 \quad [€/min] \qquad (10)$$

The cost distribution is shown in Fig. 10.

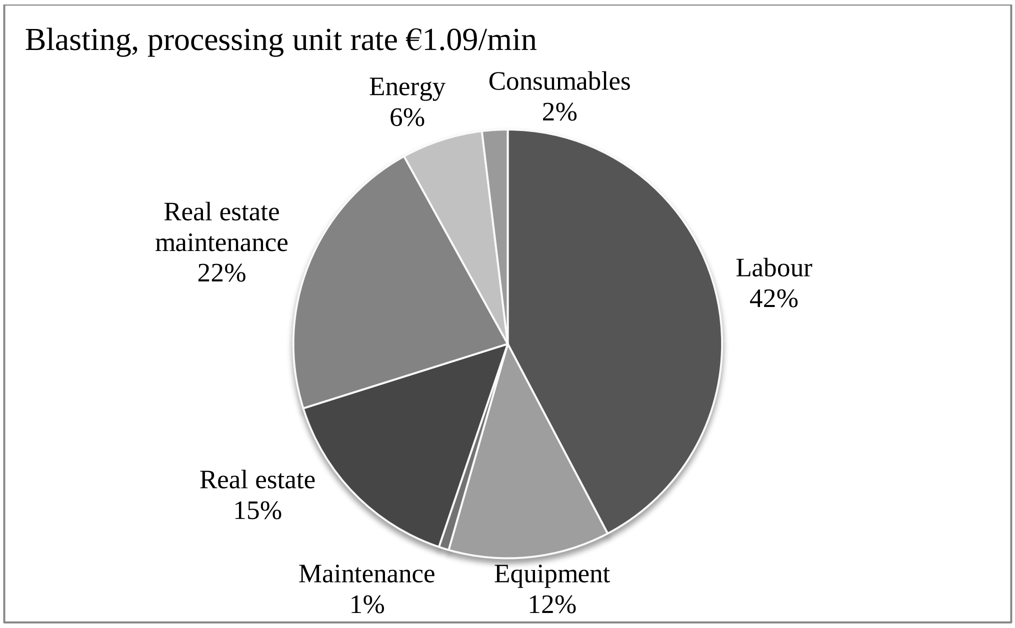


Fig. 10. Cost component distribution of blasting unit rate.

4.5.3 Cutting

Description of process:

The cutting cost centre is furnished with two tables and a moving torch carriage. The raw steel plate from which a part is to be cut lies on the cutting table. The operator does the set up and starts the equipment. At the start of the process, the equipment is away from the plate. Then it moves in the longitudinal direction while the torch carriage moves transversely and comes to the starting point of the cut. After the ignition of the torch, the cutting process proceeds at constant speed, and at the end the equipment returns to its initial position. Another worker removes the splashes from the edge and moves the plates from the table and places a new plate on the table, while the operator and equipment are working at another table. Bevelled edges are cut in one run with two or three torches fixed to the same cutting head.

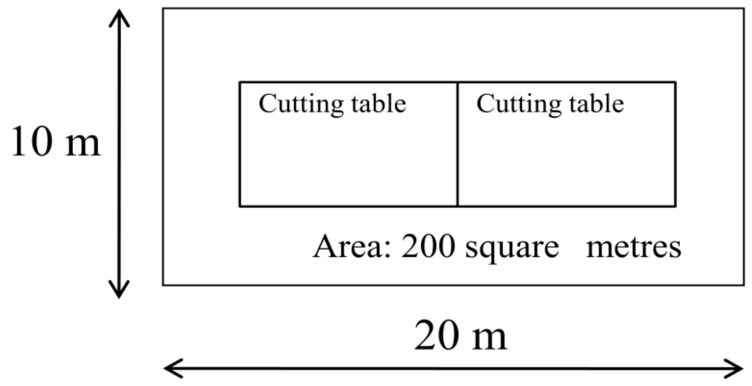


Fig. 11. Lay-out of cutting cost centre.

The cutting cost function can be expressed as:

$$C_{Cu} = (T_{NCu} + T_{PCu}) \times \left(c_{LCu} + c_{EqCu} + c_{MCu} + c_{RECu} + c_{SeCu}\right)/u_{Cu} + T_{PCu} \times (c_{CCu} + c_{EnCu}) \quad (11)$$

Of the non-productive time, 2.0 min is taken up by set-up, 0.5 min by moving the cutting head to and from the cut, and 0.5 min by lighting the torch and pre-heating. The work done to remove splashes and handling of the plates take place during the cutting process and take up no extra time. Thus, T_{NCu} = 3 min.

T_{PCu} is the cutting time. The cutting speed functions for plasma and flame cuttings of Fig. 7 were derived from the report published by The Federation of Finnish Technology Industries (former Federation of Finnish Metal, Engineering and Electrotechnical Industries), based on the Master's thesis of Niemi (1985). For comparison, the cutting speeds of Hypertherm Plasma HPR260, and the Messer Griesheim GmbH's GRICUT 1230-PM/2280-PMY nozzle for propane flame cutting, are presented.

Cutting time can be calculated from the function:

$$T_{PCu} = L_{Cu}/v_{Cu} \, [min] \quad (12)$$

where L_{Cu} [mm] is length of the cut, and v_{Cu} speed of cutting [mm/min].

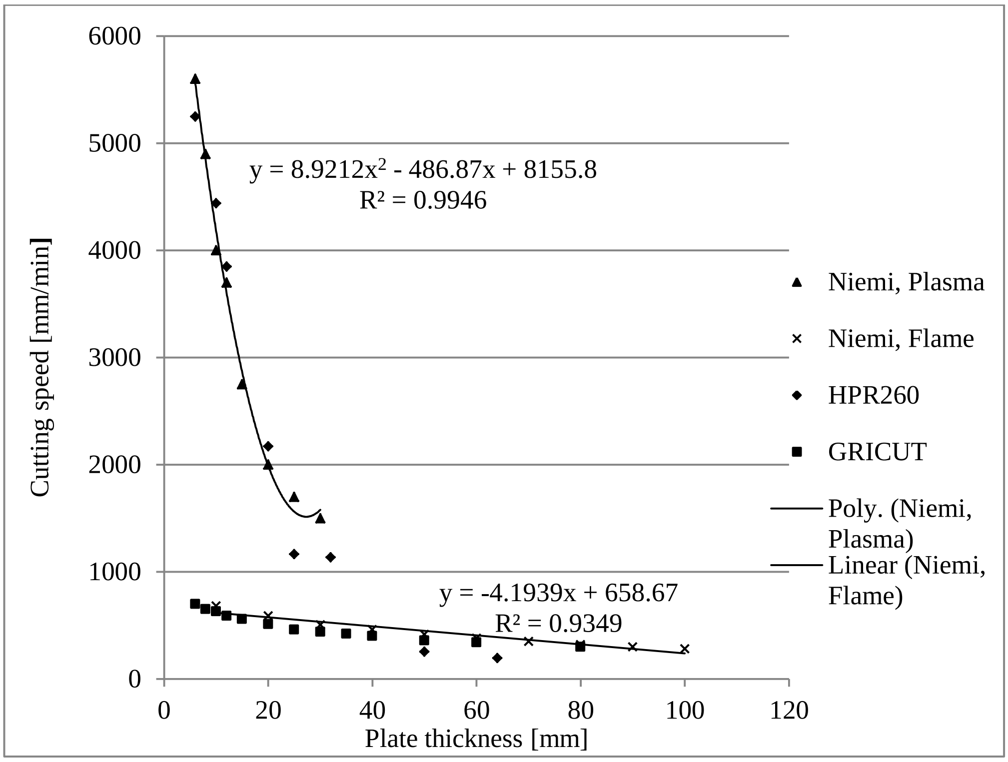


Fig. 12. Cutting speeds v_{Cu} [mm/min] depended on plate thickness [mm].

For plate thicknesses up to 30 mm, plasma cutting was chosen, flame cutting was used with greater thicknesses. X and K butt welds were an exception. The edges of these welds were cut with three-torch flame cutting equipment regardless of plate thickness.

Thus

$$T_{PCu} = L_{Cu}/(8.9212\, x\, t^2 - 486.87\, x\, t + 8{,}155.8), \text{ Plasma cutting} \quad (13)$$

$$T_{PCu} = L_{Cu}/(-4.1939\, x\, t + 658.67), \text{ Flame cutting} \quad (14)$$

c_{LCu} is the unit labour cost of the cutting process. $c_{LCu} = n_{bw}\ x\ c_l$, where n_{bw} is number of workers and c_l is minute rate of worker. One worker operating the equipment and another doing material handling are assumed to execute the process at an hourly rate of €27.68/h or for €0.92/min.

c_{EqCu} is the equipment cost, calculated according to Function (2). The equipment consist of a portal frame with side rails, one torch carriage with a plasma torch and a flame cutting torch, and an NC control unit. The investment rate i is set to 5%, and useful life of equipment n is set to 20 years. P_C is set to €280,000 (Thermcut), and resale value to €0. These figures produce an annual equipment installment of €22,468, whereby c_{EqCu} = €0.19/min.

c_{MCu} is the annual maintenance cost of equipment, set to €1,000/a or c_{MCu} = €0.01/min.

c_{RECu} is the real estate investment cost, calculated according to Function (2). The investment cost of the space for cutting, according to Fig. 11, is 200 m^2 x €912/m^2 = €182,400, the resale deduction is 200 m^2

x €12/m^2 = €2,400, *i*, is set to 5% and *n* to 50 years. These figures result in an annual real estate installment of €9,860 and c_{RECu} = €0.08/min.

c_{SeCu} is the real estate maintenance cost calculated as 200 m^2 x €72/(m^{2}a) = €14,400/a or c_{SeCu} = €0.12/min.

c_{CCu} is the cost of gases, plasma electrodes and nozzles.

Propane was chosen as the fuel gas for flame cutting. Consumption was constant for the chosen nozzle and gas pressure at 0.0063 m^3/min (GRICUT 1230-PM/2280-PMY nozzle, 0.2 bar). The price of propane was set to €18.40/m^3 (AGA), which translated into a propane cost of €0.12/min. The consumption of oxygen for the pre-heating mixture of oxygen and propane was also constant for the chosen nozzle and gas pressure at 0.025 m^3/min (GRICUT 1230-PM/2280-PMY nozzle, 2.5 bar). The price of the oxygen was set to €4.18/m^3 (Odorox, AGA), which translated into a cost of €0.1/min. The consumption of cutting oxygen correlates with the thickness of the plate to be cut. This is due the variable gas pressure determined by the plate thickness. Fig.13 presents the consumption of cutting oxygen.

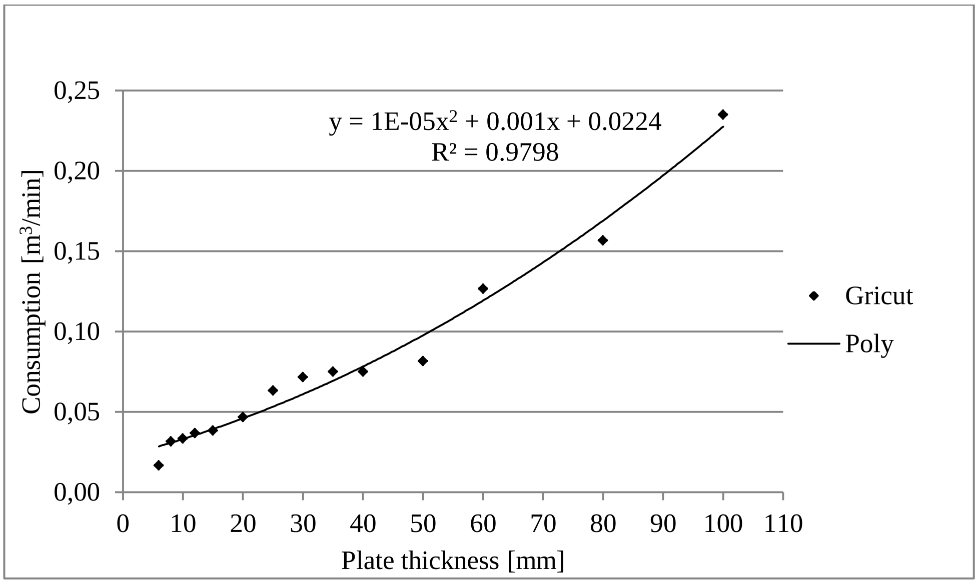


Fig. 13. Consumption of cutting oxygen [m^3/min] depended on plate thickness [mm] (GRICUT 1230-PM/2280-PMY nozzle) during flame cutting.

Nozzles for flame cutting are rather cheap and their useful life can be lengthened with maintenance. The cost of nozzles is disregarded in this thesis.

The c_{CCu} of flame cutting, using the poly line in Fig.8, can be derived from the function:

$$c_{CCu} = 0.12 + 0.1 + (1E - 05 \times t^2 + 0.001 \times t + 0.0224) \times 4.18 \ \ [€/\text{min}] \qquad (15)$$

where *t* is thickness of the plate to be cut.

In plasma cutting, pressurised air is used as shield gas, and oxygen as plasma gas. The consumption of oxygen is $4.25 m^3/h$ (HyPerformance Plasma HPR260) or $0.071 m^3/min$. At higher oxygen costs the cost of gas is €0.3/min. The cost of pressurised air is disregarded.

The cost of the nozzles and electrodes used in plasma cutting is the ratio of the cost of the parts to their useful life. This thesis assumes the price of a nozzle and electrode combination to be €40, and its life to be one shift, i.e. 480 minutes (information provided by Suomen Teknohaus Oy). Thus the cost is €0.08/min.

The c_{CCu} of plasma cutting is €0.38/min

c_{EnCu} is the cost of the energy used by the plasma cutting torch during the cutting process. The typical current consumption of a plasma cutting torch is 200 amps, which multiplied by 360 V gives a power consumption of 72 kW. An energy unit cost of €0.1/kWh translates into an energy consumption unit cost c_{EnCu} = €0.12/min. The flame cutting torch's energy consumption is disregarded.

u_C is the utiliation ratio of the cost centre (set to 1).

Function (11) assumes the following forms:

For plasma cutting

$$C_{Cu} = (3 + L_{Cu}/(8.9212 \times t^2 - 486.87 \times t + 8{,}155.8)) \times (0.92 + 0.19 + 0.01 + 0.08 + 0.12)/1 + L_{Cu}/(8.9212 \times t^2 - 486.87 \times t + 8{,}155.8)) \times (0.38 + 0.12) \quad (16)$$

==>

$$C_{Cu} = 3.96 + L_{Cu}/(6.76 \times t^2 - 368.84 \times t + 6{,}178.64) + L_{Cu}/(17.84 \times t^2 - 973.74 \times t + 16{,}311.60) \quad (17)$$

For flame cutting

$$C_{Cu} = (3 + L_{Cu}/(-4.1939 \times t + 658.67)) \times (0.92 + 0.19 + 0.01 + 0.08 + 0.12))/1 + L_{Cu}/(-4.1939 \times t + 658.67) \times (0.22 + (1E-05 \times t^2 + 0.001 \times t + 0.0224) \times 4.18 \quad (18)$$

==>

$$C_{Cu} = (3 + L_{Cu}/(-4.1939 \times t + 658.67)) \times 1.32 + L_{Cu}/(-4.1939 \times t + 658.67) \times (0.22 + (4.18 \times 10^{-5} \times t^2 + 4.18 \times 10^{-3} \times t + 0.094) \quad (19)$$

The curves representing functions (17) and (19) are presented in Fig. 14.

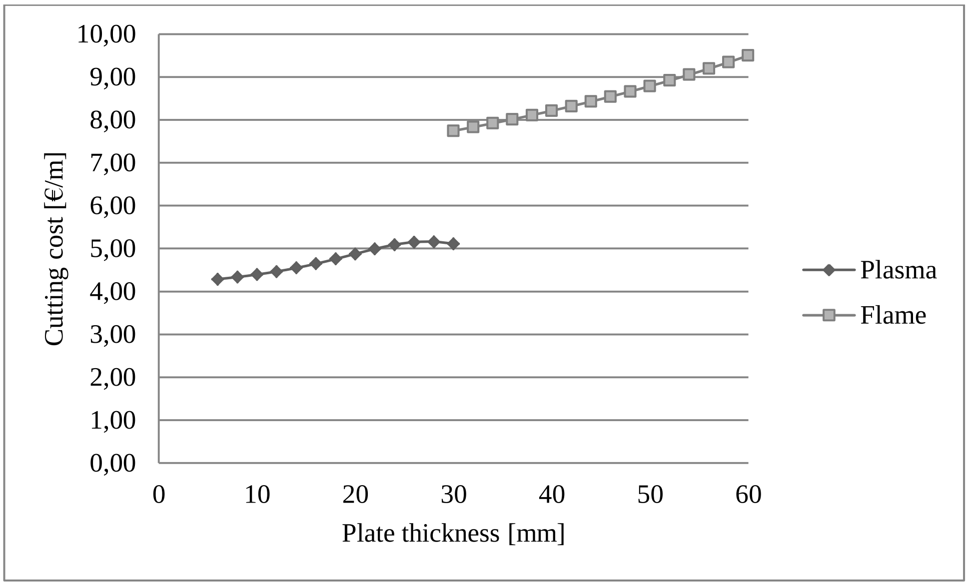


Fig. 14. Cutting cost [€/m] depending on plate thickness [mm] in plasma and flame cutting.

Distribution of cost of flame cutting cost centre is presented in Fig. 15, while there is no process ongoing. Distribution of cost of flame cutting during processing by plate thickness is presented in Fig. 16. Distribution of cost of plasma cutting during processing is presented in Fig. 17.

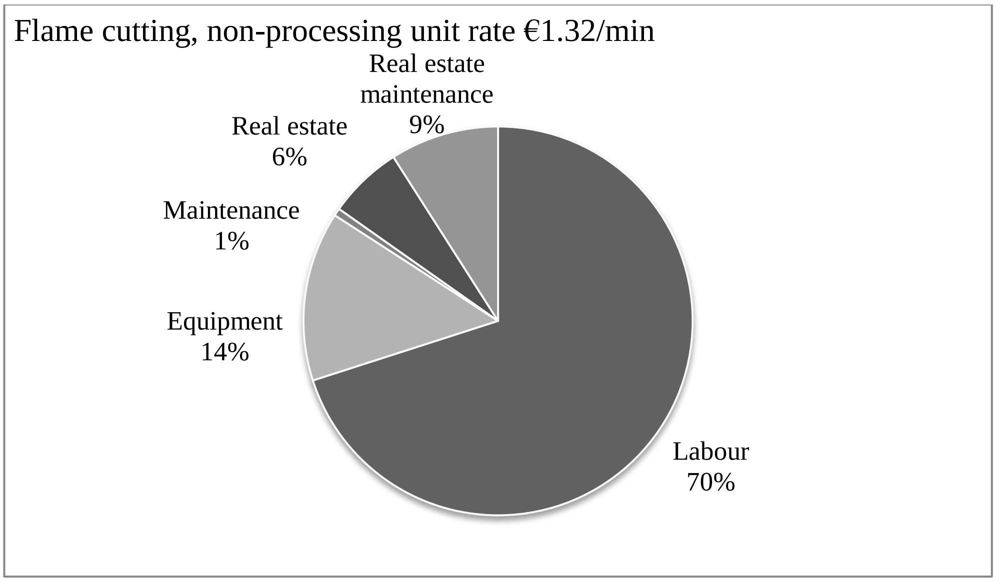


Fig. 15. Cost component distribution of flame cutting unit rate, non–processing situation.

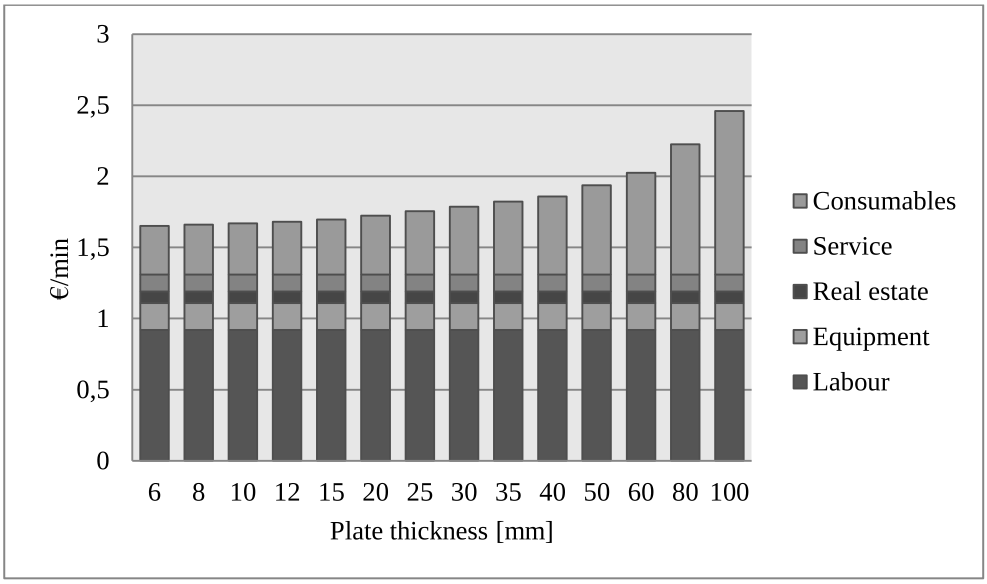


Fig. 16. Cost component distribution of flame cutting unit rate [€/min] depending on plate thickness [mm], processing situation.

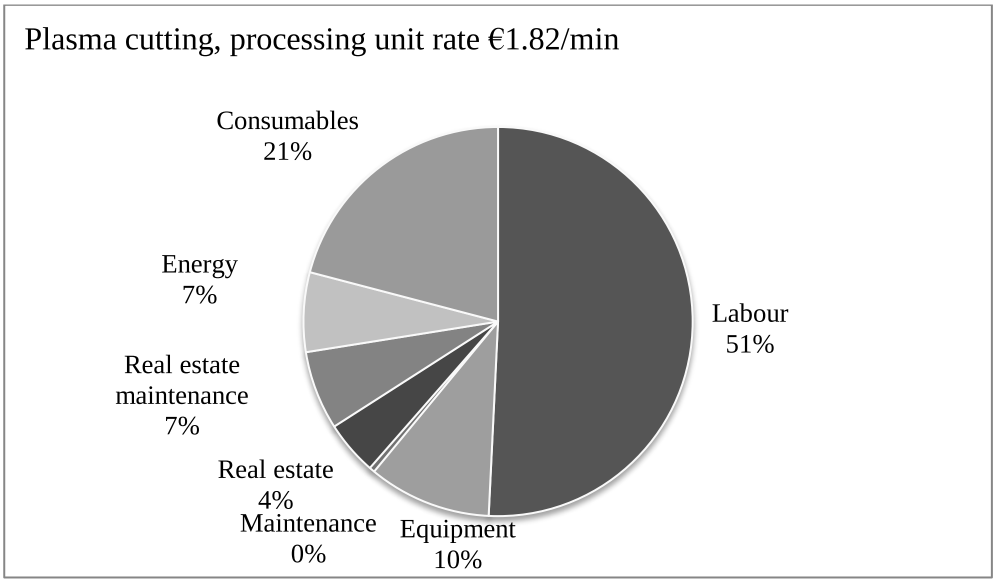


Fig. 17. Cost component distribution of plasma cutting unit rate, processing situation.

4.5.4 Beam welding

Description of process:

Beam welding is executed by the submerged arc welding (SAW) technique. This thesis considers a moving weld tower with two welding heads for simultaneous welding of two weld seams. The horizontal beam fixed to the tower that carries the welding heads can be rotated 180˚ around the tower to enable welding of another beam while preparing one for welding (i.e. turning and tacking), see Fig.

18. The solid wire process is used, and simultaneously welded seams are assumed to be of the same size and type. When welding starts, the beam to be welded is positioned on the welding table. The welding heads are positioned at the roots of the seams, flux is fed into the seams, arcs are ignited, and the welding process starts. When one pass has been welded and another pass is required, the process continues in the reverse direction, or if the weld is completed, the cantilever beam supporting the welding heads is rotated over the other table.

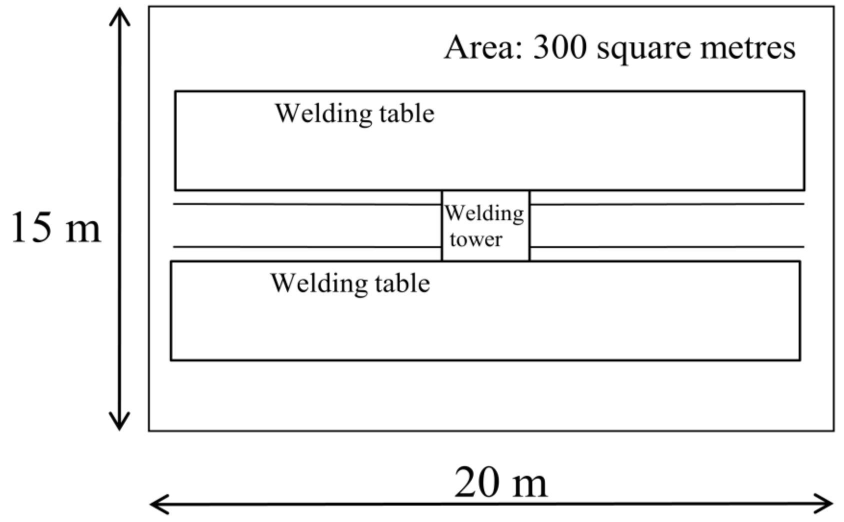


Fig. 18. Lay-out of beam welding cost centre.

The beam welding cost function may be expressed as:

$$C_{BW} = (T_{NBW} + T_{PBW}) \times (c_{LBW} + c_{EqBW} + c_{MBW} + c_{REBW} + c_{SeBW})/u_{BW} + T_{PBW} \times (c_{PMBW} + c_{EnBW}) \quad (20)$$

Of the non-productive time, 2.0 min is taken up by the setting of the welding parameters. The non-productive speed of the weld tower being 5.0 m/min (Esab), there is 2.0+2.0 min time for moving the welding tower to and from the end of the beam, and 0.25 min for starting the flux feed and arc ignition. Splashes and slag can be removed and tacking and handling of the plates done simultaneously with the beam welding process. These works can be done while the beam is being welded, or on one welding table while the welding process is underway on the other. Due to this double-table technique no additional time is required. This means that T_{NBW} = 6.25 min.

T_{PBW} represents the productive time of beam welding. The speed of the welding depends on many parameters, including welding wire dimensions, amount and type of wires, welding current, welding voltage and current polarity. This thesis uses the deposit rate of the Costcomp program (Costcomp 2008). A 100% duty cycle is used because the non-productive time is considered separately. With 5 mm solid, Costcomp gives a deposit rate of 8.34 kg/h = 0.14 kg/min. The weight of a single weld, when its length is L_w *[mm]*, is

$$W_w = L_w \times a^2 \times 7.85 \times 10^{-6} \, [kg] \quad (21)$$

for a fillet weld, where *a [mm]* is the throat size.

$$W_w = L_w \times (b^2 \times \tan\alpha)/2 \times 7.85 \times 10^{-6} \; [kg] \quad (22)$$

for a single-bevel butt weld, where b *[mm]* is the depth of the weld and α is the angle between the bevel and the plane perpendicular to the bevelled steel plate surface.

$$W_w = L_w \times b^2 \times \tan(^{\alpha}/_{2}) \times 7.85 \times 10^{-6} \; [kg] \quad (23)$$

for a V butt weld, where b *[mm]* is the depth of the weld and α is the angle between the bevelled edges.

As the simultaneously welded seams were assumed to be of the same size and type, the productive time could be calculated based on the time for one seam.

$$T_{PBW} = W_w/0.14 \; [min] \quad (24)$$

c_{LBW} is the unit labour cost of the beam welding process. $c_{LBW} = n_{bw} \; x \; c_l$, where n_{bw} is the number of workers and c_l is the minute rate of a worker. One welding equipment operator and one worker doing the material handling and preparing welded seams are assumed to execute the process at an hourly rate of €27.68/h or for €0.92/min.

c_{EqBW} is the equipment cost, calculated according to Function (2). The layout involves two welding tables for expediting the work: when the welding equipment operates at one table, material handling, tacking, turning the beam around, and splash and slag removal can be executed at the other table. The equipment consists of a welding tower with a cantilever beam with two welding heads equipped with flux hoppers and wire reels, power supply, and an NC control unit. The investment rate i is set to 5%, and the useful life of the equipment n to 20 years. P_C is assumed to be €200,000 (according to offer), and resale value €0. These figures produce an annual equipment installment of €16,049 and c_{EqBW} = €0.13/min.

c_{MBW} is the annual maintenance cost of equipment, set to €1,000/a or €0.01/min.

c_{REBW} is the real estate investment cost calculated according to Function (2). The investment cost of the space for blasting is, according to Fig. 18, 300 m^2 x €912/m^2 = €273,600, the resale deduction is 300 m^2 x €12/m^2 = €3,600, i is set to 5% and n to 50 years. These figures produce an annual real estate installment of €14,790 which translates into c_{REBW} = €0.12/min.

c_{SeBW} is the real estate maintenance cost, 300 m^2 x €72/(m^2a) = €21,600/a or €0.18/min.

c_{CBW} is the cost of wires and flux. The price of wire is set to €1.91/kg (5 mm, solid wire, ESAB), and consumption is estimated to be 0.14 kg/min (Costcomp, 2001), which translates to a wire cost of €0.27/min per welding head. The consumption of flux is comparable to the consumption of wire, and 1 kg of flux/1 kg wire is assumed (Lukkari 1997, p. 149). The price of flux is €3/kg, which translated to a flux cost of 0.14x3 = €0.42/min. Thus c_{CBW} = €0.68/min per welding head.

c_{EnBW} is the cost of the energy used by the submerged arc welding process. The typical current consumption of SAW welding with 5 mm solid wire is 800 amps, which multiplied by 30 V gives a power consumption of 24 kW/welding head. With an energy unit cost of €0.1/kWh, the energy consumption unit cost of a single welding head c_{EnBW} = 24x0.1/60 = €0.04/min. Other electronic equipments, such as motors, are disregarded.

u_{BW} is the utilisation ratio of the cost centre, set to 1.

Function (20) assumes the form:

$$\mathrm{C_{BW}} = (6.25 + L_w \times a^2 \times 7.85 \times 10^{-6}/0.14) \times (0.92 + 0.13 + 0.01 + 0.12 + 0.18)/1 + (L_w \times a^2 \times 7.85 \times 10^{-6}/0.14) \times n_{wh} \times (0.68 + 0.04) \quad (21)$$

$$\mathrm{C_{BW}} = (76.26 + \mathrm{n_{wh}} \times 40.37) \times L_w \times a^2 \times 10^{-6} + 8.5 \ \ [€] \quad (22)$$

for a fillet weld, where n_{wh} is the number of simultaneously welded seams, 1 or 2.

Correspondingly, using the applicable weld weight function, we get

$$\mathrm{C_{BW}} = (38.13 + \mathrm{n_{wh}} \times 20.19) \times L_w \times b^2 \times \tan\alpha \times 10^{-6} + 8.5 \quad (23)$$

for a single-bevel butt weld

$$\mathrm{C_{BW}} = (76.26 + \mathrm{n_{wh}} \times 40.37) \times L_w \times b^2 \times \tan(\alpha/2) \times 10^{-6} + 8.5 \quad (24)$$

for a V butt weld

Distribution of cost of beam welding during non-processing situation presented in Fig. 19, and during processing situation in Fig. 20.

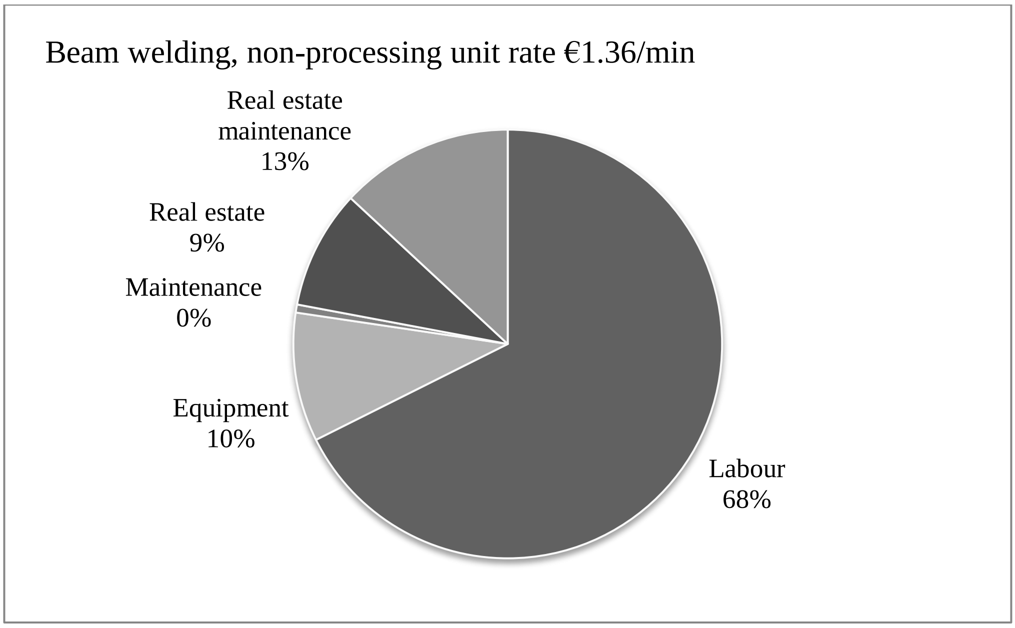


Fig. 19. Cost component distribution of beam welding unit rate, non–processing situation.

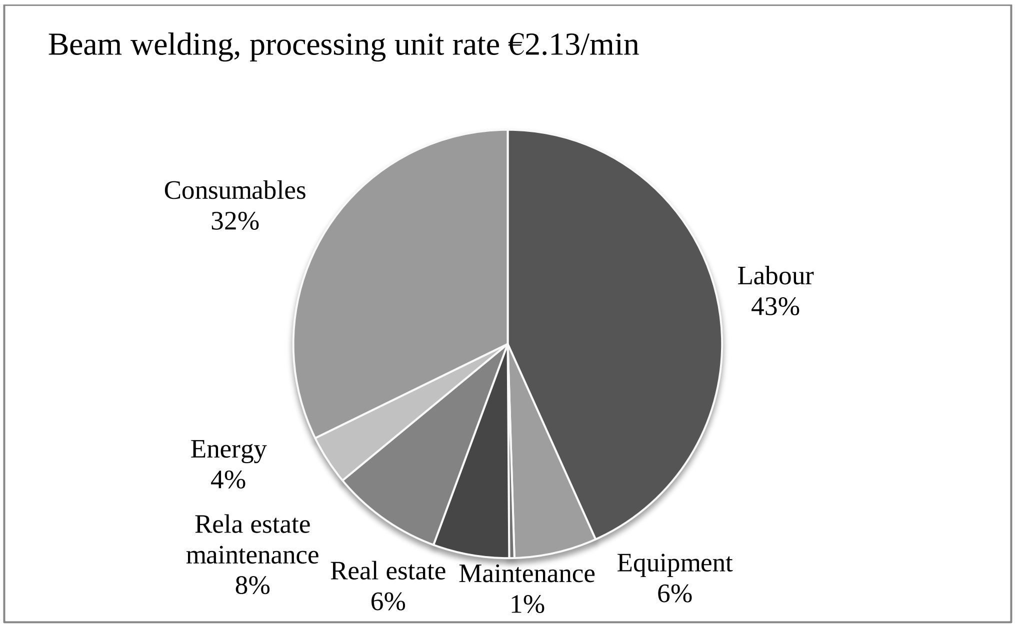


Fig. 20. Cost component distribution of beam welding unit rate, processing situation.

4.5.5 Sawing

Description of the process:

Sawing is executed with band saw equipment. The process starts when the main profile is fixed in the correct position in relation to the blade. If the profile end is to be bevelled, the saw rotates to the correct angle. The blade descends to the surface or edge of the main profile and the run of the blade starts. After the sawing is finished, the blade is stopped and raised to the stand-by position. The main profile is released and conveyed so that its other end is at the correct position with regard to the blade. The main profile is fixed and the sawing process continues as described above. The process stops when the blade is raised and the main profile is released.

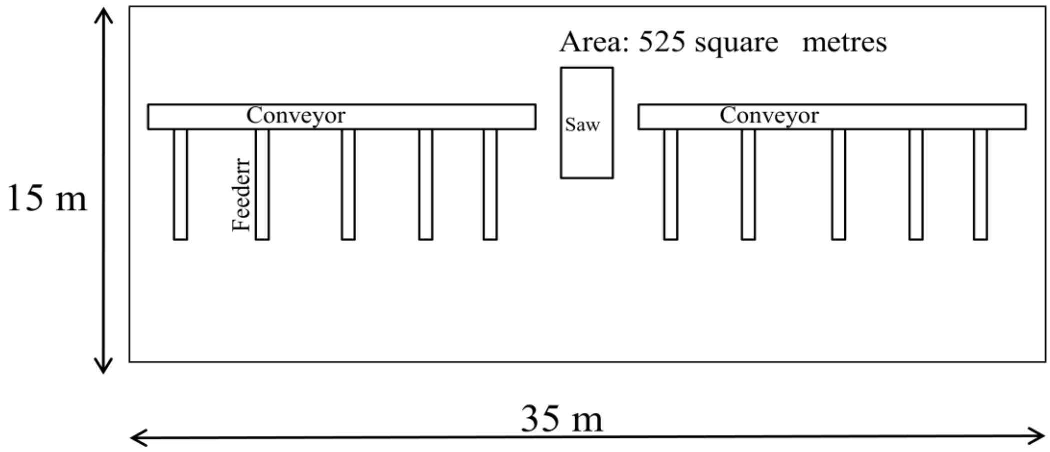


Fig. 21. Lay-out of the sawing cost centre.

The sawing cost function may be expressed as:

$$C_S = (T_{NS} + T_{PS}) \times (c_{LS} + c_{EqS} + c_{MS} + c_{RES} \ + c_{SeS})/u_S + T_{PS} \times (c_{CS} + c_{EnS}) \quad (25)$$

Non-productive time T_{NS} consists of set up of the equipment, fixing the main profile, descending the band, raising the band, releasing the main profile, conveying the main profile through the saw, fixing the main profile, descending the blade, raising the blade and releasing the main profile. Set up time includes the input of cut information, and in the case of a bevelled cut, rotating the saw. Data input is set to 2 minutes and rotating the saw to 1 minute. The time for fixing the main profile is set to 0.5 minutes, descending the blade is set to 0.25 minutes, and raising the blade is set to 0.5 minutes. The time for conveying the main profile depends on the length of the main profile. Conveying speed is set to 20,000 mm/min (Vernet Behringer), thus the conveying time is $T_{con} = L/20{,}000\ [min]$. The non-productive time, including both ends, is:

$$T_{NS} = 4.5 + 1_{(bevel1)} + 1_{(bevel2)} + L/20{,}000\ [min] \quad (26)$$

The Behringer Werkstoff-Katalog (Behringer, 1995) is used to calculate the productive sawing time T_{PS}. Productive time depends on height of the profile in sawing position, feeding speed of the blade, and grade of the material. Typically an I-profile is sawn with the web in the horizontal position, so the height is actually the width of the flange. With other profile types sawing height is assumed to be the smaller dimension of the profile height and width. The productive time function assumes the form:

$$T_{PS} = h/(S \times S_m) \qquad [\text{min}] \quad (27)$$

for the vertical part of a fixed profile, where thickness of the sawed material is comparable to plate thickness , and

$$T_{PS} = A_h/Q \qquad [\text{min}] \quad (28)$$

for the horizontal part of a profile, where the sawed material is solid.

The above h is the sawing height [mm] of the profile, S is the vertical feeding speed of the blade [mm/min], S_m is the material factor, A_h [mm^2] is the sum area of the horizontal parts of the profile. Finally, Q is the sawing efficiency [mm^2/min] of the blade for solid material. Vertical feeding speed depends on the wall thickness of the sawn main profile according to Table 2.

Wall thickness [mm]	Feeding speed S [mm/min]
-5	120
6-10	100
11-15	90
16-20	80
21-25	70
26-30	60
31-35	50
36-	40

Table 2. Feeding speed S, Behringer (1995, Table 14)

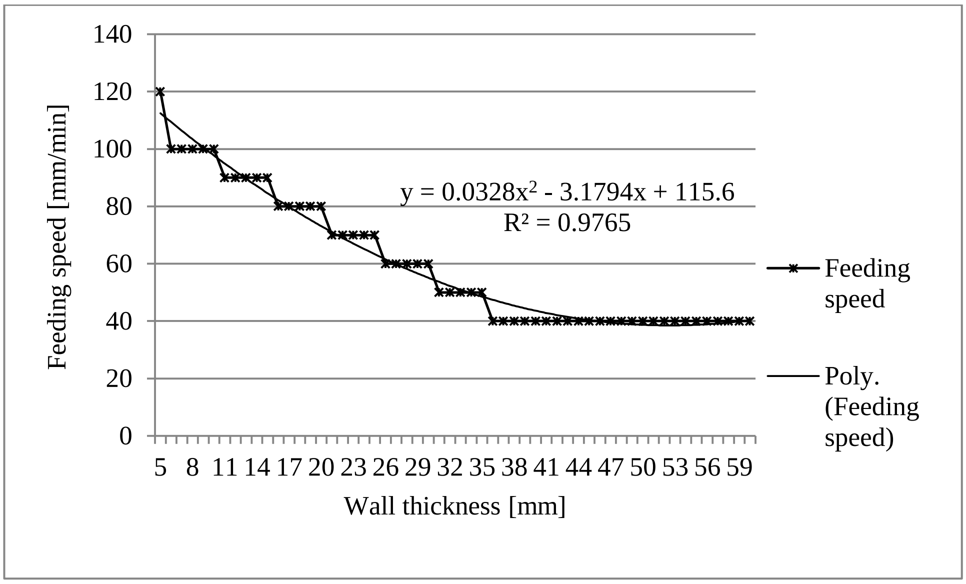


Fig. 22. Feeding speed *S* of band saw (Behringer) and fitted curve.

Thus, feeding speed can be presented in continuous form according to the poly line in Fig. 22.

$$S = 0.0328 \times t_{mv}^2 - 3.1794 \times t_{mv} + 115.6\ [mm/min] \quad (29)$$

where t_{mv} is the material thickness [mm] of the thickest plate in vertical position during sawing. For bevelled cutting, the thickness is $t_{mv} = t_m / \cos\alpha$, where t_m is the thickness of the thickest vertical plate in sawing position and α is the bevel angle in relation to an axle perpendicular to the main profile's longitudinal axis. Maximum bevel angle is limited to 45$^{\text{o}}$ (Behringer).

Material factor S_m is selected from Table 3.

Material grade	S_m
S235	1.00
S355	0.90
S400	0.80

Table 3. Material factor S_m, Behringer (1995, Table 15).

Efficiency *Q* depends on material grade and blade width. The following values apply to blade width 54 mm:

Material grade	*Q* [mm^2/min]
S235	11,300
S355	8,800
S400	6,900

Table 4. Efficiency Q, Behringer (1995, Table 10).

c_{LS} is the unit labour cost of the sawing process. c_{LS} = n_s x c_l, where n_s is the number of workers and c_l is the minute rate of a worker. A single sawing equipment operator is assumed to execute the process at an hourly rate of €27.68 or for €0.46/min.

c_{EqS} is the equipment cost, calculated according to Function (2), where P_C is the investment cost of the sawing equipment with conveyors and feeders. The investment rate i is set to 5%, and useful life of equipment n to 20 years. P_C is assumed to be €310,000 (according to offer), and resale value is €0. These figures produce an annual equipment installment of €24, 875 or €0.21/min.

c_{MS} is the annual maintenance cost of equipment, set to €1,000 or €0.01/min.

c_{RES} is the real estate investment cost calculated using Function (2). The investment cost of the space for sawing is, according to Fig. 21, 525 m^2 x €912/m^2 = €478,800, the resale deduction is 525 m^2 x €12 /m^2 = €6,300, i is set to 5% and n to 50 years. These figures produce an annual real estate installment of €25,882/a or €0.21/min.

c_{SeS} is the real estate maintenance cost calculated as 525 m^2 x €72/(m^2a) = €37,800/a or €0.31/min.

The cost of sawing consumables c_{CS} includes only the wear of saw blades. According to Behringer (Behringer, p. 3), the overall durability of the blade is calculated from the function

$$S_t = Q \times F_s \times F_{sp}, \tag{30}$$

where S_t is the total cross-section area [mm^2] a blade can saw before it has to be replaced, F_s is a parameter that depends on the equipment type, and finally F_{sp} is a parameter that depends on the thickness of material.

The value of parameter F_s is 1,350 in the case of the saw model chosen for this thesis. F_{sp} is given in Table 5.

Wall thickness [mm]	F_{sp}
-5	0.4
6-10	0.45
11-15	0.5
16-20	0,55
21-25	0.6
26-30	0.65
31-35	0.7
36-	0.8

Table 5. Value of F_{sp} that depends on material wall thickness, Behringer (2005, Table 14).

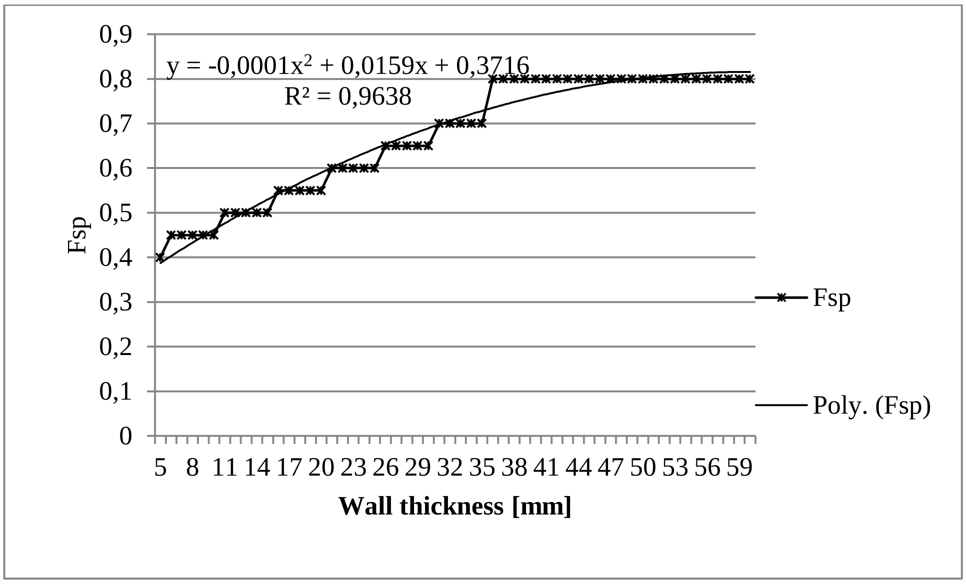


Fig. 23. Parameter F_{sp} as a function of wall thickness.

F_{sp} can be calculated using the continuous function presented in Fig. 23.

$$F_{sp} = -0.0001 \times t_{mv}^2 + 0.0159 \times t_{mv} + 0.3716, \tag{31}$$

which yields the following functions:

$$S_t = -1{,}526 \times t_{mv}^2 + 242{,}555 \times t_{mv} + 5{,}668{,}758 \text{ [mm}^2\text{], for material S235} \tag{32}$$

$$S_t = -1{,}188 \times t_{mv}^2 + 188{,}892 \times t_{mv} + 4{,}414{,}608 \text{ [mm}^2\text{], for material S355} \tag{33}$$

$$S_t = -932 \times t_{mv}^2 + 148{,}109 \times t_{mv} + 3{,}461{,}454 \text{ [mm}^2\text{], for material S400} \tag{34}$$

c_{cs} is calculated from the function

$$c_{cs} = A_t/(S_t \times T_{PS}) \times p_{SB} \text{ [€/min]} \tag{35}$$

where A_t is the total cross-section area of the sawed profile [mm^2] and p_{SB} is the price of the saw blade [€]. In this thesis the blade price was set to €100 (ProdMac Oy)

c_{EnS} is the cost of the energy used by the band saw. The total power consumption of the saw is assumed to be 10 kW in this thesis. At an energy unit cost of €0.1 /kWh the energy consumption unit cost c_{EnS} = €0.02/min. Other electronic equipments, such as conveyor motors, are disregarded.

u_S is the utilization ratio of the cost centre (set to 1).

Then, the Function (25) assumes the form:

$$C_S = (4.5 + 1_{(bevel1)} + 1_{(bevel2)} + L/20{,}000 + \sum_{i=1}^{2}(h_i/(S \times S_m) + A_{hi}/Q)) \times (0.46 + 0.21 + 0.01 + 0.21 + 0.31\ ) + \sum_{i=1}^{2}(h_i/(S \times S_m) + A_{hi}/Q) \times (A_{ti}/(S_t \times (h_i/(S \times S_m) + A_{hi}/Q)) \times 100 + 0.02)\Big)\ [€] \quad (36)$$

Distribution of cost of sawing during processing is presented in Fig. 24.

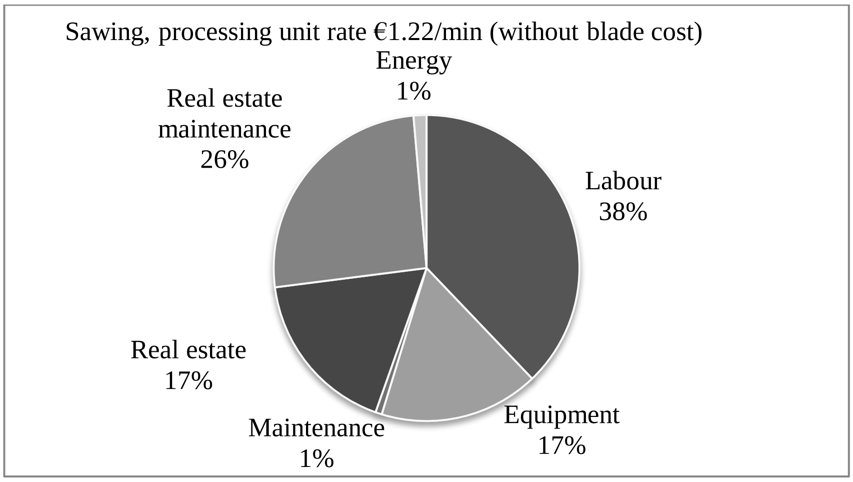


Fig. 24. Cost component distribution of sawing unit rate, processing situation.

4.5.6 Drilling

Description of the process:

In this thesis drilling is assumed to be executed on an automatic drilling line with three drilling heads, each with one spindle. Two of the heads are able to drill in opposite horizontal directions and the third in the vertical direction. The spindles can operate simultaneously. The process starts when the operator sets up the parameters for drilling. Then the main profile is fixed to the equipment and moved to the right position with regard to the first perpendicular hole location/row of holes to be drilled. The spindles pick up the correct size drill bits from tool holders and move to the surface of the main profile. Then, the spindles start rotating and holes are drilled. After drilling, the drill bit exits the hole. In case of a row of holes, the head moves to the position of the next hole and repeats the drilling process. The assumption of this thesis is that the holes of a row in any direction are of the same size, and a possible change of drill bit is executed while transferring the assembly between rows. If holes are needed in more than one perpendicular row of the main profile, the main profile is released, transferred to the next position by the conveyor, fixed again, and the above described process is repeated. If the main profile is to have holes also on a fourth surface, it will be rotated manually, transferred to the correct position, and the holes of fourth surface are drilled. Finally, the main profile is released from the fixing jaws, the heads return to the stand-by position, the main profile is transferred to the receiving conveyor, and the process ends.

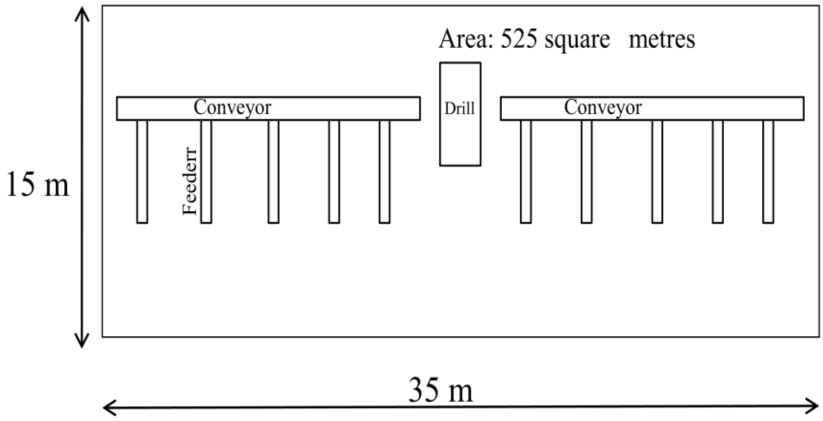


Fig. 25. Lay-out of drilling cost centre.

The drilling cost function may be expressed as:

$$C_D = (T_{ND} + T_{PD}) \times \left(c_{LD} + c_{EqD} + c_{MD} + c_{RED} + c_{SeD}\right)/u_D + T_{PD} \times (c_{CD} + c_{EnD}) \quad (37)$$

Of the non-productive time T_{ND}, 4 minutes is taken up by the set up by the operator, 0.25 minutes by picking up the drill bit, 0.2 minutes by moving the tip of the drill bit to the material surface, 0.1 minutes by the head moving from hole to hole, and 0.2 minutes by the head moving from the final the drilling position to the stand-by position. Releasing and re-fixing is assumed to take 0.2 min. Conveyor speed is set to 20,000 mm/min (Behringer), which translated to a total transfer time of *L/20,000* [min], where *L* [mm] is the length of the part. Manual turning of the main profile is assumed to take 2 minutes in the case of the fourth drilling direction. When the heads act simultaneously, the non-productive time per row is equal to the longest time calculated separately for each direction. Thus, the non-productive time of drilling is:

$$T_{ND} = 4 + 0.25 + 0.2 + (r_f - 1) \times (0.2 + 0.2) + \sum_{r=1}^{r_{13}} max \sum_{i=1}^{3} (n_{ri} - 1) \times 0.1 + 0.2 + L/20{,}000 + \{2 + 0.2 + (r_s - 1) \times (0.2 + 0.2) + 0.2 + 2 \times L/20{,}000\} \text{ [min]} \quad (38)$$

which can be reduced to:

$$T_{ND} = 4.65 + (r_f - 1) \times 0.4 + \sum_{r=1}^{r_f} max \sum_{i=1}^{3} (n_{ri} - 1) \times 0.1 + L/20{,}000 + \left\{2.4 + (r_s - 1) \times 0.4 + \sum_{r=1}^{r_s} (n_{r4} - 1) \times 0.1 + 2 \times L/20{,}000\right\} \text{ [min]} \quad (39)$$

where n_{ri} is the number of the holes in row *r* in direction *i*. r_f is the total number of rows of the first run, and r_s is the number of rows of the second run. The index *4* refers to the second run.

In the case of a second run, the main profile is assumed to be transferred first back to the starting position and then again through the drill equipment, i.e. the transfer length is *2 x L*.

The value of the productive time T_{PD} depends on the size and material of the drill bit, and the thickness of the material to be drilled. This thesis assumes an HSS drill with TiN coating. A cutting speed of 40 m/min is recommended for this type of bit with steel hardness < 200 HB (Dormer, p.T19). The feeding speed of the drill bit per round is determined on the basis of Table 6.

d	[mm]	12	15	16	20	25	30	40	50
f_n	[mm/round]	0.28	0.31	0.32	0.36	0.4	0.42	0.44	0.46

Table 6. Feeding speeds f_n of different drill bit diameters d (Dormer, p. T24)

A continuous function is derived from these values in Fig. 26.

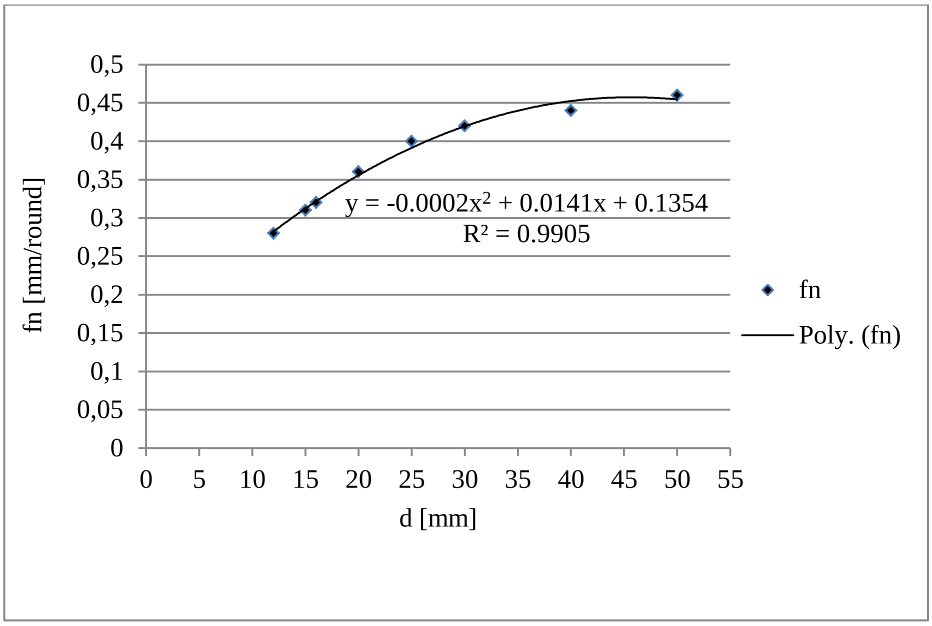


Fig. 26. Feeding speed f_n [mm/round]as a function of drill bit diameter d [mm]

The suitable rotating speed r of the spindle is derived from the function

$$r = \frac{V_c \times 1{,}000}{\pi \times d} \text{ [round/min]} \tag{40}$$

$$r = 318 \times \frac{V_c}{d} \text{ [round/min]} \tag{41}$$

where V_c is the recommended cutting speed [m/min] for the drill bit edge and d [mm] is the diameter of the bit.

Using cutting speed V_c = 40 m/min, Function (41) assumes the form

$$r = \frac{12{,}732}{d} \quad \text{[round/min]} \tag{42}$$

Feeding speed [mm/min] can be derived from

$$V_f = r \times f_n \text{ [mm/min]} \tag{43}$$

Using the polynomial line presented in Fig. 21 for feeding speed f_n gives us the following function for the total productive time of drilling the holes in the main profile used in this thesis:

$$T_{PD} = \sum_{i=1}^{r_f} \max \sum_{j=1}^{3} n_{ij} \times \frac{d_{ij}}{12{,}732} \times t_j/(-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) + \sum_{1}^{r_s} n_{is} \times \frac{d_{i4}}{12{,}732} \times t_4/(-0.0002 \times d_{i4}^2 + 0.0141 \times d_{i4} + 0.1354\ ) \text{ [min]} \tag{44}$$

where n_{ij} is the number of holes in row *i* in direction *j*, t_j is the plate thickness [mm] of direction *j*, and d_{ij} is the hole diameter [mm] of row *i* in direction *j*. The index *4* refers to the second run.

c_{LD} is the unit labour cost of the drilling process. $c_{LD} = n_D \times c_l$, where n_D is the number of workers and c_l is the minute rate of a worker. One drilling equipment operator is assumed to execute the process at an hourly rate of €27.68 or for €0.46/min.

c_{EqD} is the equipment cost derived from Function (2), where *P* is the investment cost of the drilling equipment with conveyors and feeders. The investment rate *i* is set to 5%, and useful life of equipment *n* to 20 years. *P* is set to €520,000 (according to offer), and resale value to €0. These figures produce an annual equipment installment of €41, 726 or €0.34/min.

c_{MD} is the annual maintenance cost of equipment, set to €1,000 or €0.01/min.

c_{RED} is the real estate investment cost derived from Function (2). The investment cost of the space for drilling is, according to Fig. 25, 525 m^2 x €912/m^2 = €478,800, the resale deduction is 525 m^2 x €12/m^2 = €6,300, *i* is set to 5 % and *n* to 50 years. These figures produce an annual real estate installment of €25,882 or €0.21/min.

c_{SeD} is the real estate maintenance cost calculated as 525 m^2 x €72/(m^{2}a) = €37,800/a or €0.31/min.

Only drill bits are considered consumables. The price of different sizes of bits are, according to offer, as in Table 7.

d	[mm]	14	18	22	26	32
Price p_{DB}	[€]	42	62	71	119	167

Table 7. Price p_{DB} [€] of drill bits (A530 HSS TiN 4xd).

The durability of a drill bit is assumed to be 30 min (Dormer). The bit can be edged 15 times giving it a total useful lifetime of 450 min. If we disregard the edging cost, the consumables cost can be calculated from the function:

$$c_{cD} = \sum_{k=1}^{n_{dd}} c_{cDk} = \sum_{k=1}^{n_{dd}} p_{DBk}/450 \times T_{PDk} \tag{45}$$

where n_{dd} is the number of different drill bit sizes and T_{PDk} is the subtotal drilling time with each drill bit size. T_{PDk} is calculated as the sum of the drilling times in all drilled directions:

$$T_{PDk} = \sum_{j=1}^{4} \sum_{k=1}^{n_{dd}} n_k \times \frac{d_{kj}}{12{,}732} \times t_j/(-0.0002 \times d_k^2 + 0.0141 \times d_k + 0.1354) \tag{46}$$

thus

$$c_{cD} = \sum_{j=1}^{4} \sum_{k=1}^{n_{dd}} p_{DBk}/450 \times n_k \times \frac{d_{ij}}{12{,}732} \times t_j/(-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) \tag{47}$$

The drill bit unit rate per minute is presented in Table 8.

d	[mm]	14	18	22	26	32
Unit rate p_{DBk}	[€/min]	0.09	0.14	0.16	0.26	0.37

Table 8. Drill bit unit rate [€/min]

c_{EnD} is the cost of the energy used by the drill heads. The total power consumption of the drill considered in this thesis is 10 kW. At an energy unit cost of €0.1/kWh we get an energy consumption unit cost c_{EnD} = €0.02/min. Other electronic equipments, such as conveyor motors, are disregarded.

u_D is the utilization ratio of the cost centre (set to 1).

The drilling function (37) assumes the form:

$$C_D = (4.65 + (r_f - 1) \times 0.4 + \sum_{r=1}^{r_f} max \sum_{i=1}^{3} (n_{ri} - 1) \times 0.1 + L/20{,}000 \; + \; \big(2.4 + (r_s - 1) \times 0.4 + \sum_{r=1}^{r_s} (n_{r4} - 1) \times 0.1 + 2 \times L/20{,}000\big) + \sum_{i=1}^{r_f} \max \sum_{j=1}^{3} n_{ij} \times \frac{d_{ij}}{12{,}732} \times t_j / (-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) + \sum_{i=1}^{r_s} n_{is} \times \frac{d_{i4}}{12{,}732} \times t_4 / (-0.0002 \times d_{i4}^2 + 0.0141 \times d_{i4} + 0.1354 \;)) \times (0.46 + 0.34 + 0.01 + 0.21 \; + 0.31)/1 + \sum_{j=1}^{4} \sum_{k=1}^{n_{dd}} p_{DBk}/450 \times n_k \times \frac{d_{kj}}{12{,}732} \times t_j / (-0.0002 \times d_{kj}^2 + 0.0141 \times d_{kj} + 0.1354) + (\sum_{i=1}^{r_f} \max \sum_{j=1}^{3} n_{ij} \times \frac{d_{ij}}{12{,}732} \times t_j / (-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) + \sum_{i=1}^{r_s} n_{is} \times \frac{d_{i4}}{12{,}732} \times t_4 / (-0.0002 \times d_{i4}^2 + 0.0141 \times d_{i4} + 0.1354 \;) \times 0.02) \quad [€]$$
(48)

Fig. 27 presents drilling unit rates for different drill bit sizes in the processing situation.

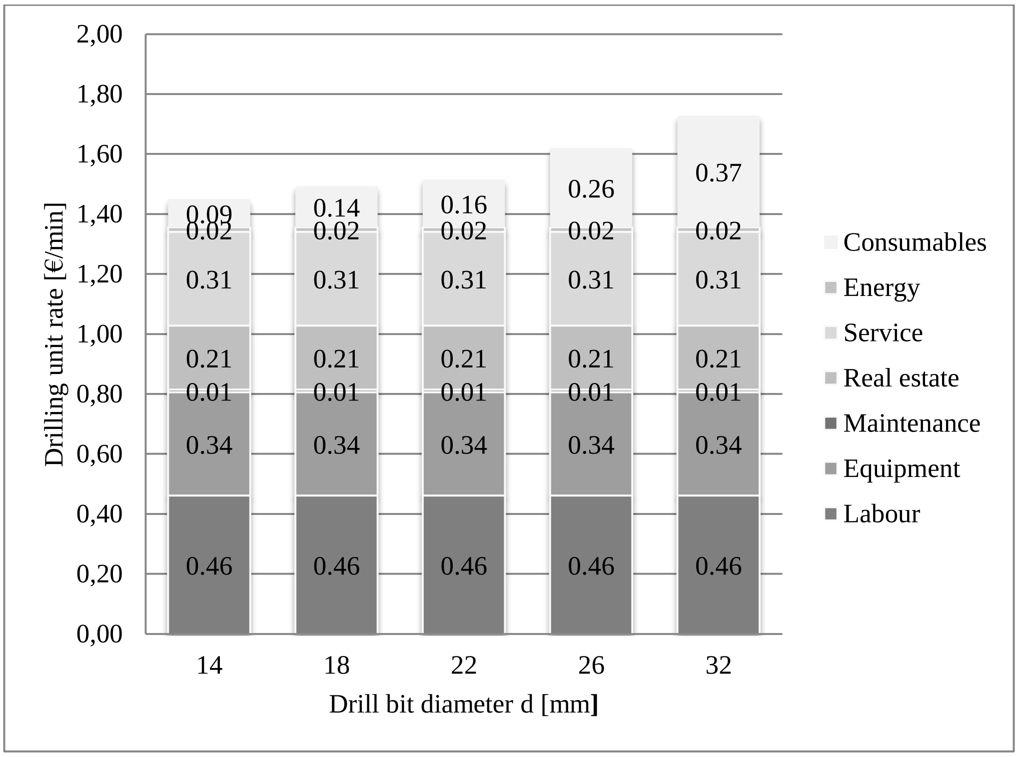


Fig.27. Cost component distribution of drilling unit rate, processing situation

4.5.7 Coping

Slots, notches, bevels and different shapes of holes are supposed to be executed with coping equipment, which uses flame cutting technology.

Description of the process:

The process starts when the operator does the set-up for the executed processes on the main profile in the NC control unit. The main profile is fixed to the clamps of the coping equipment and moved to the right position to start the coping. The torch moves to the starting point of the coping track, the flame is ignited, and coping starts. After coping the track, the torch is put out, it moves back to the stand-by position, and the main profile is transferred to the next coping position or it leaves the equipment.

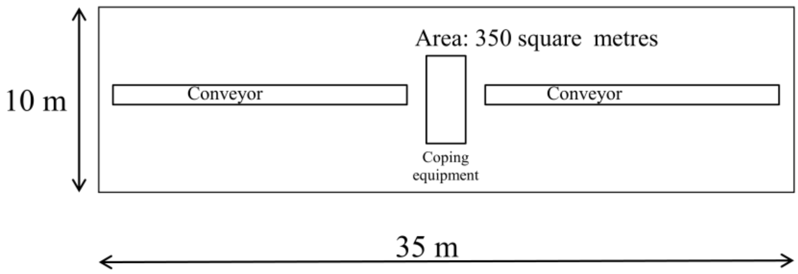


Fig. 28. Lay-out of coping cost centre.

The coping cost function can be expressed as:

$$C_{Co} = (T_{NCo} + T_{PCo}) \times \left(c_{LCo} + c_{EqCo} + c_{MCo} + c_{RECo} \ \ + c_{SeCo}\right)/u_{Co} + T_{PCo} \times (c_{CCo} + c_{EnCo}) \quad (49)$$

Of the non-productive time, 4.0 min is taken up by set-up, 0.5 min by moving the torch to and from the coped cut, and 0.5 min by igniting the torch and pre-heating. Splashes are removed from all coped cuts of the main profile after it has left the equipment. It is assumed to take 1 minute per metre. Thus,

$$T_{NCo} = 4 + n_{Co} \times (0.5 + 0.5 + 0.5) + L/20{,}000 + \sum_{i=1}^{n_{Co}} L_{Coi} \times 0.001 \ \ \text{[min]} \quad (50)$$

where n_{Co} is the total number of individual coped cuts, L is the length of the profile, and L_{Coi} is the length of the coped cut i.

T_{PCo} is coping time. The same process as in Paragraph 4.5.3 for flame cutting is assumed here.

Cutting time can be derived from the function

$$T_{PCo} = \sum_{i=1}^{n_{Co}} L_{Coi} / v_{Coi} \quad \text{[min]} \quad (51)$$

where L_{Co} [mm] is the length of each individual coped track, and v_{Co} is the coping speed of the used plate thickness [mm/min]. According to Function (14), the productive time can be presented in the form:

$$T_{PCo} \ = \ \sum_{i=1}^{n_{Co}} L_{Coi}/(-4.1939 \times t_i \ + \ 658.67) \quad (52)$$

where t_i is the thickness [mm] of the plate i.

c_{LCo} is the unit labour cost of the coping process. One equipment operator is assumed to execute the process at an hourly rate of €27.68 or for €0.46/min.

c_{EqCo} is the equipment cost derived from Function (2). The equipment consist of in and out feeding conveyors, a portal frame with a movable torch unit for flame cutting, power supply and an NC control unit. The investment rate i is set to 5%, and useful life of equipment n to 20 years. P is assumed to be €430,000 € (Ficep), and resale value €0. These figures produce an annual equipment installment of €34,504 or €0.29/min.

c_{MCo} is the annual maintenance cost of equipment, set to €1,000 that translates into €0.01/min.

c_{RECo} is the real estate investment cost derived from Function (2). The investment cost of the space for coping is, according to Fig. 28, 350 m^2 x €912/m^2 = €319,200, the resale deduction is 350 m^2 x €12/m^2 = €3,600, i is set to 5% and n to 50 years. These figures produce an annual real estate installment of €14,790 or €0.12/min.

c_{SeCo} is the real estate maintenance cost calculated as 300 m^2 x €72/(m^2a) = €21,600/a or €0.18/min.

The process presented in Paragraph 4.5.3. is chosen for coping. c_{CCo} is calculated from Function (15) as follows:

$$c_{CCo} = 0.12 + 0.1 + (1E - 05 \times {t_i}^2 + 0.001 \times t_i + 0.0224) \times 4.18 \ \text{[€/min]} \quad (53)$$

c_{EnCo} is the cost of the energy used by the flame cutting torch and conveyors. In this thesis these cost components are disregarded.

u_{Co} is the utilisation ratio of the cost centre (set to 1).

Function (49) assumes the form:

$$C_{Co} = (4 + n_{Co} \times (0.5 + 0.5 + 0.5) + L_O/20{,}000 + \sum_{i=1}^{n_{Co}} L_{Coi} \times 0.001 + \sum_{i=1}^{n_{Co}} L_{Coi}/(-4.1939 \times t_i + 658.67)\ ) \times (0.46 + 0.29 + 0.01 + 0.12 + 0.18)/1 + \sum_{i=1}^{n_{Co}} L_{Coi}/(-4.1939 \times t_i + 658.67) \times (0.22 + 1E - 05 \times t_i^2 + 0{,}001 \times t_i + 0{,}0224) \times 4.18) \ [€] \quad (54)$$

==>

$$C_{Co} = (4 + n_{Co} \times 1.5 + L_O/20{,}000 + \sum_{i=1}^{n_{Co}} L_{Coi} \times 0.001 + \sum_{i=1}^{n_{Co}} L_{Coi}/(-4.1939 \times t_i + 658.67)\ ) \times 1.06 + \sum_{i=1}^{n_{Co}} L_{Coi}/(-4.1939 \times t_i + 658.67) \times (0.22 + 1E - 05 \times t_i^2 + 0{,}001 \times t_i + 0{,}0224) \times 4.18) \ [€] \quad (55)$$

Distribution of cost of coping during non-processing situation is presented in Fig. 29, and in processing situation by plate thickness in Fig. 30.

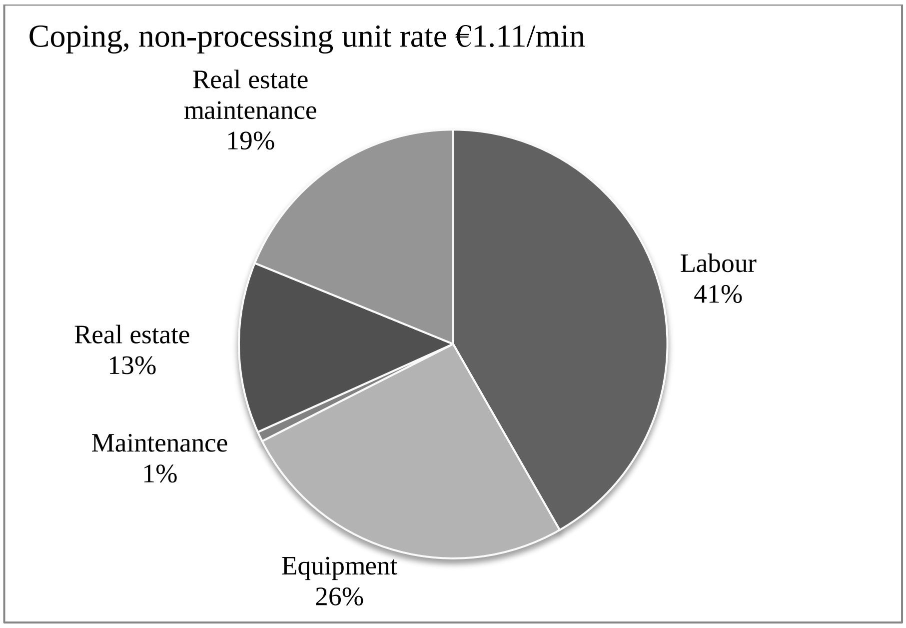


Fig. 29. Cost component distribution of coping unit rate, non-processing situation.

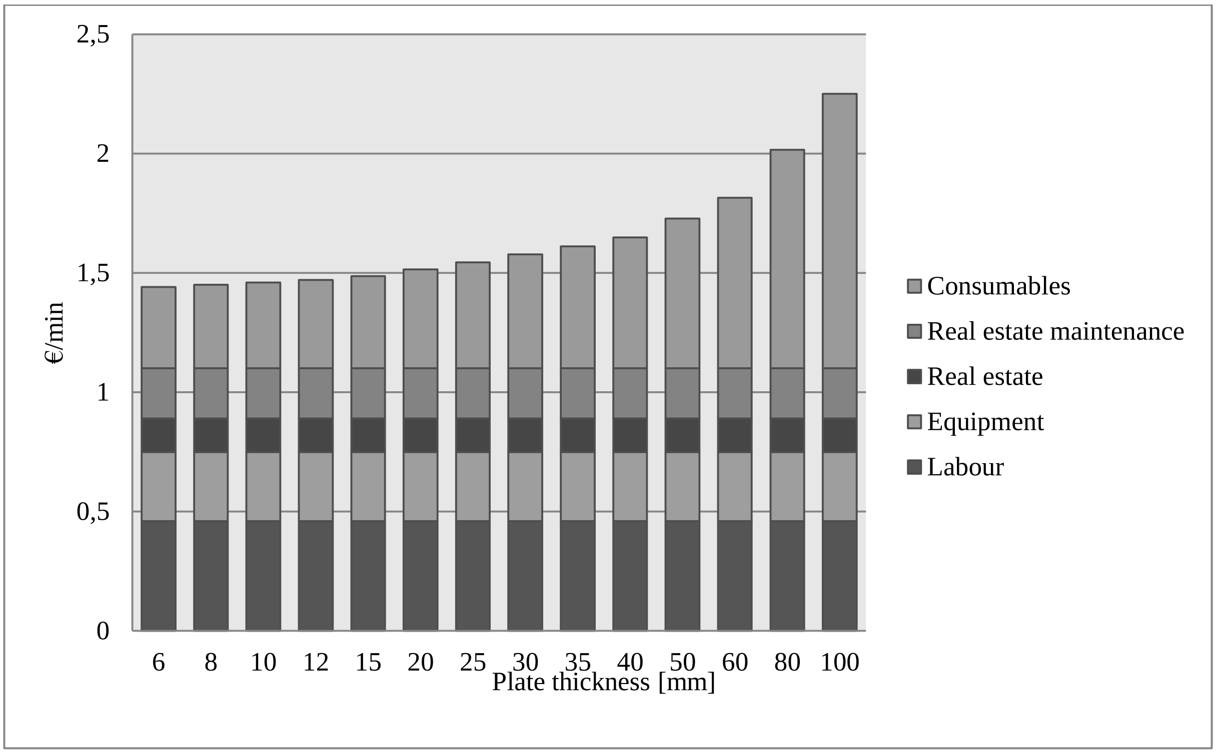


Fig. 30. Cost component distribution of coping unit rate [€/min] depends on plate thickness [mm], processing situation

4.5.8 Fabrication of parts

Here part refers to an object to be welded or bolted, i.e. assembled, to the main profile in order to fabricate a joint or to reinforce the main profile. Two types of parts are considered in this thesis: angle profiles and plates. Fabrication of both types includes blasting, cutting to appropriate dimensions and hole forming. Blasting is executed as described in Paragraph 4.5.2. Parts fabricated from plate are cut from a bigger raw plate using the plasma or flame cutting process described in Paragraph 4.5.3. The same process is applied in forming the holes of plate parts. Holes of angle profiles are punched, and the profile is cut to appropriate length in punching/shearing equipment.

The part fabrication cost functions can be presented as

$C_{PF} = C_{SM} + (C_B + C_{Cu})/u_{PF}$, for plates using cutting (56)

$C_{PF} = C_{SM} + (C_B + C_{Pu})/u_{PF}$, for angles using punching and shearing (57)

Material cost C_{SM} and blasting cost C_B functions are presented in Paragraphs 4.5.1 and 4.5.2, respectively. Functions (5) and (8) are used for plate material and blasting, respectively.

As the cutting process was described earlier, only Function (17) for plasma and Function (19) for flame cutting are presented here.

$C_{PF} = C_{SM} + L\times 0.000363 + 3.96 + L_{CuA}/(6.76 \times t^2 - 368.84\times t + 6{,}178.64) + L_{CuA}/(17.84\times t^2 - 973.74\times t + 16{,}311.60)$, for plates with t ≤ 30 mm (58)

$C_{PF} = C_{SM} + L\times 0.000363 + (3 + L_{CuA}/(-4.1939 \times t + 658.67))\times 1.32 + L_{CuA}/(-4.1939 \times t + 658.67) \times (0.22 + (4.18\times 10^{-5} \times t^2 + 4.18\times 10^{-3}\times t + 0{,}094)$, for plates with t > 30 mm (59)

where L [mm] is the length of the plate part to be blasted. As the direction of movement of the plate during the blasting process is not known, the largest dimension of the plate is considered. L_{CuA} [mm] is the total length of the track to be cut, including also the length of the hole tracks. t [mm] is thickness of the plate.

Description of the punching-shearing process

The operator makes the set up of the equipment. The raw material (angle bar) is fed into the equipment at constant speed (v_f = 20 000 [mm/min]). The bar is clamped and holes are punched, one at a time. Both flanges can be punched during the same in feeding session. If different sizes of holes are to be punched, the operator changes the punching tool. After punching the holes, the bar is conveyed forward and a shear guillotine cuts the bar to the proper length.

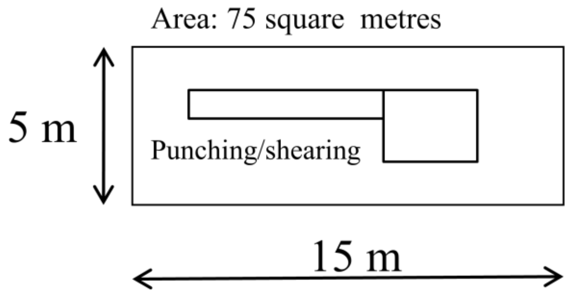


Fig. 31. Lay-out of punching-shearing cost centre.

In the angle manufacturing cost function (61), material cost C_{SMa} assumes the form:

$$C_{SM} = L \times u_{ca} \text{ [€]} \quad (60)$$

where L is the length of the angle and u_{ca} is unit price [€/m] of the angle obtained from Appendix 9.3.

C_{Pu} is the cost of the punching-shearing, which can be derived from the function:

$$C_{Pu} = (T_{NPu} + T_{PPu}) \times (c_{LPu} + c_{EqPu} + c_{MPu} + c_{REPu} + c_{SePu})/u_{PF} \quad (61)$$

The costs of consumables and energy are disregarded.

Non-productive time T_{Npu} includes changing of the tool which is set to 4 [min]. The feeding time included in productive time T_{Ppu} is calculated from the function $T_f = L_A/20{,}000$ [min]. Punching and shearing are assumed to take 0.1 [min/hole] and 0.1 [min/cut], respectively. Only the time used to cut one bar end is included. Thus, the total time used is given by

$$T_{NPu} + T_{PPu} = (n_z - 1) \times 4 + L/20{,}000 + n_h \times 0.1 + 0.1 \text{ [min]} \quad (62)$$

where n_z is the number of different sizes of holes and n_n is the number of holes.

c_{Lpu} is the unit labour cost of the punching/shearing process. One equipment operator is assumed to execute the process at an hourly rate of €27.68/h or for €0.46/min.

c_{EqPu} is the equipment cost derived from Function (2). The equipment consists of an infeed conveyor, power supply and an NC control unit. The investment rate i is set to 5%, and useful life of equipment n to 20 years. P_{Pu} is assumed to be €280,000 (Voortman), and resale value €0. These figures produce an annual equipment installment of €22,468 or €0.19/min.

c_{Mpu} is the annual maintenance cost of equipment set to €1,000 or €0.01/min.

c_{REPu} is the real estate investment cost derived from Function (2). The investment cost of the space for coping is, according to Fig. 31, calculated as 75 m^2 x €912/m^2 = €68,400, the resale deduction is 75 m^2 x €12/m^2 = €900, i is set to 5% and n to 50 years. These figures produce an annual real estate installment of €3,692 or €0.03/min.

c_{SePu} is the real estate maintenance cost calculated as 75 m^2 x €72/(m^2a) = €5,400/a or €0.04/min.

u_{PF} is the utilisation ratio of the cost centre (set to 1).

Function (62) assumes the form:

$$C_{Pu} = ((n_z - 1) \times 4 + L_A/20{,}000 + n_h \times 0.1 + 0.1\,) \times (0.46 + 0.19 + 0.01 + 0.03 \; + 0.04)/1 \text{ [€]} \quad (63)$$

and finally Function (57) can be presented in the following form:

$$C_{PFa} = L \times u_{ca} + L \times 0.000363 + ((n_z - 1) \times 4 + L/20{,}000 + n_h \times 0.1 + 0.1\,) \times (0.46 + 0.19 + 0.01 + 0.03 \; + 0.04) \text{ [€]} \quad (64)$$

Distribution of cost of punching-shearing is presented in Fig. 32.

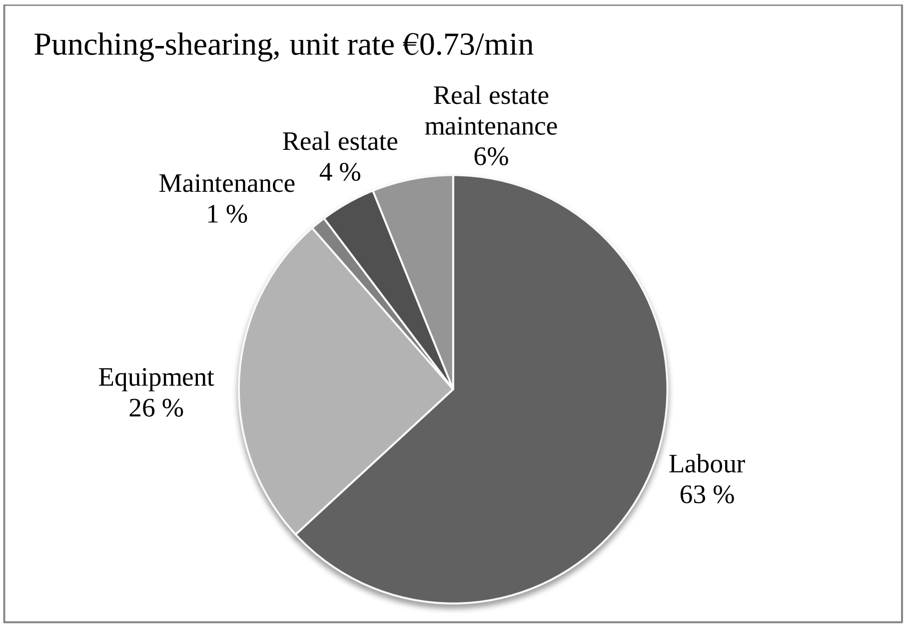


Fig. 32. Cost component distribution of punching-shearing unit rate.

4.5.9 Assembling

Here assembling means welding or bolting parts to the main profile. Welding is executed in two phases: first a part is tack welded and then the welding procedure required by the designer is executed. The position of the main profile during welding is assumed to be such that welding can be done in a flat position. Bolting is executed by putting the bolted part in place and assembling bolts, nuts and washers and tightening them to the defined moment.

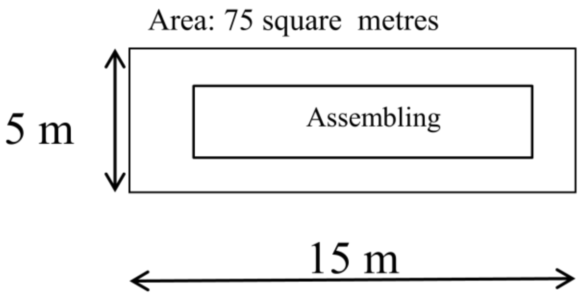


Fig. 33. Lay-out of assembling cost centre.

The assembly cost function may be expressed as:

$$C_{PA} = (T_{NPA} + T_{PPA}) \times \left(c_{LPA} + c_{EqPA} + c_{MPA} + c_{REPA} + c_{SePA}\right)/u_{PA} + c_{CPA} + T_{PPA} \times c_{EnPA} \quad (65)$$

Non-productive time and maintenance costs of assembly are disregarded. Consumables are regarded as non-time-related.

Assembly by welding

The results of Schreve et al. (1999) are applied to tack welding. They examined tack welding of parts in a jig. The assembled products were batched, so it can be assumed repetition affected the results. In this thesis batch size is 1 and no jig is used. The following measures taken by Schreve et al. are applied (Schreve et al., 1999, p. 733, Tables 1, 2 and 3):

- Deburring of parts before assembly, 0.5 [min/part]
- Insertion of a part in the main profile. In this thesis part size is assumed to be between 300 and 1 000 [mm], and alignment with other parts is critical. Table 2 of Schreve et al. gives an insertion time of 0.5 [min].
- Fastening and unfastening of the part with a clamp, 0.18 and 0.09 [min/part], respectively.
- Tacking, 0.09 x N_{tack} + 0.05 [min/part], N_{tack} is the number of tacks/part, and is here assumed to be 3.

Total tacking time per part is

$$T_{PTa} = 0.5 + 0.18 + 0.09 + 0.5 + 0.09 \times 3 + 0.05 = 1.59 \text{ [min]} \quad (66)$$

CostComp software (2008) was used to calculate welding times. Gas metal arc welding with mixed gas (MAG M) was chosen as the welding process of this thesis. Fillet weld and single-bevel butt weld were also considered. The welding position is assumed to be flat.

Using a deposit rate of 28% and wire size 1.0 [mm], CostComp produces the following data concerning a fillet weld:

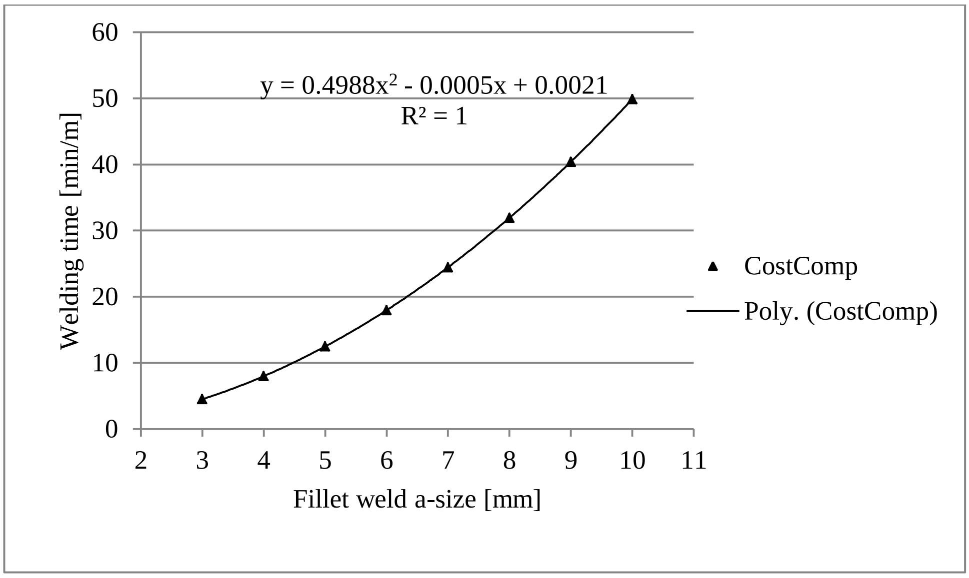


Fig. 34. Welding time [min/m] as a function of fillet weld size (CostComp).

By using the poly line presented in Fig. 34, welding time can be derived from the function

$$T_{Pfw} = L_{fw}/1{,}000 \times (0.4988 \times a^2 - 0.0005 \times a + 0.0021) \text{ [min]} \quad (67)$$

where L_{fw} is the length of the fillet weld [mm] and a is the size of the weld [mm].

The corresponding figure for a single-bevel butt weld is given in Fig. 35. The gap is set to 0 and the bevel angle to 45º. Depth of the weld refers to the distance from the surface of the plate to the bottom of the weld.

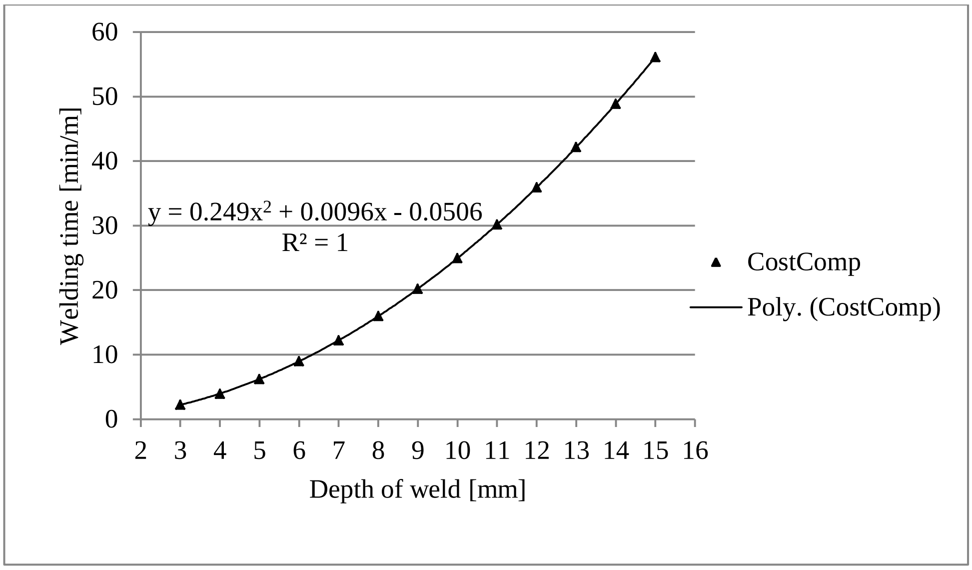


Fig. 35. Welding time [min/m] as a function of single-bevel butt weld depth [mm] (CostComp).

By using the poly line presented in Fig. 35, welding time can be derived from the function

$$T_{Pbw} = L_{bw}/1{,}000 \times (0.249 \times b^2 + 0.0096 \times b - 0.0506) \text{ [min]} \quad (68)$$

where L_{bw} is the length of the single-bevel butt weld [mm] and b is the depth of the weld [mm].

Assembly by bolting

Bolting is carried out in the same cost centre as assembly welding. The process consists of inserting the part in place, inserting bolts in holes, inserting washers and nuts, and finally tightening the bolts.

The same time as in tack welding is applied to inserting the part in place, i.e. 0.5 [min]. The time applied to inserting the bolt, washer and nut, and tightening the bolt is 0.75 [min/bolt].

$$T_{Pb} = 0.5 + n_b \times 0.75 \text{ [min]} \quad (69)$$

where n_b is the total number of bolts.

c_{LPA} is the unit labour cost of the assembly process. One equipment operator is assumed to execute the assembly process at an hourly rate of €27.42 or for €0.46/min.

c_{EqPA} is the equipment cost derived from Function (2), where P is the investment cost of the MAG welding equipment. The investment rate i is set to 5%, and useful life of equipment n to 10 years. P is assumed to be €5,000, and resale value €0. These figures produce an annual equipment installment of €3,672 or €0.01 /min.

c_{REPA} is the real estate investment cost derived from Function (2). The investment cost of the space for assembling is, according to Fig. 33, calculated as 75 m^2 x €912/m^2 = €68,400, the resale deduction is 75 m^2 x €12/m^2 = €900, *i* is set to 5% and *n* to 50 years. These figures produce an annual real estate installment of €3,692 or €0.03/min.

c_{SePA} is the real estate maintenance cost calculated as 75 m^2 x €72/(m^{2}a) = €5,400 €/a or €0.04/min.

c_{CPA} is the non-time-related consumables cost of assembly. It includes the costs of welding wire, welding shield gas, and bolts, nuts and washers. Wire consumption is derived from the functions

$w_{cf} = L_{fw} \times a^2 \times 0.00000785$ [kg], for a fillet weld, and (70)

$w_{cb} = L_{bw} \times d^2/2 \times 0.00000785$ [kg], for a single-bevel butt weld (71)

The unit price of 1.0 [mm] solid wire is set to €1.91 €/kg (ESAB, OK Autrod 12.51).

Gas consumption is assumed to be 0.4 m^3/kg of wire (Lukkari, 2006), and the unit price is set to €11.10/m^3 (MISON® 25; Ar + 25 % CO_2 + 0.03 % NO), which results in a gas price of €4.44/kg of wire.

Thus, the cost of welding consumables may be derived from the functions

$c_{CPA} = L_{fw} \times a^2 \times 0.00000785 \times (1.91 + 4.44)$ [€], for a fillet weld, and (72)

$c_{CPA} = L_{bw} \times b^2/2 \times 0.00000785 \times (1.91 + 4.44)$ [€], for single-bevel butt weld (73)

The consumables cost of bolts, washers and nuts is calculated by Function (7). Appendix 9.4 is used for unit costs.

c_{EnPA} is the cost of the energy used by the welding equipment. With solid 1.0 mm wire and welding current parameters 200 A and 30 V, the resulting total power consumption of the equipment is 6 kW. With an energy unit cost of €0.1/kWh, the energy consumption unit cost c_{EnPA} = €0.01/min.

u_A is the utilisation ratio of the cost centre (set to 1).

The function for assembly cost (65) assumes two forms:

Assembly by welding

$$C_{PA} = (1.59 + L_{fw}/1{,}000 \times (0.4988 \times a^2 - 0.0005 \times a + 0.0021) + L_{bw}/1{,}000 \times (0.249 \times b^2 + 0.0096 \times b - 0.0506)) \times (0.46 + 0.01 + 0.03 \ + 0.04)/1 + (L_{fw} \times a^2 + L_{bw} \times b^2/2) \times 7.85 \times 10^{-6} \times (1.91 + 0.44) + (L_{fw}/1{,}000 \times (0.4988 \times a^2 - 0.0005 \times a + 0.0021) + L_{bw}/1{,}000 \times (0.249 \times b^2 + 0.0096 \times b - 0.0506) \times 0.01)) \ [€] \quad (74)$$

Assembly by bolts

$$C_{PA} = (0.5 + n_b \times 0.75) \times (0.46 + 0.01 + 0.03 \ + 0.04)/1 + \sum_{i=1}^{k} n_i \times (c_{Bi} + c_{Ni} + c_{wi}) \ [€] \quad (75)$$

Distribution of cost of assembling in non-processing situation is presented in Fig. 36.

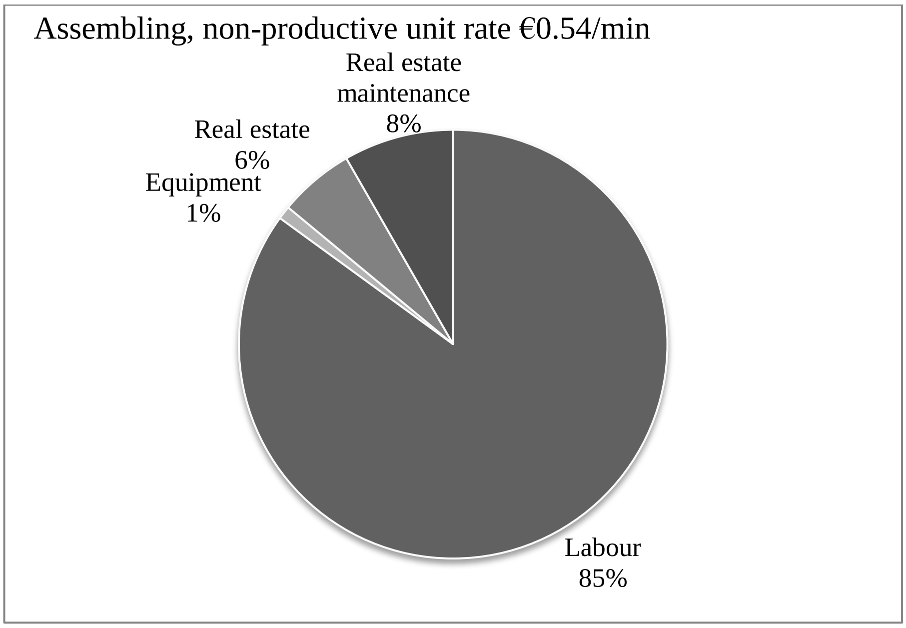


Fig. 36. Cost component distribution of assembling, non-productive situation.

4.5.10 Post-treatment and inspection

For post-treatment two processes are considered. Firstly, deburring of the edges of the main profile, and secondly inspection of the welds. The processes are executed in the same cost centre as assembling. The time for deburring is assumed to be 2.0 [m/min] = 0.0005 [min/mm].

The inspection method is defined by the designer. Test methods include visual testing (VT), radiograph testing (RT), ultrasonic testing (UT), penetrant testing (PT) and magnetic particle testing (MT). UT and MT are considered in this thesis. Testing is carried out by one worker, and the testing speed, including reporting, is assumed to be 1.0 [m/h] = 0.06 [min/mm] for UT, and 4.0 [m/h] = 0.015 [min/mm] for MT.

The post-treatment cost can be derived from the function

$$C_{PT} = T_{PPT} \times (c_{LPT} + c_{REPT} \ + c_{SePT})/u_{PT} \ [€] \quad (76)$$

c_{LPT} is the unit labour cost of the post-treatment process. One equipment operator is assumed to execute the process at an hourly rate of €27.32 or for €0.46/min.

c_{REPA} is the real estate investment cost derived from Function (2). The investment cost of the space for coping is calculated as 75 m^2 x €912/m^2 = €68,400 €, the resale deduction is 75 m^2 x €12/m^2 = €900, *i* is set to 5% and *n* to 50 years. These figures produce an annual real estate installment of €3,692 or €0.03/min.

c_{SePT} is the real estate maintenance cost calculated as 75 m^2 x €72/(m^{2}a) = €5,400/a or €0.04/min.

Function (76) can also be presented in the form:

$$C_{PT} = (L_{PT} \times 0.0005 + L_{UT} \times 0.06 + L_{MT} \times 0.015) \times (0.46 + 0.03 + 0.04)/1 \ [€] \quad (77)$$

where L_{PT} is the total length of the edges to be deburred, L_{UT} is the length of *UT*-tested welds, and L_{MT} is the length of the MT-tested welds.

Distribution of cost of post treatment process is presented in Fig. 37.

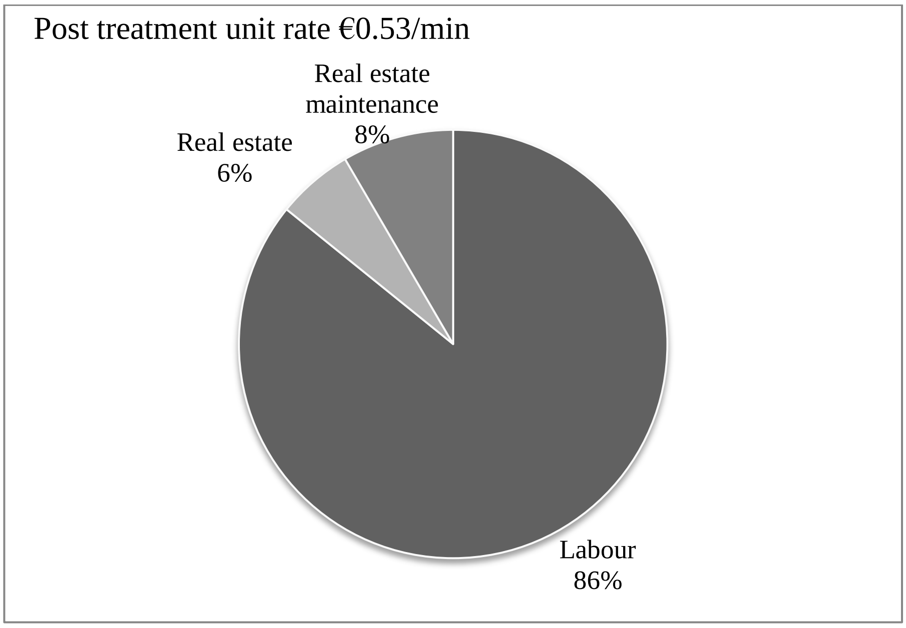


Fig. 37. Cost component distribution of post-treatment.

4.5.11 Coating

In this thesis coating process includes painting and drying subprocesses. Painting is carried out with a spray gun. Structures are painted in a separated space. When the painting system requires more than one paint film, the assembly is assumed to be kept indoors to minimise the time required for over-coating dryness. Before the assembly can be moved outdoors, the top film has to be touch-dry.

Painting is done by one worker, who uses a spray gun connected to the paint equipment. The flow through the gun depends both on the size of the tip through which the paint is sprayed and the hydraulic pressure. Paint manufacturers give their recommendations for tip size. In this thesis the size is set to 0.4 [mm] (0.015 inch) (Teknos). The other parameter of the tip is the angle of the paint spray. This is set to 50°. Over-spraying can account for 80% of paint consumption (Graco).

The size of the tip and hydraulic pressure together determine the flow of paint through the gun. Each tip-size has an optimum pressure which results in a constant flow [litres/min]. In this thesis with a 0.4 mm tip the flow is set to 0.9 [l/min] = 900,000 [mm^3/min] (Graco).

The designer determines the paint system on the basis of information about the paint type, the number and thickness of each individual film, and the surface cleaning process prior to painting. Film thickness is given as dry film thickness (DFT). In this thesis cleaning class Sa2½ is considered. That quality can be achieved by blasting.

To estimate the actual volume of paint to be sprayed, the coverage data of International Marine Coatings are applied (International Marine Coatings, 2010). In the case of a blasted simple structure, spray painted in a well ventilated indoor space with a single or a two component paint, the coverage data present the components of the total loss t_{loss} as loss due to the surface profile, distribution, application and wastage. The following function was derived from the coverage data for this thesis:

$$t_{loss} = 10\,microns\ + 20\% \times DFT + \ 5\% \times DFT + 5\% \times DFT \text{ [microns]} \tag{78}$$

$$t_{loss} = 0.01\ + 0.3 \times DFT \text{ [mm]} \tag{79}$$

The wet film thickness (WFT) which has to be sprayed depends on the volume solids of the paint. For the paints considered in this thesis it varies between 40% and 50%.

Description of the process:

The painting is executed by one worker. The assembly lays on supports and is not moved during painting. When the required paint thickness has been applied, the assembly will be left to dry in a space whose dimensions equal the *length of the assembly x twice the narrowest width dimension*.

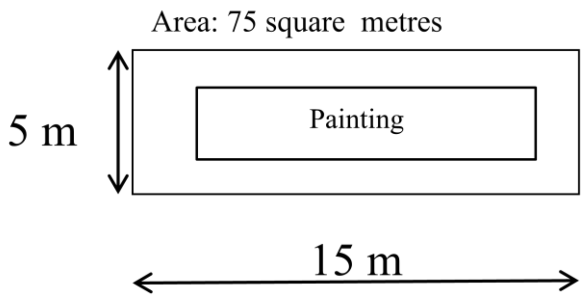


Fig. 38. Lay-out of the painting cost centre.

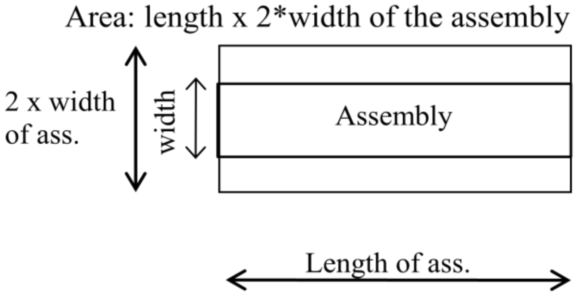


Fig. 39. Lay-out of the drying cost centre.

The painting cost function disregards the equipment, maintenance, and energy costs due to their assumed minor influence on the total cost. Non-productive time is not considered here either.

Thus, the painting cost function assumes the form:

$$C_P = T_{PP} \times (c_{LP} + c_{REP} \; + c_{SeP})/u_P + c_{CP} \text{ [€]} \tag{80}$$

The cost of the consumable (paint) is non-time-related.

Productive painting time, $T_{PP,}$ is calculated using the required wet film thickness and the paint flow through the spray gun.

$$T_{PP} = \sum_{i=1}^{n_f} 1/v_{si} \times (DFT_i + t_{iloss})/f_{pg} \times A \text{ [min]} \tag{81}$$

where n_f is number of films, v_{si} is the volume solids of paint of film i[decimal, ≤1], DFT_i is the dry thickness of film *i* [mm], t_{iloss} is the total loss of film *i*, f_{pg} is the flow through the spray gun [mm^3/min], and *A* [mm^2] is the total area of assembly to be painted.

The requirements for the paint system in this thesis are class C3/M according to EN ISO 12944-5. Appendix 9.5 presents four different paint types with film structures that meet the C3/M requirements.

In the case of the alkyd painting system Function (81) gets assumes the form:

$$T_{PPAl} = (1/0.48 \times (0.08 + 0.01 + 0.3 \times 0.08) + 2 \times 1/0.45 \times (0.04 + 0.01 + 0.3 \times 0.04))/ 900\,000 \times A \text{ [min]} \tag{70}$$

$$T_{PPAl} = 0.513/900{,}000 \times A \text{ [min]} \tag{82}$$

The factor 0.513 [mm^3] of the function means total consumption of paint per 1 mm^2 to obtain the specified DFT of 160 microns (0.160 mm).

Accordingly, the following functions can be written:

$$T_{PPEp} = 0.481/900{,}000 \times A \text{ [min], for epoxy (DFT 160 microns)} \tag{83}$$

$$T_{PPPu} = 0.352/900{,}000 \times A \text{ [min], for polyurethane (DFT 120 microns)} \tag{84}$$

$$T_{PPAc} = 0.522/900{,}000 \times A \text{ [min], for acryl (DFT 160 microns)} \tag{85}$$

c_{LP} is the unit labour cost of the painting process. One worker is assumed to execute the process at an hourly rate of €27.59 or for €0.46/min.

c_{REP} is the real estate investment cost derived from Function (2). The investment cost of the space for coating is, according to Fig. 38, 75 m^2 x €912/m^2 = €68,400, the resale deduction is 75 m^2 x €12/m^2 = €900, i is set to 5% and n to 50 years. These figures produce an annual real estate installment of €3,692 or €0.03/min.

c_{SeP} is the real estate maintenance cost calculated as 75 m^2 x €72/(m^2a) = €5,400/a or €0.04/min.

c_{CP} is the consumables cost of painting consisting of the price of paint (both components in the case of two-component) and solvent. The amount of paint can be calculated by adapting Function (81) as follows:

$$c_{CP} = \sum_{i=1}^{n_f} uc_p/v_{si} \times (DFT_i + T_{iloss}) \times A \text{ [€]} \tag{86}$$

where uc_p is the unit cost of paint [€/mm^3]. Appendix 9.5 gives the unit prices (Teknos) for the chosen paints in the colour of the lowest price group. Thus we get:

$$c_{CPAl} = 3.87E-06\ x\ A \text{ [€] for the alkyd system} \tag{87}$$

$$c_{CPEp} = 4.11E-06\ x\ A \text{ [€] for the epoxy system} \tag{88}$$

$$c_{CPPu} = 4.58E-06\ x\ A \text{ [€] for the polyurethane system} \tag{99}$$

$$c_{CPAc} = 5.22E-06\ x\ A \text{ [€] for the acryl system} \tag{90}$$

Function (80) can now be presented in the form:

$$C_P = \sum_{i=1}^{n_f} 1/v_{si} \times (DFT_i + t_{iloss})/f_{pg} \times A \times ((0.46 + 0.03 \ + 0.04)/1 + \sum_{i=1}^{n_f} uc_p/v_{si} \times (DFT_i + t_{iloss}) \times A \text{ [€]} \tag{91}$$

Painting function (91) can assume the following forms for different paint systems:

$$C_P = 4.17E-06 \times A \text{ [€] for the alkyd system (AK)} \tag{92}$$

$$C_P = 4.39E-06 \times A \text{ [€], for the epoxy system (EP)} \tag{93}$$

$$C_P = 4.79E-06 \times A \text{ [€], for the polyurethane system (PUR)} \tag{94}$$

$$C_P = 5.53E-06 \times A \text{ [€], for the acryl system (AY)} \tag{95}$$

Distribution of cost of different painting systems without drying are presented in Fig. 40.

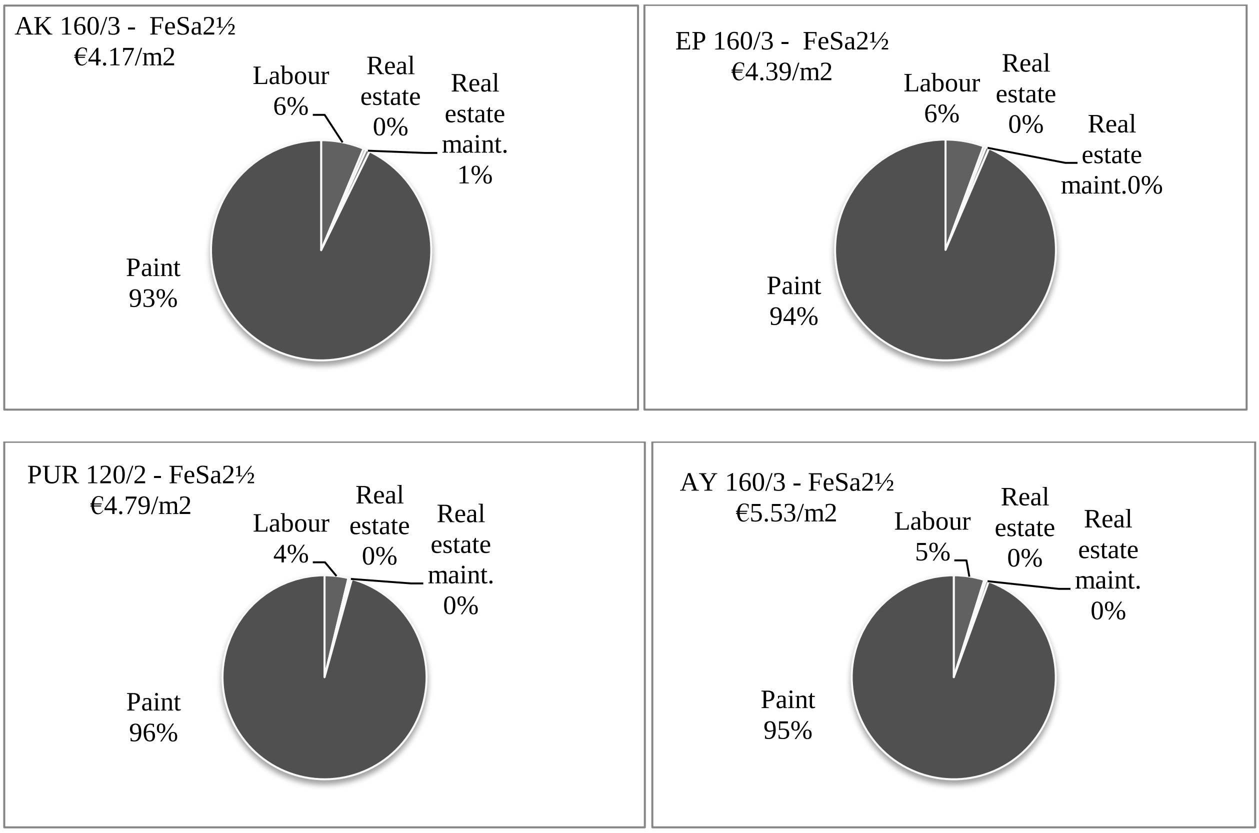


Fig. 40. Unit costs of different painting systems (drying not included).

Drying

A painted assembly needs to dry between film additions (for re-spraying) and before further handling (touch dryness). The drying times of chosen paints are given in Appendix 9.5. The cost function of drying consists of space cost, i.e. real estate and maintenance cost. Thus:

$$C_{Dy} = \sum_{i=1}^{n_f} T_{Dyi} \times (c_{ReDy} + c_{SeDy}) \times A_{Dy} \text{ [€]} \tag{96}$$

where T_{Dyi} [min] is the drying time of film i, and A_{Dy} is the area required for drying of the assembly [m^2]. A_{Dy} is taken in this thesis as $A_{Dy} = L_A \times 2 \times W_{Amin}$ [m^2], where L_A [m] is the length of the assembly, and W_{Amin} [m] is the narrowest width dimension of the assembly.

c_{REDy} is the real estate investment cost derived from Function (2). The investment cost of the space for drying is €912/m^2, the resale deduction is €12/m^2, *i* is set to 5% and *n* to 50 years. These figures produce an annual real estate installment of €49/(m^{2}a) or €0.00041/(m^{2}min).

c_{SeDy} is the real estate maintenance cost, which is €72/(m^{2}a) or €0.00060 /(m^{2}min).

Drying function (96) can now be presented in the form:

$$C_{Dy} = \sum_{i=1}^{n_f} T_{Dyi} \times 0.00101 \times L_A \times 2 \times W_{Amin} \text{ [€]} \tag{97}$$

For the paint systems shown in appendix 9.5 the final coating function assumes these forms:

$C_{Dy} = 0.36 \times L_A \times W_{Amin}$ [€] for the alkyd paint system (98)
$C_{Dy} = 1.7 \times L_A \times W_{Amin}$ [€] for epoxy the paint system (99)
$C_{Dy} = 3.28 \times L_A \times W_{Amin}$ [€] for the polyurethane paint system (100)
$C_{Dy} = 0.84 \times L_A \times W_{Amin}$ [€] for the acryl paint system (101)

4.5.12 Transporting

Transportation of assemblies can be carried out by truck, train or ship. Truck is the most flexible mode and does not usually require intermediate unloading and reloading. The capacity of rail transport is huge, but the workshop or site very seldom has a siding that eliminates the need of intermediate loading and final transporting by truck. For overseas transport ship is usually the only possible solution.

This thesis examines domestic truck transportation with a Euro trailer. The internal dimensions of the Euro trailer are L x W x H = 13.62 x 2.48 x 2.70 m^3 (DHL) and its volume 91 m^3. The maximum load it can carry is 24 tonnes. In some countries the road weight limitations may be lower. In this thesis two constraints are set for the cargo: maximum weight of the total cargo must be below 24,000 kg, and maximum volume below 91 m^3. This leads to a limit ratio of 264 kg/m^3. If the weight/volume ratio of the assembly is below or equal to this limit ratio, then the cost of transportation will be determined by volume, and if above, it is determined by weight. Here, volume is calculated for a rectangular box with the external dimensions of the assembly assuming no overlap during the loading of assemblies.

The cost curves for volume base transportation, Fig. 41, and weight base transportation, Fig. 42, can be drawn based on an offer received from a domestic carrier:

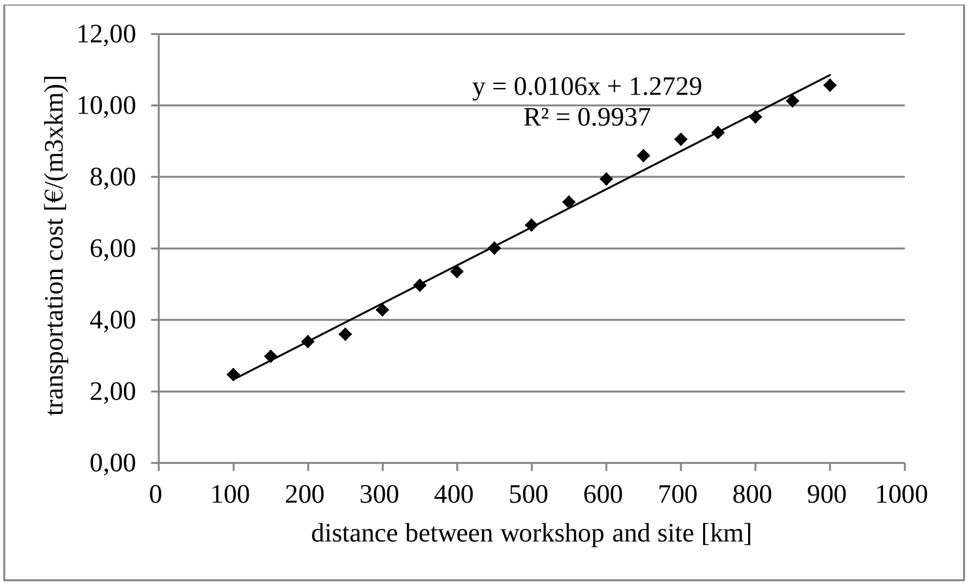


Fig. 41. Unit cost of transporting based on volume.

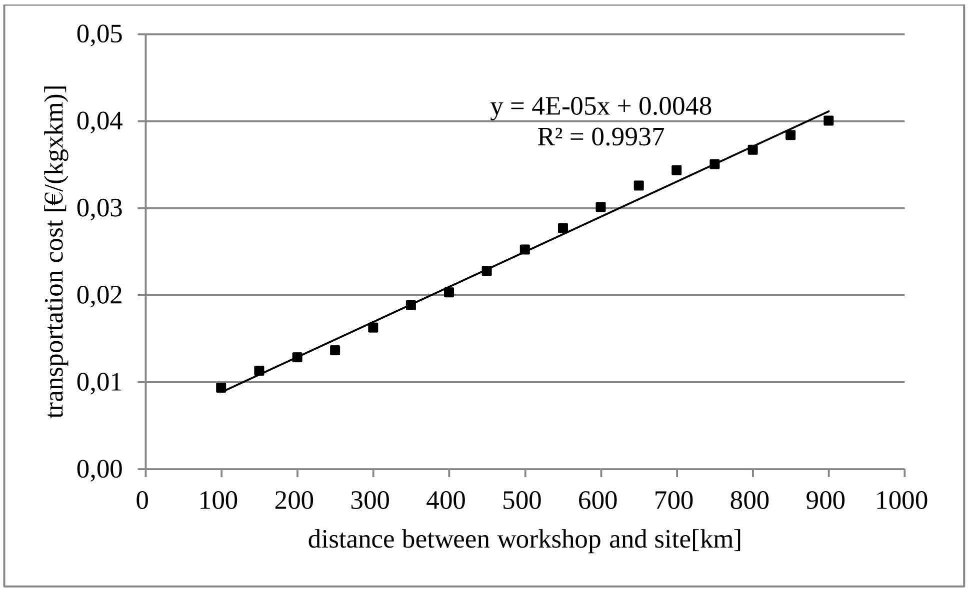


Fig. 42. Unit cost of transporting based on weight.

The cost functions of the transportation of the assembly can be presented in the following forms:

$$C_T = V_A \times (0.0106 \times d_{ws} + 1.2729)\ [€] \tag{102}$$

$$C_T = W_A \times (0.00004 \times d_{ws} + 0.0048)\ [€] \tag{103}$$

where
C_T = cost of transporting [€]
W_A = weight of the assembly [kg]
V_A = volume of the assembly [m3], calculated on the basis of its external dimensions
d_{ws} = distance between workshop and site [km]

Equation (102) is used when W_A/ V_A is equal to or smaller than 264. Otherwise Function (103) is used.

4.5.13 Erecting

Here, erecting is defined as work carried out at site to join complete pre-manufactured assemblies together by bolting into a finished skeleton. In reality, the parts of assemblies may arrive to the site separately, particularly when subcontractors fabricate the parts. The cost of the assembling of the parts is presented in Paragraph 4.5.9.

In this thesis the erection of the steel skeleton is assumed to be done by installing each assembly individually to its final position in the skeleton. Optimisation of erection time might in some cases require joining assemblies into larger entities on the ground, and then lifting them in place. Such optimisation is typically done by the erecting company on site depending on local conditions.

The calculation of the erection cost is based on a study by Knuuttila (2011). In his study the erection time of a certain number of steel skeleton assemblies was examined, and the observations were analysed to determine the correlation between some chosen parameters and erection time.

Description of the erection resources:

Erection involves the following workers, tasks and equipment:

The fork lift driver unloads the assemblies from the truck, moves them to the storage area, and from there to the lifting area. One fork lift is used.

The rigger works on the ground in the lifting area and decides the order in which assemblies are lifted, informs the fork lift driver of it, attaches the lifting lines or hooks of the crane to the assembly, and gives the crane driver permission to start the lift. No special equipment is involved.

The Crane driver operates the crane during lifting and moves the crane to a new position between lifts if required. The crane driver operates the crane described later.

The joining group consists of two workers: the main joiner and his helper. They adjust the assembly in the correct position when it is lifted to its final location, fasten the bolts, release the lines or hooks, and give the crane driver permission to return the hook to the lifting area. Afterwards, they verify the straightness of the skeleton and drive the bolts to the designed tightness. The helper operates the man lift and passes the required bolts to the main joiner who executes the bolting. No special equipment is needed for erecting the columns of the first vertical tier, but other joints are installed using the man lift. A cordless impact wrench is used to tighten the bolts.

The foreman plans future works, orders material to the site, supervises the work, and communicates with other parties on site.

Description of the erecting process:

The fork lift driver moves the assembly from the storage area to the lifting area according to the request of the rigger. The rigger attaches the lines or hooks to the assembly and gives the crane driver permission to start the lift. The crane driver moves the assembly to its final location. The main joiner and his helper adjust the assembly and fasten the bolts or welds the seams. Thereafter, they release the lines or hooks and give the crane driver permission to return the main hook to the lifting area.

In this thesis it is assumed that the crane works only for one joining group, and that the critical path in relation to time is lifting the assembly, fastening the joints and returning the hook. Thus, the fork lift operations are done simultaneously and are part of the erecting cycle.

Erection cost is derived from the function:

$$C_E = T_E \times (c_{LE} + c_{EqE}) / u_E \tag{104}$$

where

C_E = cost of erecting of one assembly [€]

T_E = calculated duration of erecting cycle of an assembly [min], consisting of

T_{El} = time for lifting [min]

$T_{E\mathrm{j}}$ = time for joining [min]

T_{Em} = time for man lift moving [min]

T_{Er} = time for hook return [min]

c_{LE} = unit cost of labour [€/min]

c_{EqE} = unit cost of equipment [€/min]

u_E = efficiency factor

Erecting time

Erecting time consists of five (four in case of a column) phases: lifting the assembly from the lifting area to the final position, joining the assembly's front end, moving the man lift to the back end, joining the back end, releasing the hook and returning it to the lifting area. In the case of a column joining of the back end is omitted, but the workers still need to go to the top of the column to release the hook. Knuuttila reported three different tower crane speeds (Knuuttila, p. 22): 0.45 m/s (= 27 m/min) for lifting beams and braces, 0.27 m/s (= 16 m/min) for lifting columns, and finally 0.60 m/s (= 36 m/min) for returning the hook to the lifting area. The speeds assume a straight distance l_s [m] between the lifting area and the final position. As the nominal speeds of the tower crane were 1.33 m/s for vertical movement, 1.83 m/s for horizontal movement and 4.2 deg/s for rotating, the actual lifting speed is determined mainly by the behaviour of the assembly during lifting, which means that the actual speeds obtained from Knuuttila's report may also be used for mobile cranes.

A hypothesis was developed for correlation of amount of bolts and joining time in advance for joining assemblies. Six different types of joints were used. Time variation between different types of joints were studied, but no notable differences were found. Results of measurements showed rather wide variance in times, Fig. 43. The linear least square method gave R^2 = 0.49. Yet, it was decided to use two minimum values of the measured times per amount of bolts, since it had been possible to assemble the bolts within such time periods. These values and a curve derived from the values are shown in Fig. 44.

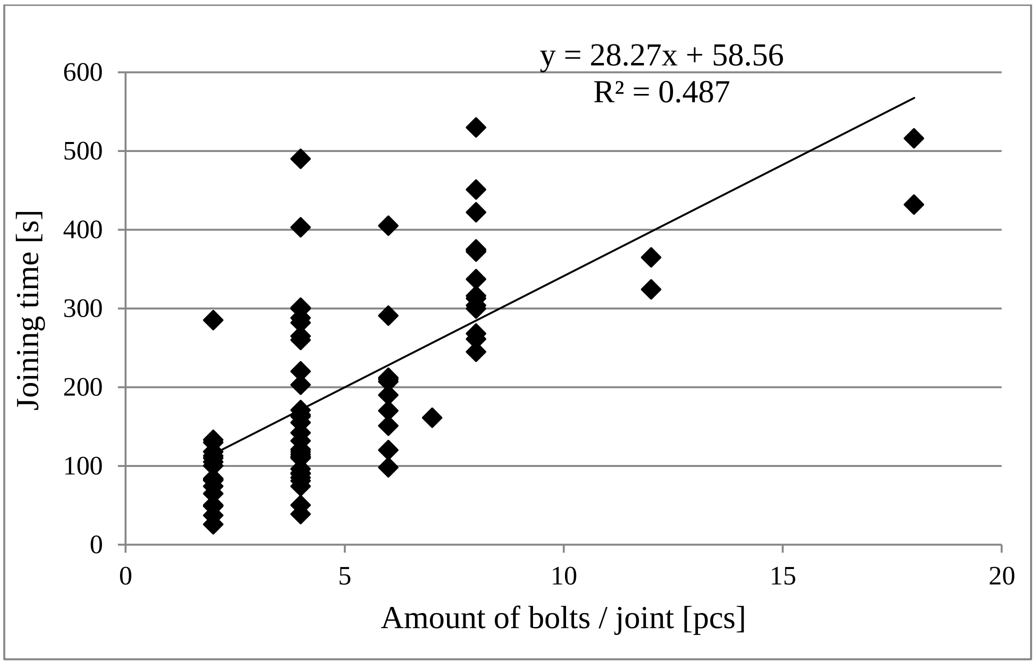


Fig. 43. Joining time of six different joint types (Knuuttila, 2011).

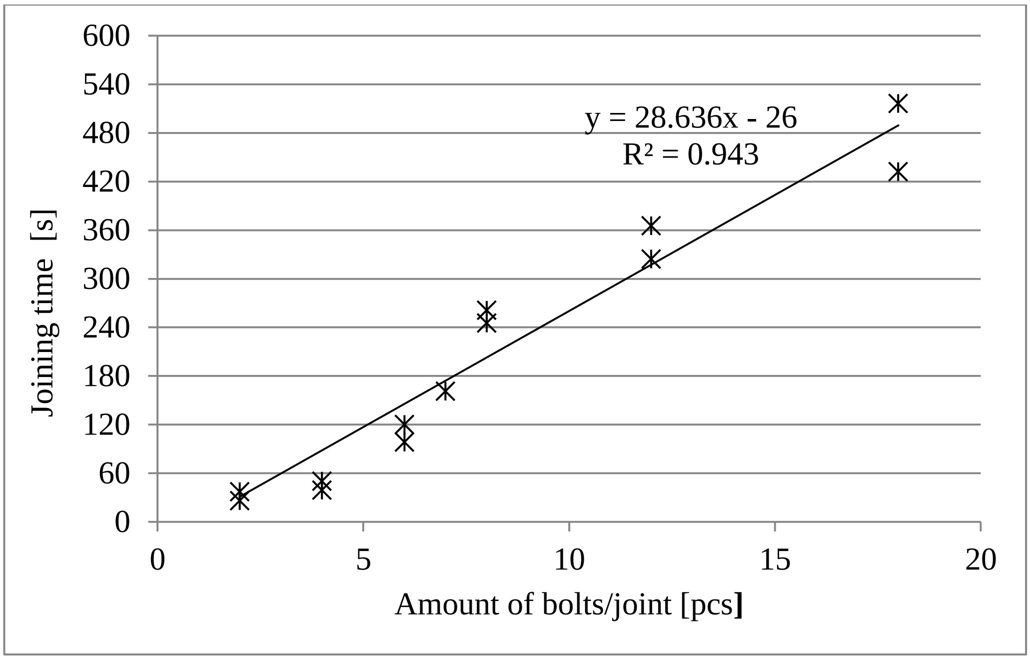


Fig. 44. Two minimum measured time values per amount of bolts in joint (Knuuttila, 2011).

Knuuttila came up with the following function:

$$T_{Ej} = 30 \times \ n_{bi} - 26 \text{ [s]} \tag{105}$$

which can be presented as

$$T_{Ej} = 0.5 \times \ n_{bi} - 0.42 \text{ [min]} \tag{106}$$

where

T_{Eb} = time spent joining with bolts [min]

n_{bi} = amount of bolts in joint i [pcs], ≥ 2

For calculating the time of moving the man lift from the front end to the back end of an assembly, a speed of 30 m/min (30,000 mm/min) is used. T_{Em} is calculated based on the length of the assembly:

$$T_{Em} = L_A/30{,}000 \text{ [min]} \tag{107}$$

where T_{Em} is time required to move the man lift [min] and L_A [mm] is the length of the assembly.

Thus, the function for erecting time can be presented as:

for beams and braces:

$$T_E = l_s/27 + 0.5 \times n_{b1} - 0.42 + 0.5 \times n_{b2} - 0.42 + L_A/30{,}000 + l_s/36 \text{ [min]} \tag{108}$$

for columns:

$$T_E = l_s/16 + 0.5 \times n_b - 0.42 + L_A/30{,}000 + l_s/36 \text{ [min]} \tag{109}$$

As there are many disturbances at the site due to weather conditions, breaks, deviations in manufactured measurements, misunderstandings in communication, etc., the real erecting time rarely is the sum of the theoretical times per erected assembly. For that reason, an efficiency factor was calculated by dividing the theoretical erecting time of functions (108) and (109) by the actual time used. Observations were made on five days. The study produced the value 0.36 for u_E (Knuuttila, App. 12).

Labour cost

As the site is usually not close to the workers' residences, a daily allowance is to be added to the wages. This thesis applies a domestic daily allowance of €34/d or €0.07/min (assuming an 8 hour work day). It is added to the wage, which according to Table 1 is set to €26.84/h which translated into €0.45 /min. Thus the total per worker is €0.52/min. In this thesis the number of site workers is set to 6, but as the crane driver's wage cost is included in the rent of the crane, the total labour cost of five workers is €2.60/min.

Fixed site cost

The fixed site cost includes site huts and accommodation and travelling costs. A 6 m^2 area is reserved for washing and changing of clothes per worker. An office of 12 m^2 is used by the foreman. The monthly rent on the huts and office is set to €10/m^2 for a total area of 42 m^2. Accommodation cost amounts to €140 /week/worker and travelling costs every second week (2 x 200 kms/worker) to a unit cost of €0.42/km. Combined the above costs results in a unit cost of €0.10/min/worker or €0.5/min for five workers.

Equipment cost

Crane

The choice of crane is based, at least, on the weight of the lifted assembly, the required lifting height, and the maximum horizontal distance between the crane car and the assembly. It is assumed to be the greater of the distance between the car and the lifting area or the car and the assembly's final position. Possible crane types include at least construction cranes (tower cranes), mobile cranes and crawler cranes, depending on required capacity and whether the crane needs to be moved to different locations on site. A mobile or crawling crane may be equipped with a folding jib. This thesis considers a hydraulic straight telescopic boom mobile crane.

Usually erecting companies do not invest in the crane but rather hire it, which is why rent is considered in this thesis. The total rent of the crane consists of transporting the crane to and from the site, assembling and disassembling it, time-based rent and insurance. The rent includes the cost of the driver, fuels and the accessories needed during lifting. Transporting and assembly and disassembly costs depend on the location of the site, and do not vary with time. To be able to add the costs to the time-based rent, an estimation of the duration of the erecting work is needed. In this thesis these costs are allocated to the 8 weeks rent. For cranes with a nominal capacity smaller than 130 tonnes, the cost is around 0.6% of the rent, but for bigger cranes it might be up to 2.3% (500 tonnes). Lifting insurance is set to 1.1% of the time-based rent.

Cranes costs were collected from four Finnish crane hiring companies that provided a total of 21 offers. The companies normally quote their prices as €/day or €/week. The rents were converted to a cost unit of €/min based on an 8 hour day and a 40 h/week working time. The offers and a continuous curve derived from them are shown in Fig. 45.

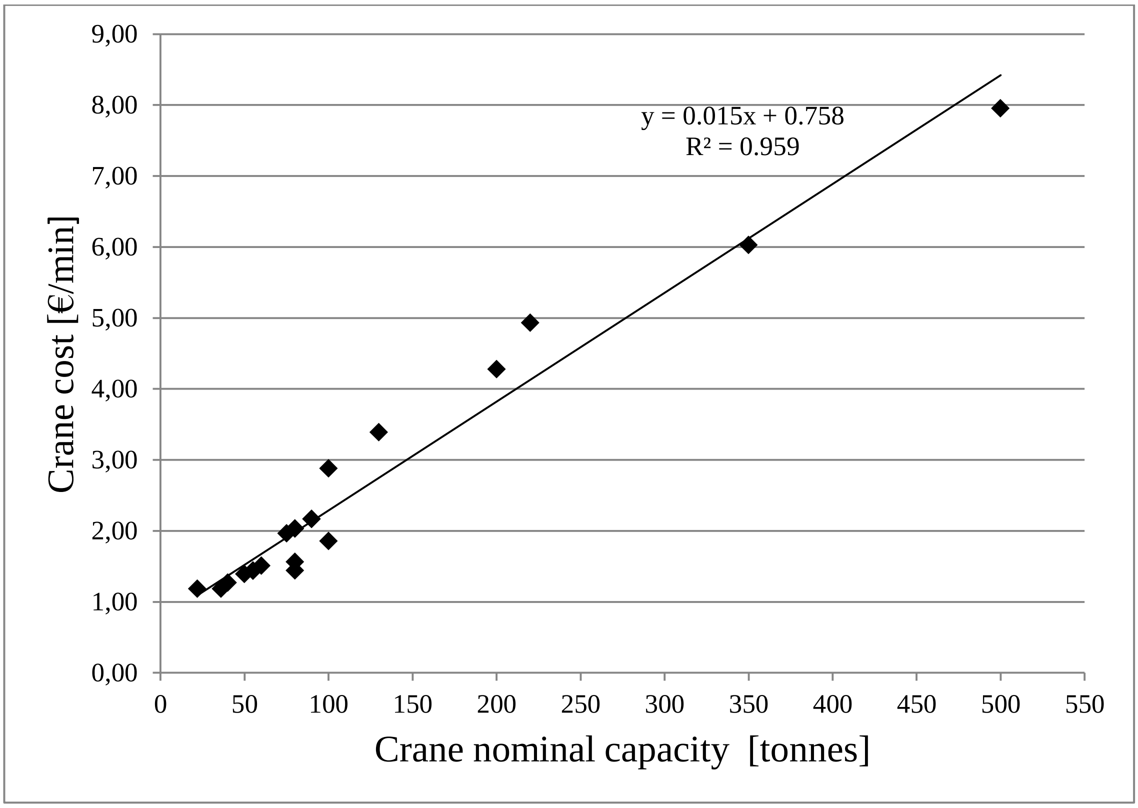


Fig. 45. Crane cost [€/min] based on nominal crane capacity [tonnes].

The nominal capacity of the crane [tonnes] indicates the maximum load the crane can lift using the shortest boom length, the maximum counterweight, and the optimal lifting direction in relation to the car. Technical data by Liebherr (Liebherr technical data, for 35 to 500 tonnes cranes) and Kobelco (for a 25 tonne crane) set a maximum load at a 3 metres horizontal distance from the car. The lifting capacity versus horizontal distance for different nominal load cranes are shown in Fig. 46.

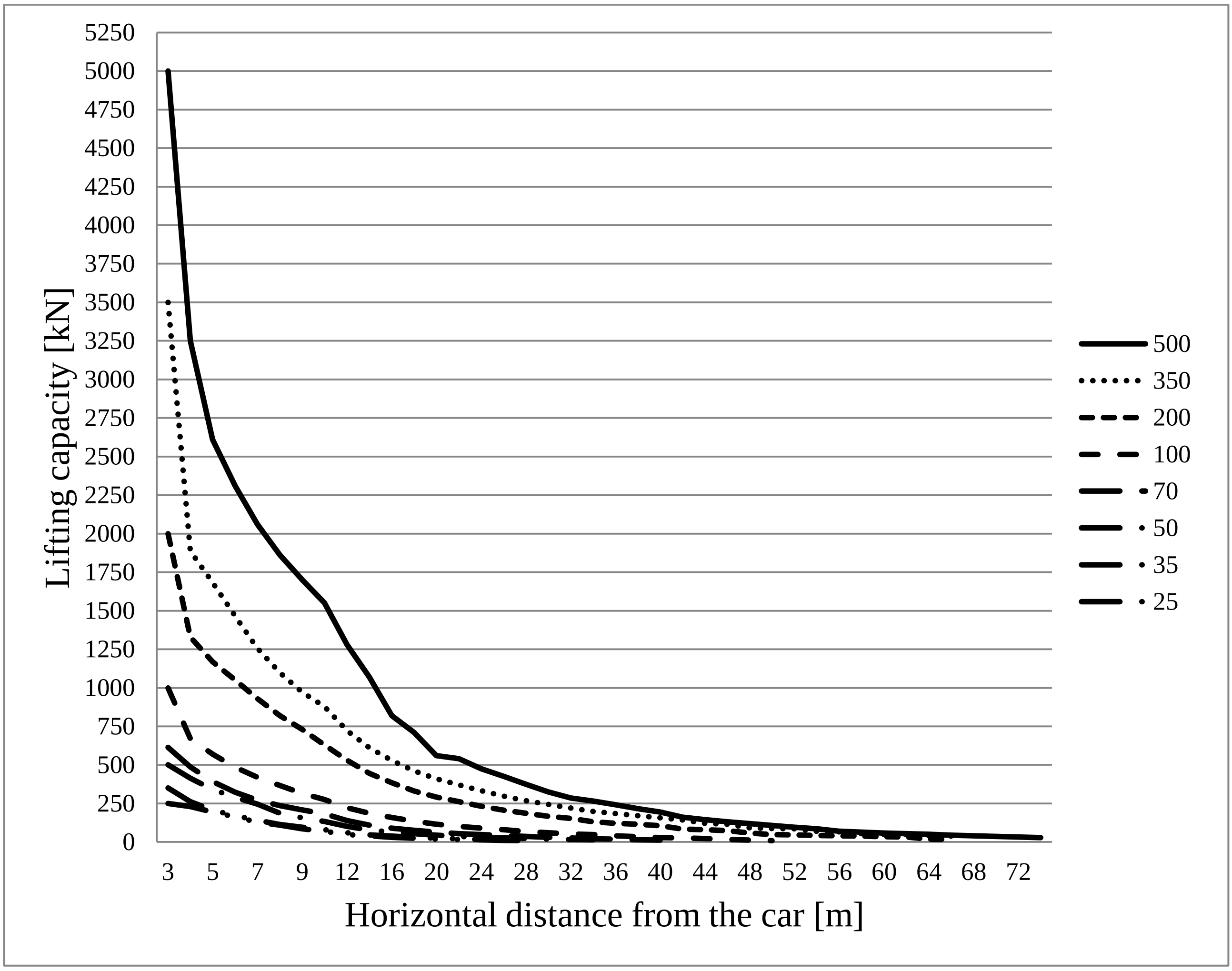


Fig. 46. Lifting capacity of different nominal capacity [tonnes] cranes (Liebherr and Kobelco).

The selection of the crane depends on the horizontal distance of the final position of the assembly from the crane car and the load to be lifted. The vertical distance of the final position may also be a limiting constraint, thus requiring the use of a bigger crane with a longer boom.

Appendix 9.6 presents the allowable lifting loads for various nominal crane capacities with respect to horizontal distances.

Man lift

The selection of the man lift is based on the required reach of the basket. Most critical is the height it reaches. The horizontal distance can usually be adjusted by locating the vehicle close to the final position of the assembly.

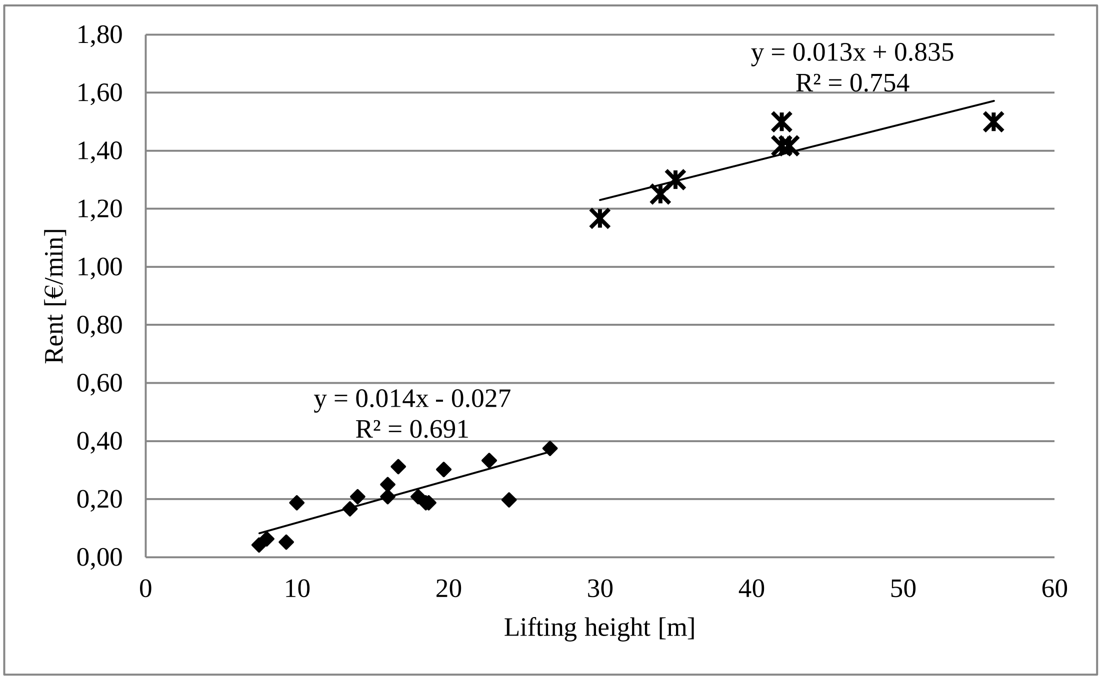


Fig. 47. Rent of the man lift [€/min], lifting height < 30 m, and ≥ 30 m, based on offers.

Values of the offers received and curves derived from the values are shown in Fig. 47. The cost function of the man lift is divided in two separate functions depending on the required lifting height. This is due to the different man lift types.

Fork lift

The rent of the fork lift is set to €0.10/min.

Erecting cost

Function (104) assumes now the following forms, depending on assembly classification and final location height:

for beams and braces below 30 metres

$$C_E = (63 \times l_s/972 + 0.5 \times (n_{b1} + n_{b2}) - 0.86 + L_A/30{,}000) \times (2.60 + 0.5 + 0.1 + 0{,}0153 \times Nc + 0.758 + 0{,}0146 \times h_s - 0.0277)/0.36 \ [€] \quad (110)$$

for beams and braces 30 metres or above

$$C_E = (63 \times l_s/972 + 0.5 \times (n_{b1} + n_{b2}) - 0.86 + L_A/30{,}000) \times (2.60 + 0.5 + 0.1 + 0{,}0153 \times Nc + 0.758 + 0{,}0131 \times h_s + 0.8359)/0.36 \quad [€] \quad (111)$$

for columns below 30 metres

$$C_E = (\frac{13 \times l_s}{144} + (0.5 \times n_b - 0.43) + L_A/30{,}000) \times (2.60 + 0.5 + 0.1 + 0{,}0153 \times Nc + 0.758 + 0{,}0146 \times h_s - 0.0277\ ) /0.36 \ \ [€] \tag{112}$$

for columns 30 metres or above

$$C_E = (13 \times \frac{l_s}{144} + (0.5 \times n_b - 0.43) + L_A/30{,}000) \times (2.60 + 0.5 + 0.1 + 0{,}0153 \times Nc + 0.758 + 0{,}0131 \times h_s + 0.8359\ \ ) /0.36 \ \ [€] \tag{113}$$

where

l_s = straight distance between the lifting area and assembly's final position [m]

n_{b1} = number of bolts per joint 1 [pcs]

n_{b2} = number of bolts per joint 2 [pcs]

L_A = length of the assembly [mm]

N_c = nominal capacity of the crane [tonnes]

h_s = height of the assembly's final position from the man lift location [m]

Unit cost of the erection using different nominal capacity cranes is shown in Fig. 48. As an example, cost distribution of beam erection with certain variables is shown in Fig. 49.

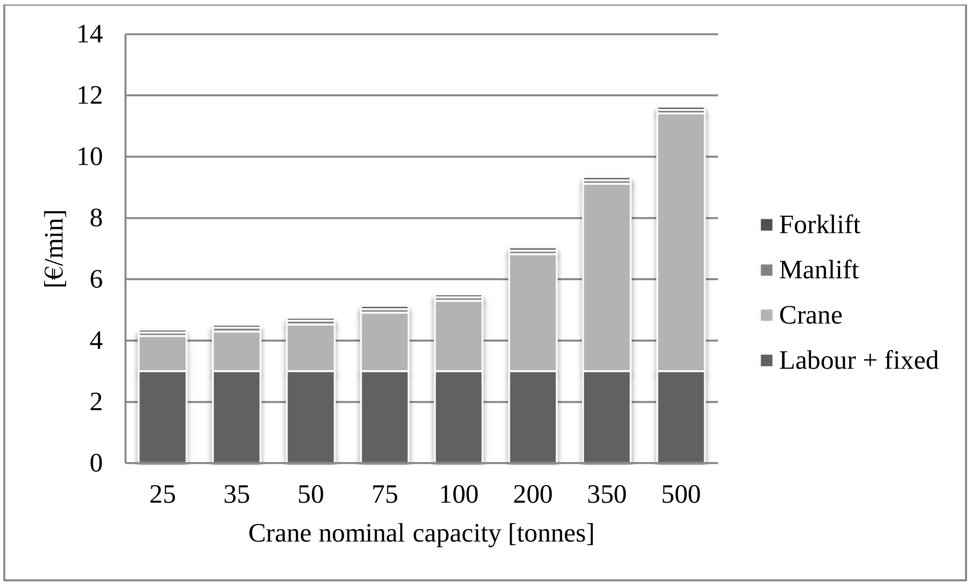


Fig. 48. Different components of site costs [€/min].

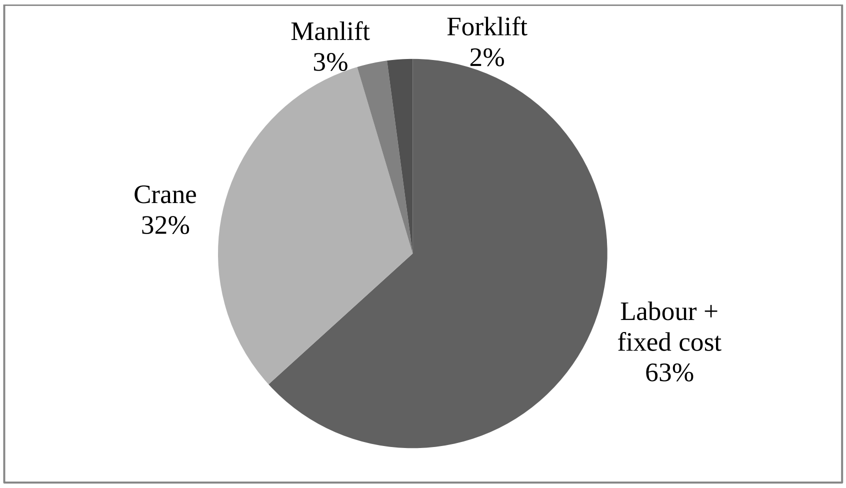


Fig. 49. Distribution of cost components using a 50-tonnes crane. Beam is fastened with 8 bolts, L_s 20 m and L_h 10 m

4.5.14 Summary of proposed costing method

The proposed costing method includes a function for material and separate sub-functions for each cost centre needed to produce features of the skeletal steel structure. The total cost function is (3):

$$C_T = C_{SM} + C_B + C_{Cu} + C_{BW} + C_S + C_D + C_{Co} + C_{PF} + C_{PA} + C_{PT} + C_P + C_T + C_E$$

where
C_T = total cost [€],

and the sub-functions representing individual cost centres are as follows (the reference numbers of detailed sub-functions created in Section 4 are presented in parentheses):

C_{SM} = material cost [€], functions (5) for plates, (6) for profiles, and (7) for bolts, nuts and washers
C_B = blasting cost [€], function (10)
C_{Cu} = cutting cost [€], functions (17) for plasma cutting, and (19) for flame cutting
C_{BW} = beam welding cost [€], functions (22) for fillet welding, (23) for single-bevel butt weld, and (24) for V butt weld
C_S = sawing cost [€], function (36)
C_D = drilling cost [€], function (48)
C_{Co} = coping cost [€], function (55)
C_{PF} = part fabrication cost [€], functions (58) for plates with thickness ≤ 30 mm, (59) for plates with thickness > 30 mm, and (64) for angle-steel
C_{PA} = part assembling cost [€], functions (74) for assembling by welding, and (75) for assembling by bolts
C_{PT} = post-treatment cost [€], function (77)
C_P = coating cost [€], functions (98) for alkyd, (99) for epoxy, (100) for polyurethane, and (101) for acryl coating.

C_T = transporting cost [€], function (102) or (103), depending on weight-volume ratio
C_E = erecting cost [€], functions (110) for beams and braces lifted less than 30 metres above ground level and (111) for beams and braces lifted higher than 30 metres, (112) for columns lifted less than 30 metres, and (113) for columns lifted higher 30 metres above ground level.

The structure of all sub-functions is the same. It is based on the time consumed at each cost centre. The time is multiplied by the time-related cost of the cost centre [€/min], which gives us the subtotal cost [e]. Non-time-related costs are then added. A cost centre's costs include equipment, real estate, labour and consumables costs. These costs are presented in literature and equipment manufacturers' datasheets. That means that the cost structure in question does not represent any actual workshop's layout and equipment structure, but is generic. Yet, all the parameters defining the workshop environment are adjustable to enable fine-tuning of the functions to fit the chosen actual workshop.

A totally new approach for cost estimation is presented for erecting. It is based on the actual erecting time of an assembly, consisting of the time required to lift and bolt the assembly to its final position. Input data for creating the erection function was obtained from an actual erection site.

5. Evaluation of the proposed costing method

5.1 Method summary

As summarised in Chapter 4.5.14, the proposed costing method consists of sub-functions for material and each individual process needed to produce the features that the designer has defined.

Material cost

The material cost function (5) for plates is based on the one used by the Finnish steel fabricator Rautaruukki. It consists of steel weight, which is multiplied by the unit price of steel. The unit price consists of two components: a basic price and feature-based add-ons. The influence of these add-ons, based on steel grade, plate thickness, total quantity and quantity per thickness of steel and finally the requirement of mill-made ultrasonic testing, are well under the designer's control. The unit price and add-ons used in this thesis can be found in Appendix 9.2.

The pricing of profiles, bolts, nuts and washers is more straightforward than that of plates. Function (6) for profiles includes the weight and unit price of a material. The unit price depends on profile type and material grade. Prices of bolts, nuts and washers depends on dimensions, material grade and coating. The price of bolts depends also on whether they are fully or partially threaded. The unit prices used in this thesis are presented in Appendices 9.3 and 9.4.

As the total cost of a structure depends largely on material cost, it is essential that the designer checks the current steel price before starting the cost estimation.

Process cost

When an assembly is being manufactured in a workshop by line production using NC equipment, it is transferred from one set of equipment to another, each producing some feature of the assembly. There are two attributes related to equipment. These are: required space (real estate) and required number of workers (labour) to operate the equipment. In this thesis the space containing the equipment and workers is called a cost centre. Building, lighting, ventilating and heating, installing equipment and the workers of the cost centre all have their fixed costs [€/min] depending on the payback periods chosen for the space and equipment. These costs accrue whether there production takes place at the cost centre or not. When the equipment is running, the cost components of the consumables used in production and the energy needed to run the equipment have to be considered. The consumables consist of welding rods, gases and replacement production tools, such as saw blades, drill bits, etc. Some of these components are time-related, some are not. When electrical equipment is used in workshops, the energy cost component depends on its power consumption and operating time.

While production is ongoing at the cost centre, two types of time are considered. First, some additional steps are needed before the actual production stage. The control of the equipment has to be set up by the operator, and the assembly has to be placed in the right position, clamped to the equipment and the productive tool needs to move to the surface of the assembly. In-between the productive stages, the assembly usually needs to be transferred through the equipment. After the productive stage, the tool returns to the starting position and the assembly has to be released. The time consumed in these activities is called non-productive time. The second type of time is called productive time, which refers to the time the tool is acting on the assembly − sawing, drilling, cutting, etc.

The utilisation ratio is a factor used to estimate the capacity of the cost centre. When the cost centre is fully loaded, the value of the utilisation ratio is 1. A lower value means that there is unused capacity at the cost centre. This thesis assigns the ratio the value of 1.

Based on these assumptions, the cost function for a cost centre can be presented in the following form (4):

$$C_k = (T_{Nk} + T_{Pk}) \times \left(c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} \ + c_{Sek}\right)/u_k + T_{Pk} \times (c_{Ck} + c_{Enk}) + C_{Ck}$$

where
C_k = total cost of cost centre k [€]
T_{Nk} = non-productive time of cost centre k [min]
T_{Pk} = productive time of cost centre k [min]
c_{Lk} = unit labour cost of cost centre k [€/min]
c_{Eqk} = equipment installment unit cost of cost centre k [€/min]
c_{Mk} = unit cost of equipment maintenance of cost centre k [€/min]
c_{REk} = unit cost of real estate of cost centre k [€/min]
c_{Sek} = unit cost of real estate maintenance of cost centre k [€/min]
c_{Ck} = unit cost of time-related consumables needed in processing at cost centre k [€/min]
c_{Enk} = unit cost of energy needed in processing at cost centre k [€/min]
C_{Ck} = total cost of non-time-related consumables used at cost centre k [€]
u_k = utilisation ratio of cost centre k [decimal, ≤1]

The non-productive time of each cost centre is determined during visits to workshops and from videos, literature and interviews. Non-productive times in this thesis are not based on any particular equipment model or workshop.

The productive time is derived from the input provided by the equipment and tool manufacturers, and in some cases from literature; thus it is based on the performance of one type of equipment or tool model. However, as the grounds of the performance are presented in functions, it is possible to fine-tune them to suit a nonconforming case.

Unit costs are compiled from suppliers' catalogues, cost lists and by inviting offers. These costs are time-related and have to be updated periodically. The unit costs presented here are 2009 Finnish costs.

The novelty of the thesis is based on the completeness and transparency of functions (3) and (4). They cover the complete delivery chain from workshop to site, and include almost all manufacturing, transportation and erection processes. Furthermore, they are {1} transparent and thus adjustable, {2} continuous, and {3} suitable for integration with BIM in future. The only method found in literature that covers the entire delivery chain, that of Watson et al. (2009), lacks features {1}, {2} and {3}. Ensuring the reliability of the method over time in a changing production environment, and making it simple enough to use, requires these three features.

5.2 Reliability

To prove the reliability of the method, it was decided to compare the results obtained with the method to real life data. That was assumed to give more reliable results than a mere comparison with values found in literature. Eight different assemblies were chosen for the comparison. These assemblies differed in their features and were examples of their unit price group (UPG). The inquiry sent to workshops included an example drawing of the assembly of each UPG, shown in Appendix 9.8, and the total mass of each UPG assembly group. The costs yielded by the method were compared to prices of the offers received from five European workshops and the costs obtained with the estimation tool presented by Watson et al. (1996). When an exact value was not found from the tables of Watson et al. (1996), interpolation was used. No extrapolation was required. Workshops made their offer based on different unit prices [€/kg] for each UPG. The unit prices included material, manufacturing, transporting, erecting, overheads and profit. The prices were based on the real industrial building project, about 1,500 tonnes in size, of which the named eight unit price groups covered 80%. The offers of the workshops are based on the cost level of 2007.

The following test assemblies were used:

UPG	Assembly	kg/m
1	Welded box column	370
2	Welded I-beam, heavy	173
3	Welded I-column	387
4	Hot rolled I-column	97
5	Horizontal brace, hot rolled tube	21
6	Wall brace, welded box	197
7	Hot rolled I-beam, h ≤ 300	57
8	Welded I-beam, h > 300	83

Table 9. Unit price groups (UPG), description of assemblies and their unit weights

The costs calculated with the estimation tool (Watson et al., 1996) were divided by the exchange rate of 1.38 (AUD/Euro).

The steel grade of the main profiles and parts was S355. As the quantity of the steel was sufficient, no cost additions related to amount of steel were used. The UT inspection add-on cost was used only for column base plates. Only visual test of welds were used, thus causing no extra costs.
Surface treatment was specified to be provided by the epoxy system. The transporting distance was set to 250 km, and the lifting height and length were set to 15m and 10 m, respectively.

The cost provided by the proposed method and the costs given by the estimating tool (Watson et al.), when average costs of the workshops are set to 100% for each UPG, are then compared.

FBCM stands for the feature-based costing method, AVWS for the average price of workshops, and WDK for the tool of Watson et al.

Results of comparison are shown in Table 10 and Fig. 50.

The average relative cost provided by FBCM was 116% and that by WDK 115% of the AVWS. Standard deviations within the eight UPGs were 26% and 42%, respectively. Average standard deviation of the workshops was 12%.

Range of prices of workshops is presented in the max and min columns of Table 10.

UPG	AVWS	max	min	FBCM	WDK
1	100%	125%	85%	93%	79%
2	100%	123%	77%	115%	117%
3	100%	117%	88%	101%	87%
4	100%	111%	88%	105%	73%
5	100%	116%	91%	166%	193%
6	100%	115%	90%	95%	88%
7	100%	110%	89%	133%	139%
8	100%	108%	84%	114%	144%

Table 10. Relative costs of assemblies when AVWS is 100%.

The same information is also presented in Fig. 50.

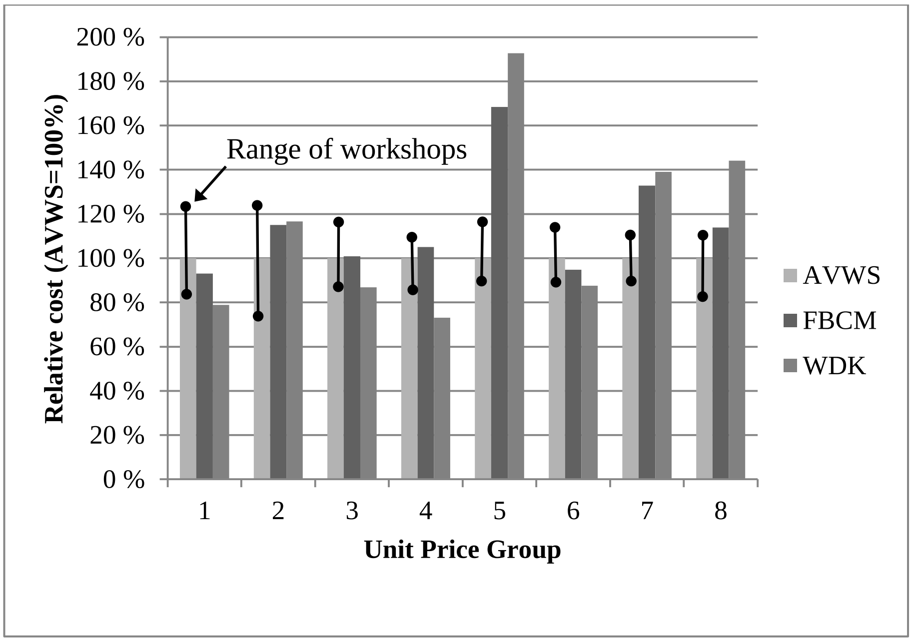


Fig. 50. Relative costs of assemblies when AVWS is 100%.

The cost yielded by FBCM included four major components: material, manufacturing, transporting and erecting. Their relative shares of the total cost of the assembly are presented in Table 11.

UPG	Material	Manufacturing	Transporting	Erecting
1	85%	13%	1%	1%
2	68%	26%	1%	5%
3	74%	24%	1%	1%
4	85%	13%	1%	1%
5	44%	39%	0%	17%
6	72%	22%	1%	5%
7	57%	22%	1%	20%
8	64%	28%	1%	7%
Av.	69%	23%	1%	7%

Table 11. Relative shares of cost components of test assemblies, calculated by FBCM.

As an example, the calculation of the cost of assembly 1A129 (UPG 3) using FBCM is shown in Appendix 9.7.

5.3 Practicality

To judge the practicality of the proposed method for achieving the aim of the thesis set in Paragraph 1.5, and the proposed new design process presented in Section 3, two studies were carried out. Both focussed on optimising the stiffness of joints from the economic viewpoint.

First, a single span beam, shown in Fig. 51, under uniform load was designed with three different joint rigidity (Haapio & Heinisuo, 2010), namely hinged, semi-rigid and rigid. Structural design was done according to EN considering stresses and deflections. The joint was of the end-plate type, and the beam had a constant moment capacity along the span. Semi-rigid joints were designed to distribute equal moments to the beam and joints ($qL^2/16$), thus optimising the moment of the beam.

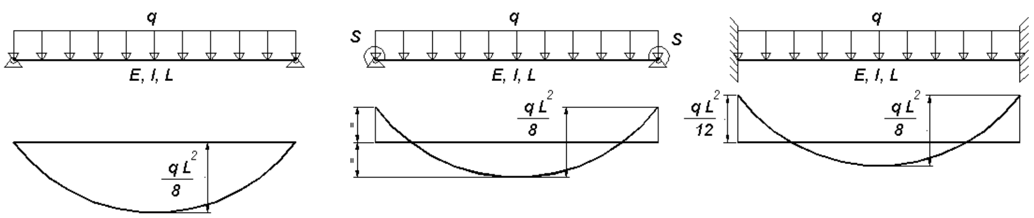


Fig. 51. Bending moment diagrams for hinged, semi-rigid and rigid joints.

The costs of the three solutions were calculated using FBCM, and the results are shown in Table 12. Note, the costs do not include transporting and erecting costs.

		Hinged	Semi-rigid	Rigid
		IPE 300	IPE 220	IPE 240
Material unit cost	[€]/kg	1.5	1.5	1.5
Beam material	[€]	316.50	196.50	230.25
Blasting	[€]	1.82	1.82	1.82
Sawing	[€]	10.12	8.80	9.14
Part fabrication	[€]	8.92	19.73	22.66
Assembling	[€]	6.92	14.18	17.33
Post-treatment	[€]	0.31	0.22	0.24
Coating	[€]	25.00	18.38	20.19
Total cost	[€]	**369.59**	**259.63**	**301.63**
Relative cost		142%	100%	116%
Total unit cost	[€]/kg	1.75	1.98	1.97
Difference in beam material cost	[€]	120.00	0.00	33.75
Difference in manufacturing cost	[€]	-10.04	0.00	8.25

Table 12. Cost of a single-span beam at different joint rigidities.

The hinged joint solution was 24% and the rigid joint solution 16% more expensive than the semi-rigid solution. The semi-rigid solution saved material costs (€120.00) compared to the hinged solution, although manufacturing was more costly (€10.04). Both material and manufacturing costs were lower with the in semi-rigid solution, €33.75 and €8.25, respectively, compared to the rigid solution. Transportation and erection costs were not considered.

In the second study, a two storey, two bay steel frame shown in Fig. 52 was optimised by varying the rotational stiffnesses of the joints (Haapio et al., 2011).The dimensions and materials of the main profiles were kept the same to determine the influence of the joint fabrication costs on the entire frame cost.
Storey height was 3.5 m and length of the beam 7.0 m.

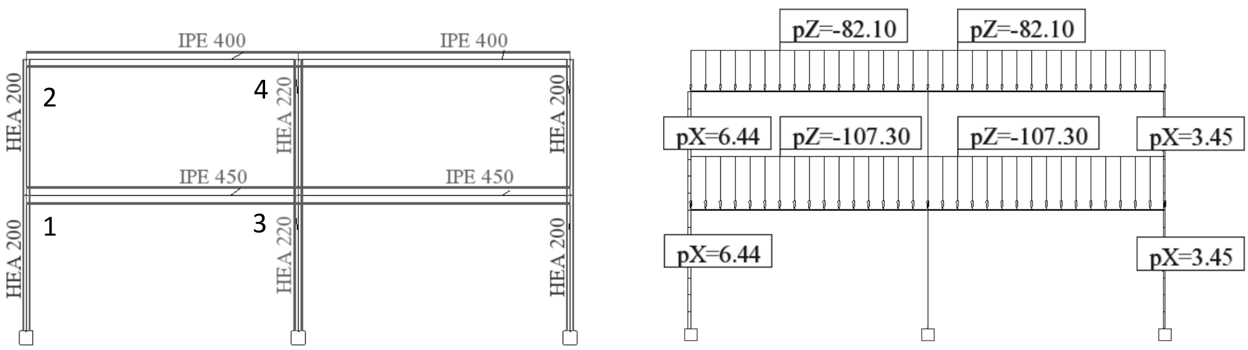


Fig. 52. Test frame.

In Fig. 52 pX refers to uniform load [kN/m^2] in the x-direction (positive from left to right), and pZ to uniform load [kN/m^2] in the z-direction (positive upwards).

Optimisation was executed in steps, starting with absolutely rigid joints. Joints were constructed to fulfill the requirements set in EN 1993-1-8 (2005) for rigid joints. Figures 53-56 show the layout of these joints. Only beam-to-column joints were considered. Base plate joints were supposed to be rigid.

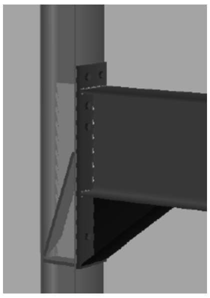


Fig. 53. Initial rigid joint 1.

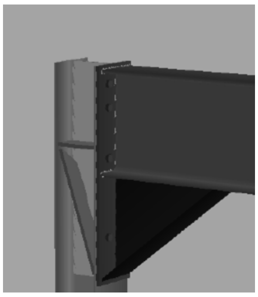


Fig. 54. Initial rigid joint 2.

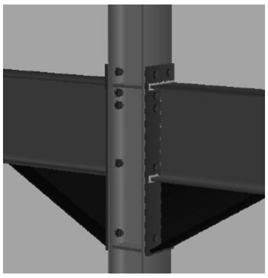


Fig. 55. Initial rigid joint 3.

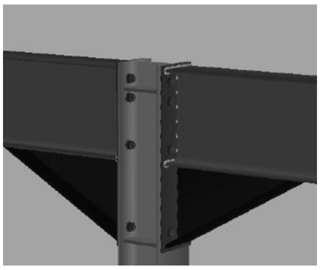


Fig. 56. Initial rigid joint 4.

The utility ratios of the members and utility ratios and actual moments and stiffnesses of initial (Step I) joints are shown in Table 13:

Member	Utility ratio	Joint	Utility ratio	Actual moment of joint [MPa]	Actual stiffness [kNm/rad]
HEA200	0.89	1	0.83	198.3	191 623
HEA220	0.96	2	0.46	115.6	116 836
IPE450	0.98	3	1.00	594.5	316 561
IPE400	0.97	4	1.00	448.6	162 782

Table 13. Utility ratios and joint features of test frame with rigid joints (Step I).

The next step was to evaluate the actual rotational stuffinesses of the joints in Figures 53-56, and then to recalculate the moments using these values. As the moments in Joints 3 and 4 were a bit smaller, the joint dimensions could be decreased still leaving enough resistance.

Then, step by step, the rotational stiffnesses of the joints were reduced keeping the main profiles constant. The optimisation was stopped at Step VI, when stiffnesses of Joints 1 and 2 were reduced by 15%, and stiffnesses of Joints 3 and 4 by 25% compared to the initial values.
Reduction was done by decreasing the height, width and thickness of the joint plates, reducing the amount of bolts, and decreasing the dimensions of the welds. The end-plate joint was not changed.

Layouts of the final joints are shown in Figs. 57-60.

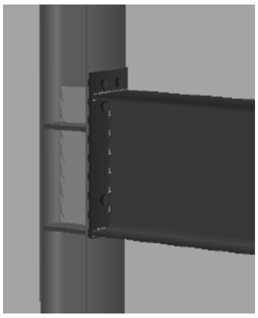


Fig. 57. Final semi-rigid joint 1.

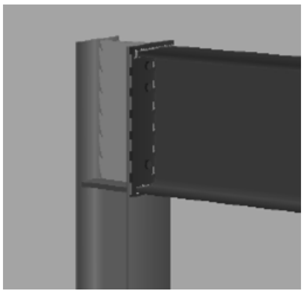


Fig. 58. Final semi-rigid joint 2.

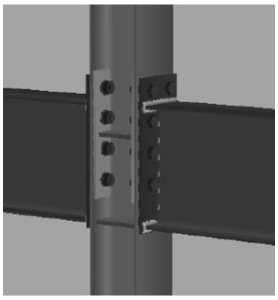


Fig. 59. Final semi-rigid joint 3.

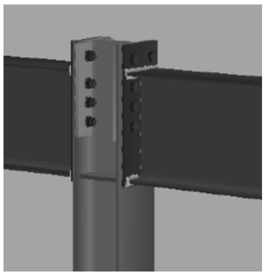


Fig. 60. Final semi-rigid joint 4.

The utility ratios of the members and utility ratios and actual moments and stiffnesses of final (Step VI) joints are shown in Table 14:

Member	Utilisation	Joint	Utilisation	Actual moment of joint [MPa]	Actual stiffness [kNm/rad]
HEA200	0.82	1	0.94	163.6	28 767
HEA220	0.94	2	0.97	99.1	17 591
IPE450	0.74	3	0.98	449.4	79 056
IPE400	0.67	4	0.99	306.7	40 304

Table 14. Utility ratios of test frame with optimised semi-rigid joints (Step VI).

It can be seen that the utility rates of the members have decreased from the initial situation, thus providing an extra safety margin for member design.

The costs of the frames calculated with FBCM are presented in Fig.55. They include material and manufacturing costs, but neither transporting nor erecting costs. The cost of the initial frame (Step I) was €7,470, while the cost of the final frame (Step VI) was €6,535. The saving of €935 is 12.5% of the initial frame cost.

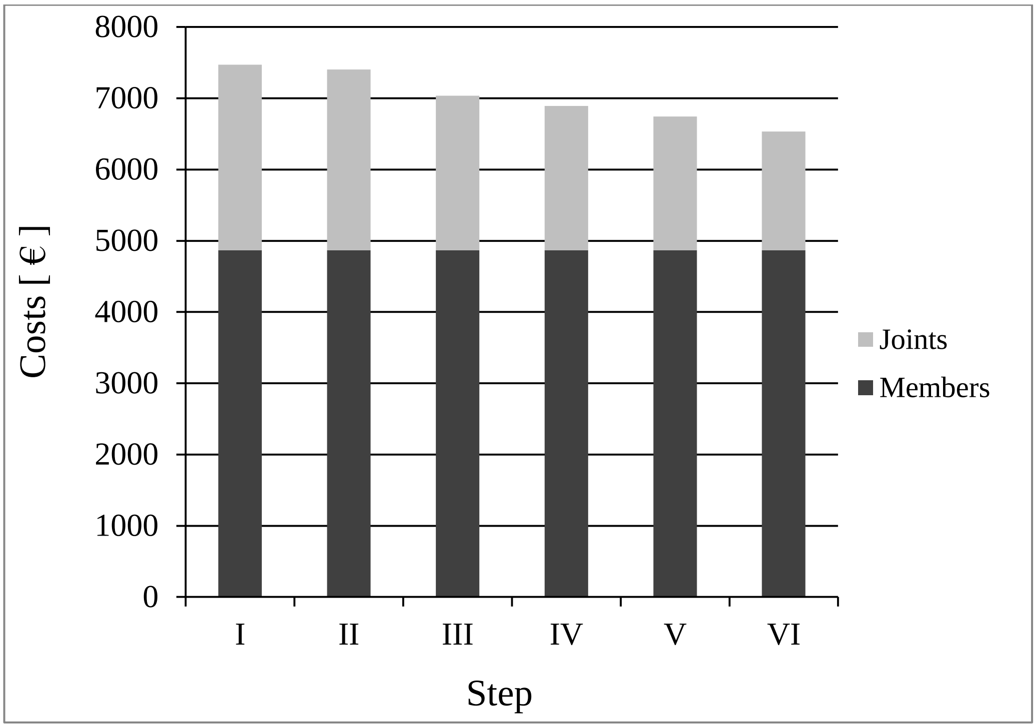


Fig. 61. Material and manufacturing costs of steel frame.

In conclusion, it can be said that significant savings can be achieved by considering joint stiffness at an early stage of design as proposed in Section 3.

Similar results to those made in these two studies are found in literature, see Simões (1996), Anderson et al. (1987) and Grierson & Xu (1992). However, the cost calculations of these studies are based on more basic methods than the one presented here.

5.4. Sensitivity

The cost function (4) includes three types of components: non-productive time, productive time and unit costs for investment, material, labour and energy. As the production functions are created using data received from equipment and tool fabricators, they can be regarded reliable for the described equipment and tool types, which should ensure stable productive time. Unit costs, which are received from literature and suppliers should also be reliable, but are costs of the period when the information was collected (in the case of this thesis the year 2009). The most significant unit cost is that of steel. As can be seen from Table 11, the share of material varies from 44% to 85% of total cost.

Furthermore, the price of steel is rather volatile, as can be seen from Fig. 62. Therefore, it is essential to update the cost of steel whenever making an estimate.

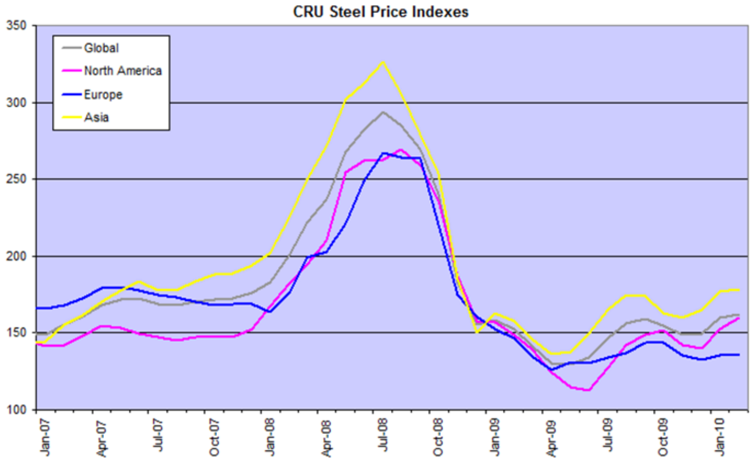


Fig. 62. Steel price index from Jan 2007 to Jan 2010 (CRU Steel Price Index)

The most uncertain component is non-productive time. It includes the entire period when the assembly is at the cost centre deducting the productive time. Non-productive time depends e.g. on organisation of work and workers' skills, which makes it workshop-dependent. No actual workshop was used in this thesis to determine non-productive time – literature, videos and interviews were used instead.

An example is provided to show the significance of non-productive time. The cost of a welded beam with end plate joints and stiffeners along the beam (UPG8, see Appendix 9.8.8) was estimated based on default non-working times (100%), 50% decreased (50%) and 50% increased (150%) non-productive times in cost functions. The results are listed in Table 12.

	Non-productive time		
	50 %	100 %	150 %
Material	100 %	100 %	100 %
Blasting	100 %	100 %	100 %
Cutting	82 %	100 %	118 %
Beam welding	87 %	100 %	113 %
Sawing	83 %	100 %	117 %
Drilling	60 %	100 %	146 %
Part fabrication	67 %	100 %	109 %
Assembly	100 %	100 %	100 %
Post treatment	100 %	100 %	100 %
Coating	100 %	100 %	100 %
Transportation	100 %	100 %	100 %
Erection	100 %	100 %	100 %
Total	97 %	100 %	102 %

Table 15. Variation in cost in respect of non-productive time

No non-productive time was included in the process function for blasting, assembly, post treatment, coating, transportation and erection. Table 15 shows that the influence of non-productive time is the largest in the case of drilling cost. When non-productive time varies within the 50% to 150% range, the drilling cost varies from 67% to 146%, respectively, compared to the cost based on default non-productive time. However, the effect on total cost was only -3% to +2%, as can be seen from Table 15.

6. Summary and discussion

The research problem presented in Paragraph 1.4 was to develop a costing method for skeletal steel structures, which enables the designer to take into account the cost effects of a structure's features under the designer's control, and which covers the delivery chain from workshop to the erection site. The method should include all essential cost components of the workshop and erection site, and it must be transparent to enable updating the parameters which affect costs.

As a result, a new costing method (FBCM) is presented in the form of a function (3) and its sub-functions (5) to (112). To evaluate the method, its reliability, practicality and sensitivity were tested.

The idea of the method is to present the origin of each cost component individually, based on the nature of the cost. It could be called a "deep knowledge" approach as distinct from the "shallow knowledge" approach, where cost estimation is based on rules of thumb or general unit costs like €/kg of steel.

As the main user of the method is the designer, all variables are chosen so that they can be included in the structural model defined during the design phase.

It can be argued, that when material costs of the assembly are compared with the manufacturing plus erecting costs, the latter should include as complete costs of the processes as possible. A typical example is the adding of stiffeners to the main profile. If only material costs are considered, a stiffened structure is easily selected. Especially the roles of real estate cost and real estate maintenance cost are significant. As can be seen e.g. from Fig. 24, the share of these costs can be as high as 43% of the total process cost. These cost components are missing from the methods found from literature.

To prove the reliability of the proposed method, the costs of eight test assemblies (see Appendix 9.8) were estimated by the method, and the results were compared with offers received from five workshops and the results of a cost method presented in literature (WDK, Watson & al, 1996). The results of this comparison are presented in Table 10 and Fig. 50. The costs estimated by the proposed method were on average 16% higher for the eight assemblies than the quotes submitted by workshops. It must be noted, that offers from workshops are prices which include overheads and profit, whereas the results produced by the proposed method, as well as those obtained from literature, represent pure costs without the mentioned extra expense items. Thus, the costs estimated by the new method would seem to be overestimated. In any case, the standard deviation is more important. In the case of the costs of test assemblies, standard deviation between results of proposed method and average of the offers from workshops was 26%. Table 10 shows that the cost of assembly UPG 5 is significantly and that of UPG 7 slightly overestimated. Both assemblies are light-weight profiles as can be seen from Table 9. Further, Table 11 shows that the relative share of erection cost is largest with these two UPGs.

As the proposed method estimates the erection cost based not on weight, but erection time, and since the workshop prices are weight-based, this may result in relatively higher erection cost estimates for light weight assemblies using FCBM. Similar overestimation happens also with WDK, which assumes weight to have a very small effect on the erection cost. If the result for UPG5 is disregarded, then the deviation of the results by FBCM drops to 13%, which is very close to the average deviation (12%) between the workshops' offers. It should be noted, that the proposed method includes default pre-set parameters, listed in Appendix 9.1, which are not related to any actual workshop. It can be concluded, that even when using default parameters, the results, omitting the light weight profile UPG5, vary within the same range as those of workshops.

Practicality was illustrated by two examples. By taking into account the necessary rotational stiffnesses of the joints, and estimating the costs of the joints, it was shown that using semi-rigid joints can lead to savings of up to 13% and 30% in the cost of the entire structure compared to just selecting a traditional rigid or hinged joint, respectively. Especially example two which deals with the cost of the frame, showed that savings could be obtained by modifying just the joints while leaving the main profiles as they are. In other words, in this case no savings could have been found if only the main profiles had been studied. It should be noted, that in both examples neither transportation nor erection costs were considered.

The reaping of the benefits of a more economical structure requires a new approach in design. The approach is presented in Fig. 7, which demonstrates that the stiffnesses of the joints must be included in the dimensioning of the main frame. Software tools already on the market make it possible. Design offices can easily create libraries of joints including pre-calculated design values as an initial input for the dimensioning calculations of frame members. The integration of joint design has been described by Heinisuo, Laasonen, Ronni & Anttila (2010). They concluded that by using a product model, the finite element method, and the component method, it is possible to take joint stiffness into account in frame analysis.

These examples prove that with proposed method it is possible and practical to analyse the cost differences of even highly detailed structures.

Finally, the sensitivity of the method was examined by two parameters. Firstly, as the material cost share is significant – in the test assemblies it varies between 44% and 85% of total cost – it is essential to check current steel costs before starting the cost calculation. The great fluctuation in steel costs is demonstrated in Fig. 62. The unit prices used in this thesis are found in Appendices 9.2, 9.3 and 9.4.

Secondly, the consequences of non-productive time were studied, as this parameter is the most uncertain one of the functions. It was found that even it has a significant impact on some individual process costs, while having a minor effect on total cost.

The designer must consider many details in order to be able to design an economical structure. Starting with material selection, the designer should consider the effect of steel grades and the total amount

[kg] of steel plates of equal thickness. It might turn out that having even a bit too thick plate than required by statical calculation for a certain part of structure the total cost is lower if there is less amount of different plate thicknesses in the entire project. When selecting the joint types, the designer must consider the moment and rotational capacity she/he can reach with the chosen joint type as well as the manufacturing cost. Especially when stiffening plates are required, it is always worthwhile also considering a simple solution without stiffeners, even if it means thicker material. As a rule of thumb, every feature increases costs, and if they can be avoided by adding more base material, a comparison estimate should be made. When determining the coating system, the designer must be aware of the latest paint specifications and the maximum film thickness that can be sprayed, to be able to minimise the number of films, as every extra film prolongs the time required for the coating process. To optimise the transportation cost, a minimum volume should be achieved. That means avoiding all types of projections, which increase the entire assembly volume. At least shipping companies calculate the volume based on the outer dimensions of the assemblies, even if they can be overlapped. Site costs depend on two main factors: the number of assemblies and the number of bolts per assembly. These numbers should be minimised keeping in mind that larger bolts are more expensive.

When a designer aims for an economically optimal, she/he should consider the whole delivery chain of the structure from workshop to site. Conventional methods usually allow optimising only part of the delivery chain, thereby disregarding possible cost increases in other parts of the chain. The proposed method gives the designer a tool to estimate the total cost of the structure with the chosen features and the possibility to optimise total cost.

The final conclusion is that the proposed method provides a reliable and practical tool for a designer to evaluate the economy of her/his structural decisions already at an early stage of design, while allowing optimising the structure to minimise its cost by altering the stiffness of joints and structural details taking into account the cost effects of the alterations.

Proposed further studies

In the creation of a costing method for a designer, the key concern is still the interface between the designer and the cost method. As it is impractical to use the method manually in a real, productive design environment, a link between the structural model and the cost method has to be built. Using the initial pre-set manufacturing and erecting parameters, the input data needed for calculating the cost by the method presented here can be obtained directly from the building information model (BIM) created by the designer. This approach is presented in Heinisuo et al. (2010). In future, cost calculation will be a “hidden” function of BIM allowing the designer to see immediately the cost effects of her/his decisions without having to conduct a separate cost analysis. The research on integration of BIM and the costing method should be continued. That is very important to make the tool available for designers.

Although the method was created for use by designers, it also allows simulating line production when manufacturing is assumed to be line-oriented. The productivity of the line is best, when the flow is constant. When similar assemblies are manufactured, the slowest process is the bottleneck of the line. Utilisation of parameter μ, which was given the value 1 in this thesis, allows better simulation of the manufacture of an assembly and its cost by "punishing" the slowest process by giving the other processes a lower value of μ, depending on the total time ratio between the process in question and the slowest process. This kind of simulation leads to optimisation of the fabrication process as a whole, instead of optimisation of separate sub-processes. In reality, if there are different kinds of assemblies, workshops try to arrange the order of assemblies on line so that the slowest process does not retard overall production.

The influence of repeats and series is disregarded. Sarma & Adeli (2000) highlight the importance of using fewer shape-dimensions, and as indicated by the steel material costs (App. 9.2), in the case of small amounts of steel plate mass and thickness, the add-ons may be remarkable – up to 9%. When using an automated NC manufacturing line, it is, however, assumed that the length of the series does not play as significant a role as it may do when manufacturing is carried out in a jig, like in the case of a truss. If the feeding of design data to NC control is automated, the length of the series does not necessarily increase the productivity of the line, i.e. decrease costs.

7. Conclusion

This study deals with skeletal steel structures used for industrial, commercial or office buildings or constructions such as beams, columns and braces, which are produced in a workshop, transported to the site and erected there.

According to Evers & Maatje (2000), the cost breakdown of steel structure is roughly as follows:
1) Design 13%
2) Material 38%
3) Production 27%
4) Coating 10%
5) Erection 12%

It is a widely accepted fact (e.g. Evers & Maatje, 2000, p.17) that the designer plays a significant role in determining the costs of structures. According to Evers & Maatje (2000), 88% of the costs are determined during the design phase. The designer needs to know the breakdown of the costs of structures to be able to make economical decisions.

On the other hand Salokangas (2009, p. 5) found material cost to be from 18% to 53% of total cost depending on the type of structure – a service platform support structure and a series of high wind columns, respectively. Thus, the total cost of a structure cannot be estimated directly on the basis of material cost, unless the estimator is well aware of the nature of the structure.

Based on the literature review, and considering the economy of steel structures, there is a clear need for a parametric costing method, which is transparent, parametric, covers the whole delivery chain and which can be integrated with existing design tools. So far, a method has not been created which would enable the designer to evaluate the entire cost impacts of her/his decisions.

The research problem is formulated as follows:
Based on what was concluded above, the research problem is to develop a costing method for skeletal steel structures, which enables the designer to take into account the cost effects of a structure's features under her/his control, and which covers the delivery chain from the workshop to the erection site. The method should include all essential cost components of the workshop and erection site and be transparent to allow updating parameters that affect costs.

This thesis aims to develop a method, which gives the designer detailed information of the cost structure of the manufacturing, transportation and erecting processes. The method should take into consideration those features of the structures that affect costs. It should be suitable for different process environments as it uses pre-set parameters that can be altered according to the actual environment, and variables that can be obtained from the structural model. The method should be targeted to the early stage design, as the potential for finding the most economical solutions is largest at that stage (Evers & Maatje (2000)). Therefore it should include, as a default, all needed environmental parameters, to enable the designer to concentrate on structural solutions.

Weynand et al. (1998, p. 6) concluded that use of semi-rigid joints gave the most economical structure in the studied cases. To achieve the full advantage of semi-rigid joints requires including joint behaviour in the structural analysis model. That leads to the need to add initial joint parameters to the product model or structural analysis model.

The following design process is proposed to draw possible further economic benefits from modelling the joints in the basic design stage:

1. Introduce the initial members and joints into a product model with joint spring factors/moment resistances.
2. Execute the structural analysis with initial member sections and chosen joints.
3. Check the manufacturer's profile and joint databases.
4. Check stresses of the members and shear stresses of the joints (moment check of joint is not needed as the moment of a joint is limited to full resistance).
5. Increase or decrease member and/or joint sizes according to the structural analysis.
6. When sizes are adequate, estimate the cost of the frame.
7. Vary the joint type with new joint parameters.
8. Repeat steps 1-5.
9. Choose the optimal alternative.

The following approach is selected to solve the research problem:
The delivery chain of a steel structure is simulated and modelled based on the different processes needed to produce an erected steel skeleton with specified features. The modelling uses mathematical functions describing the costs, which include process variables that the designer can alter to determine their effect on total cost, and pre-set environment-based, but changeable parameters that define those attributes of the process environment, which affect the costs.

This thesis focusses on six cost components: labour, material, investment (equipment and real estate), consumables, energy and maintenance (equipment and real estate) costs. Costs are divided in two categories: time-dependent and non-time-dependent. Time-dependent costs include labour, investments, energy, maintenance, and some consumables costs, while non-time-dependent costs consist of material and some consumables costs. Overhead and profit costs are not considered.

In this thesis, the proposed total cost function for an assembly, divided to subcosts of the cost centres, can be presented as follows:

$$C_T = C_{SM} + C_B + C_{Cu} + C_{BW} + C_S + C_D + C_{Co} + C_{PF} + C_{PA} + C_{PT} + C_P + C_T + C_E$$

where
C_T = total cost [€]
C_{SM} = material cost [€]

The costs of cost centres are:

C_B = blasting cost [€]
C_{Cu} = cutting cost [€]
C_{BW} = beam welding cost [€]
C_S = sawing cost [€]
C_D = drilling cost [€]
C_{Co} = coping cost [€]
C_{PF} = part fabrication cost [€]
C_{PA} = part assembling cost [€]
C_{PT} = post-treatment cost [€]
C_P = painting cost [€]
C_T = transporting cost [€]
C_E = erecting cost [€]

The cost function for an assembly processed in workshop cost centre *k*, presented in generic form, is:

$$C_k = (T_{Nk} + T_{Pk}) \times (c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} + c_{Sek})/u_k + T_{Pk} \times (c_{Ck} + c_{Enk}) + C_{Ck}$$

where
C_k = total cost of cost centre k [€]
T_{Nk} = non-productive time of cost centre k [min]
T_{Pk} = productive time of cost centre k [min]
c_{Lk} = unit labour cost of cost centre k [€/min]
c_{Eqk} = equipment installment unit cost of cost centre k [€/min]
c_{Mk} = unit cost of equipment maintenance of cost centre k [€/min]
c_{REk} = unit cost of real estate of cost centre k [€/min]
c_{Sek} = unit cost of real estate maintenance of cost centre k [€/min]
c_{Ck} = unit cost of time-related consumables needed in processing at cost centre k [€/min]
c_{Enk} = unit cost of energy needed in processing at cost centre k [€/min]
C_{Ck} = total cost of non-time-related consumables used at cost centre k [€]
u_k = utilisation ratio of cost centre k [decimal, ≤1]

To prove the reliability of the proposed method, the costs of eight test assemblies were estimated using the method, and the results were compared with offers received from five workshops and the results of a method presented in literature. The costs estimated by the proposed method were on average 16% higher for the eight assemblies than the quotes submitted by workshops. It should be noted that offers from workshops are prices, which include overheads and profit, whereas the results produced by the proposed method, as well as those obtained from literature, represent pure costs without the mentioned extra expense items. Thus, the costs estimated by the new method would seem to be overestimated. In any case, the standard deviation is more important. In the case of the costs of test assemblies, standard deviation between results of proposed method and average of the offers from workshops was 26%. If the result for one of the assemblies, the light weight brace, is disregarded, the deviation of the results by the proposed method drops to 13%, which is very close to the average deviation (12%) between workshops' offers. It should be noted that the proposed method includes default pre-set parameters shown in Appendix 9.1, which are not related to any actual workshop. Thus, it can be concluded that even when using the default parameters, the results, omitting the light weight profile, vary within same range as those for the workshops.

Practicality was illustrated by two examples, a single-span beam and a two-storey, two-bay frame. By taking into account the necessary rotational stiffnesses of the joints, and estimating the costs of the joints showed that using semi-rigid joints can lead to savings of up to 13% and 30% in the cost of the entire structure compared to just selecting a traditional rigid or hinged joint, respectively. Especially in the frame example savings were achieved by modifying only the joints, while the main frame profiles remained the same. In other words, no savings could have been achieved in this case if only the main profiles had been studied.

The final conclusion is that the proposed method provides a reliable and practical tool for a designer to evaluate the economy of her/his structural decisions already at an early stage of design, while allowing optimising the structure to minimise its cost by altering the stiffness of joints and structural details taking into account the cost effects of the alterations.

In the creation of a costing method for the designer, the key concern is still the interface between the designer and the cost method. As it is impractical to use the method manually in a real, productive design environment, a link between the structural model and the cost method has to be built. Using the initial pre-set manufacturing and erecting parameters, the input data needed for calculating the cost by the method presented here can be obtained directly from the building information model (BIM) created by the designer. This approach is presented in Heinisuo et al. (2010). In future, cost calculation will be a "hidden" function of BIM allowing the designer to see immediately the cost effects of her/his decisions without having to conduct a separate cost analysis. Research on the integration of BIM and the costing method should be continued. That is very important to make the tool available for designers.

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9. Appendices

Appendix 9.1 Pre-set values for cost functions

Appendix 9.2 Steel plate price

Appendix 9.3 Unit prices of profiles

Appendix 9.4 Unit prices of bolts, nuts, and washers

Appendix 9.5 Unit prices and features of the paints

Appendix 9.6 Allowable lifting load of nominal crane capacities regarding horizontal distance

Appendix 9.7 Example: Cost calculation for assembly using proposed method

Appendix 9.8 Drawings of the test assemblies

Appendix 9.1 Pre-set values for cost functions

Blasting

Labour	hourly cost	27.68	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	Investment	200,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	16,049	€/a
	equipment unit cost	0.13	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	400	m2
	investment	364,800	€
	interest rate	5%	
	life	50	a
	resale value	4,800	€
	annual cost	19,720	€/a
	real estate unit cost	0.16	€/min
Real estate maintenance	annual cost	28,800	€/a
	real estate maintenance unit cost	0.24	€/min
Energy	power	40	kW
	energy unit cost	0.07	€/min
Consumables	grains		
	consumption	0.042	kg/min
	cost	0.5	€/kg
	consumables unit cost	0.02	€/min

Cutting

Labour	hourly cost	27.68	€/h
	number of workers	2	
	labour unit cost	0.92	€/min
Equipment	investment	280,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	22,468	€/a
	equipment unit cost	0.19	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	200	m2

	investment	182,400	€
	interest rate	5%	
	life	50	a
	resale value	2,400	€
	annual cost	9,860	€/a
	real estate unit cost	0.08	€/min
Real estate maintenance	annual cost	14,400	€/a
	real estate maintenance unit cost	0.12	€/min
Energy (Flame)		N/A	
Consumables (Flame)	consumption of oxygen	varies	m3/min
	unit cost of oxygen	4.18	€/m3
	consumption of propane	0.0063	m3/min
	unit cost of propane	18.40	€/m3
	cost of nozzle	40	€
	usable life of nozzle	3,900	min
	consumables unit cost	varies	
Energy (Plasma)	power of process	72	kW
	cost of energy	0.1	€/kWh
	energy unit cost	0.12	€/min
Consumables (Plasma)	consumption of oxygen	0.0710	m3/h
	unit cost of oxygen	4.18	€/m3
	cost of nozzle	40	€
	usable life of nozzle	480	min
	consumable unit cost	0.38	€/min

Beam welding

Labour	hourly cost	27.68	€/h
	number of workers	2	
	labour unit cost	0.92	€/min
Equipment	investment	200,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	16,049	€/a
	equipment unit cost	0.13	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	300	m2
	investment	273,600	€
	interest rate	5%	
	life	50	a

	resale value	3,600	€
	annual cost	14,790	€/a
	real estate unit cost	0.12	€/min
Real estate maintenance	annual cost	21,600	€/a
	real estate maintenance unit cost	0.18	€/min
Energy	power	48.00	kW
	energy unit cost	0.08	€/min
Consumables	Wire		
	consumption	0.14	kg/min
	cost	1,91	€/kg
	Flux		
	consumption	1.00	kg/wire (kg)
	cost	3.00	€/kg
	consumable unit cost	0.69	€/min
Sawing			
Labour	hourly cost	27.68	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	Investment	310,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	24,875	€/a
	equipment unit cost	0.21	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	525	m2
	investment	478,800	€
	interest rate	5%	
	life	50	a
	resale value	6,300	€
	annual cost	25,882	€/a
	real estate unit cost	0.2□	€/min
Real estate maintenance	annual cost	37,800	€/a
	real estate maintenance unit cost	0.31	€/min
Energy	power of process	10	kW
	cost of energy	0.1	€/kWh
	energy unit cost	0.02	€/min
Consumables	blade		
	consumption	0.14	kg/min

	cost	100.00	€/pcs
	unit cost	14.14	€/min
Drilling			
Labour	hourly cost	27.68	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	Investment	520,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	41,726	€/a
	equipment unit cost	0.34	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	525	m2
	investment	478,800	€
	interest rate	5%	
	life	50	a
	resale value	6.30	€
	annual cost	25,882	€/a
	real estate unit cost	0.21	€/min
Real estate maintenance	annual cost	37,800	€/a
	real estate maintenance unit cost	0.31	€/min
Energy	power of process	9	kW
	cost of energy	0.1	€/kWh
	energy unit cost	0.02	€/min
Consumables	drill bits		
Coping			
Labour	hourly cost	27.68	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	Investment	430,000	€
	interest rate	5%	
	life	20	a
	resale value	€0	
	annual cost	34,504	€/a
	equipment uni cost	0.29	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	350	m2

	investment	319,200	€
	interest rate	5%	
	life	50	a
	resale value	4,200	€
	annual cost	17,255	€/a
	real estate unit cost	0.14	€/min
Real estate maintenance	annual cost	25,200	€/a
	real estate maintenance unit cost	0.21	€/min
Energy	power of process	N/A	kW
	cost of energy	0.1	€/kWh
	energy unit cost	0	€/min
Punching-shearing			
Labour	hourly cost	27.68	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	investment	280,000	€
	interest rate	5%	
	life	20	a
	resale value	0	€
	annual cost	22,468	€/a
	equipment unit cost	0.19	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	75	m2
	investment	68,400	€
	interest rate	5%	
	life	50	a
	resale value	900	€
	annual cost	3,697	€/a
	real estate unit cost	0.03	€/min
Real estate maintenance	annual cost	5,400	€/a
	real estate maintenance unit cost	0.04	€/min
Assembling			
Labour	hourly cost	27.42	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Equipment	investment	5,000	€
	rate	5%	
	life	10	a
	resale value	0	€

	annual cost	648	€/a
	equipment unit cost	0.01	€/min
Maintenance	annual cost	1,000	€/a
	maintenance unit cost	0.01	€/min
Real estate	area	75	m2
	investment	68,400	€
	interest rate	5	
	life	50	a
	resale value	900	€
	annual cost	3,697	€/a
	real estate unit cost	0.03	€/min
Real estate maintenance	annual cost	5,400	€/a
	real estate maintenance unit cost	0.04	€/min
Post-treatment			
Labour	hourly cost	27.32	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Real estate	area	75	m2
	investment	68,400	€
	interest rate	5%	
	life	50	a
	resale value	900	€
	annual cost	3,697	€/a
	real estate unit cost	0.03	€/min
Real estate maintenance	annual cost	5,400	€/a
	real estate maintenance unit cost	0.04	€/min
Painting			
Labour	hourly cost	27.32	€/h
	number of workers	1	
	labour unit cost	0.46	€/min
Real estate	area	75	m2
	investment	68,400	€
	interest rate	5%	
	life	50	a
	resale value	900	€
	annual cost	3,697	€/a
	real estate unit cost	0.03	€/min
Real estate maintenance	annual cost	5,400	€/a
	real estate maintenance unit cost	0.04	€/min

Appendix 9.2 Steel plate price

Hot rolled plate

	[€/tonne]
Basic price (incl. edge cutting add-on €12/tonne)	
c_{SMBPl}	1,169

Steel grade add-on:

c_{SMG}	[€/tonne]
S235	0
S355	35

Thickness add-on (plate width 2,200<b<2,500 mm):

c_{SMT}	
5<= t < 6 mm	140
6<= t < 7	82
7<= t < 8	35
8<= t < 10	23
10<= t < 12	12
12<= t < 15	0
15<= t < 20	0
20<= t < 40	12
40<= t < 50	12
50<= t < 60	47
60<= t < 80	58

Quantity add-on:

c_{SMQ}	
< 5000 kg	64
< 10 000 kg	34
< 15 000 kg	8
> 15 000 kg	0

Quantity per thickness add-on:

c_{SMTQ}	
< 2,000 kg	N/A
< 3,000 kg	90
< 5,000 kg	33
> 5,000 kg	0

Ultrasonic inspection add-on (acc. EN 10160)

c_{SMUT}	
N/A	0
S0+E0	44
S1+E1	48
S2+E2	69
S3+E3	73
100% S1+E2	76

Appendix 9.3 Unit prices of profiles

Hot rolled profiles	Profile	Grade	[€/kg]
	IPE, HEA	S235	1.5
		S355	1.6
	RHS	S355	1.88
	Angles	S235	1.5

Appendix 9.4 Unit prices of bolts, nuts, and washers

DIN931, partially threaded
Hexacon 8.8 Hot dip galvanised

	[€/pcs]					
Length	M12	M16	M20	M24	M30	M36
20	N/A	N/A	N/A	N/A	N/A	N/A
25	N/A	N/A	N/A	N/A	N/A	N/A
30	N/A	N/A	N/A	N/A	N/A	N/A
35	N/A	N/A	N/A	N/A	N/A	N/A
40	N/A	N/A	N/A	N/A	N/A	N/A
45	N/A	N/A	N/A	N/A	N/A	N/A
50	0.39	N/A	N/A	N/A	N/A	N/A
55	0.50	0.78	N/A	N/A	N/A	N/A
60	0.45	0.83	N/A	N/A	N/A	N/A
65	0.56	0.89	1.57	N/A	N/A	N/A
70	0.51	0.94	1.61	N/A	N/A	N/A
75	N/A	1.00	1.70	2.96	N/A	N/A
80	0.58	1.04	1.78	3.01	N/A	N/A
90	0.64	1.16	1.96	3.32	6.99	N/A
100	0.71	1.26	2.11	3.61	7.40	N/A
110	0.76	1.41	2.32	3.89	7.77	N/A
120	0.83	1.53	2.50	4.16	8.14	17.46
130	0.92	1.63	2.65	4.35	8.66	17.65
140	0.99	1.73	2.83	4.63	9.38	18.24
150	1.04	1.86	2.98	4.82	9.85	N/A
160	1.18	2.00	3.20	5.35	10.13	19.31
180	1.25	2.22	3.61	5.91	11.02	20.67
200	1.43	2.48	3.98	6.34	11.78	21.84
220	2.06	3.15	6.94	7.45	12.47	N/A
240	3.28	3.38	7.35	10.11	N/A	24.57
260	3.57	3.91	10.59	12.97	18.47	N/A
280	N/A	5.26	N/A	13.63	N/A	26.72
300	N/A	5.69	11.43	14.07	20.07	N/A

DIN933, fully threaded
Hexacon bolt 8.8 hot dip galvanised

	[€/pcs]					
Length	M12	M16	M20	M24	M30	M36
20	0.26	N/A	N/A	N/A	N/A	N/A
25	0.22	0.49	N/A	N/A	N/A	N/A
30	0.24	0.52	0.93	N/A	N/A	N/A
35	0.26	0.55	1.28	N/A	N/A	N/A
40	0.30	0.58	1.01	2.58	N/A	N/A
45	0.32	0.61	1.13	N/A	N/A	N/A
50	0.36	0.65	1.14	2.78	N/A	N/A
55	N/A	0.72	1.30	2.83	N/A	N/A
60	0.39	0.73	1.36	2.91	5.73	N/A
65	N/A	N/A	N/A	N/A	N/A	N/A

70	0.45	1.04	2.00	3.04	6.09	14.06
75	N/A	N/A	N/A	N/A	N/A	N/A
80	0.64	1.21	2.26	3.30	6.44	N/A
90	0.84	1.51	2.32	3.73	6.70	N/A
100	0.92	2.40	2.39	3.85	7.88	16.08
110	N/A	N/A	N/A	N/A	8.76	N/A
120	1.27	2.54	N/A	4.80	12.60	19.58
130	N/A	N/A	N/A	N/A	N/A	N/A
140	1.36	5.64	N/A	N/A	13.70	N/A
150	N/A	N/A	6.70	9.80	N/A	N/A
160	N/A	N/A	N/A	N/A	N/A	N/A
180	N/A	N/A	N/A	N/A	N/A	27.56
200	N/A	N/A	7.50	N/A	25.30	N/A
220	N/A	N/A	N/A	N/A	N/A	N/A
240	N/A	N/A	N/A	16.25	N/A	N/A
260	N/A	N/A	N/A	N/A	N/A	N/A
280	N/A	N/A	N/A	N/A	N/A	N/A
300	N/A	N/A	N/A	N/A	N/A	N/A

DIN 934-8/10
Nut, hot dip galvanised
[€/pc]

M12	M16	M20	M24	M30	M36
0.10	0.27	0.54	0.98	2.13	4.45

DIN 7989
Washer, hot dip galvanised
[€/pc]

					DIN 125
M12	M16	M20	M24	M30	M36
0.30	0.46	0.65	0.82	1.41	1.76

Appendix 9.5 Unit prices and features of the paints

Paint system	Paint type	Price/film €/l	Volume solids [%]	DFT [microns]	Environmental class	Drying time/film (+23 °C) per film [h]	Total [h]
AK 160/3 - FeSa2½	Alkyd	7 8 48	45 45 80	40 40	C3/M	1+1+1	3
EP 160/3 - FeSa2½	Epoxy	8 8 10	50 50 48	60 60 40	C3/M	4+4+6	14
PUR 120/2 - FeSa2½	Polyurethane	13 13	50 50	60 60	C3/M	24 + 3	27
AY 160/3 - FeSa2½	Acryl	10 10	48 48 40	60 60 40	C3/M	3+3+1	7

Appendix 9.6 Allowable lifting load of nominal crane capacities regarding horizontal distance

(Kobelco 25 tonnes, Liebherr LTM Mobile Crane-series 35 - 500 tonnes)

Horizontal distance [m]	Nominal crane capacity [tonnes] 25	35	50	70	100	200	350	500
3	250	350	500	614	1,000	2,000	3,500	5,000
4	230	262	413	487	671	1,330	1,886	3,250
5	194	207	341	393	571	1,170	1,683	2,610
6	163	171	290	322	485	1,050	1,466	2,310
7	130	142	245	272	419	930	1,257	2,060
8	109	114	186	236	367	820	1,097	1,860
9	86	95	156	208	316	730	971	1,700
10	70	80	134	182	275	630	878	1,550
12	49	60	101	139	222	530	723	1,280
14	41	47	78	110	187	445	612	1,070
16	31	38	64	89	159	385	528	820
18	24	31	54	75	136	330	462	710
20	19	25	44	64	116	292	409	560
22	17	21	37	54	102	261	371	540
24	14	17	31	48	89	232	332	475
26	11	14	27	42	79	207	298	425
28	9		23	36	68	186	268	375
30			19	31	61	167	243	325
32			16	26	53	152	220	285
34			14	21	48	132	198	266
36				18	40	121	185	242
38				14	35	115	170	217
40				12	29	106	156	194
42					26	83	144	161
44					22	80	121	145
46					16	74	116	132
48					13	58	92	119
50					8	49	88	108
52						47	85	96
54						42	69	85
56						40	66	70
58						39	54	64
60						35	51	58
62						33	48	54
64						18	42	50
66						16	39	45
68								41
70								37
72								33
74								29

Appendix 9.7 Example: Cost calculation for assembly using proposed method

Assembly: Welded beam 1A129, see Appendix 9.8.8

Material cost of main profile plates, Function (5)

$$C_{SM} = W_{SMPl} \times (c_{SMBP} + c_{SMG} + c_{SMT} + c_{SMQ} + c_{SMQT} + c_{SMUT})$$

Basic costs of steel material and add-ons are from Appendix 9.2.

Steel grade is S355, and it is assumed that the total quantity of add-ons > 15,000 kg, quantity per thickness is > 5,000 kg, and no ultrasonic test is required.

Web C_{SM} = 1 x 0.37 x 0.006 x 6.407 x 7,850 x (1.169 + 0.035 + 0.082) = €143.59
Flanges C_{SM} = 2 x 0.25 x 0.015 x 6.407 x 7,850 x (1.169 + 0.035) = €454.16
Material, main profile = €597.75

Bolts, nuts and washers material costs are obtained using Function (7) and Appendix 9.3. Bolt length is assumed to be 75 mm for M24 bolts, and 90 mm for M30 bolts.

6 x M24-75 C_{Bo} = 6 x (2.96 + 0.98 + 0.82) = €29 €
6 x M30-90 C_{Bo} = 6 x (6.99 + 2.13 + 1.41) = €63 €
Material, bolting = €91.74

Blasting cost, Function (10)

$$C_B = L_B \times 0.000363$$

Web L_B = 6,407 mm C_B = €2.33
Flanges L_B = 6,407 mm C_B = 2 x 2.33= €4.66
Blasting = €6.99

In cutting of main profile plates, as thicknesses of all plates are less than 30 mm, plasma cutting Function (17) will be used

$$C_{Cu} = 3.96 + L_{Cu}/(6.76 \times t^2 - 368.84 \times t + 6{,}178.64) + L_{Cu}/(17.84 \times t^2 - 973.74 \times t + 16{,}311.60)$$

Web L_{Cu} = 2 x (370 + 6407) = 13,554 mm t = 6 mm C_{CU} = €8.40
Flanges, total 2 pcs L_{Cu} = 2 x (250 + 6407) = 13,314 mm t = 15 mm C_{CU} = 2 x €12.43
Cutting = €33.26

Beam welding, Function (22)

$$\mathrm{C_{BW}} = (76.26 + \mathrm{n_{wh}} \times 40.37) \times L_w \times a^2 \times 10^{-6} + 8.5 \ [€]$$

n_{wh} = 2 (two welding heads), L_w = 6,407 mm, a = 5 mm

C_{BW} /side= €33.94 → C_{BW} = 2 x 33.94 = €67.88
Beam welding = €67.88

Sawing, Function (36)

$$C_S = (4.5 + 1_{(bevel1)} + 1_{(bevel2)} + L/20{,}000 + \sum_{i=1}^{2}(h_i/(S \times S_m) + A_{hi}/Q)) \times (0.46 + 0.21 + 0.01 + 0.21 + 0.31\ ) + \sum_{i=1}^{2}(h_i/(S \times S_m) + A_{hi}/Q) \times (A_{ti}/(S_t \times (h_i/(S \times S_m) + A_{hi}/Q)) \times 100 + 0.02)\Big)$$

Both ends are perpendicular, so bevel add-ons will be omitted. The main profile will be sawn with the web in the horizontal position, thus *h* = 250 mm.

For sawing of the vertical flanges, the feeding speed S must be solved using Function (29)

$$S = 0.0328 \times t_{mv}^2 - 3.1794 \times t_{mv} + 115.6$$

t_{mv} = 15 mm → *S* = 75.29 mm/min

S_m = 0.9 for material S355

A_h = 6 x 370 = 2,220 mm^2

A_t = 6 x 370 + 2 x 15 x 250 = 9,720 mm^2

Q = 8 800 mm^2/min for S355

$$S_t = -1{,}188 \times t_{mv}^2 + 188{,}892 \times t_{mv} + 4{,}414{,}608$$

t_{mv} = 15 mm → S_t = 6,980,688 mm^2

L = 6,407 mm

C_S = (4.5 + 0 + 0 + 6 407/20,000 + 2 x (250/(75.29 x 0.9) + 2,220/8,800)) x 1.20 + 2 x (250/(75.29 x 0.9) + 2,220/8,800) x (9,720/(6,980,688 x (250/(75.29 x 0.9) + 2,220/8,800)) x 100 + 0.02) = €15.70

Sawing = €15.70

Drilling main profile, Function (48)

$$C_D = (4.65 + (r_f - 1) \times 0.4 + \sum_{r=1}^{r_f} max \sum_{i=1}^{3}(n_{ri} - 1) \times 0.1 + L/20{,}000\ +\ \big(2.4 + (r_s - 1) \times 0.4 + \sum_{r=1}^{r_s}(n_{r4} - 1) \times 0.1 + 2 \times L/20{,}000\big) + \sum_{i=1}^{r_f} \max \sum_{j=1}^{3} n_{ij} \times \frac{d_{ij}}{12{,}732} \times t_j/(-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) + \sum_{i=1}^{r_s}\ n_{is} \times \frac{d_{i4}}{12{,}732} \times t_4/(-0.0002 \times d_{i4}^2 + 0.0141 \times d_{i4} + 0.1354\ \ )) \times (0.46 + 0.34 + 0.01 + 0.21\ \ \ + 0.31)/1 + \sum_{j=1}^{4} \sum_{k=1}^{n_{dd}} p_{DBk} \times n_k \times \frac{d_{kj}}{12{,}732} \times t_j/(-0.0002 \times d_{kj}^2 + 0.0141 \times d_{kj} + 0.1354) + (\sum_{i=1}^{r_f} \max \sum_{j=1}^{3} n_{ij} \times \frac{d_{ij}}{12{,}732} \times t_j/(-0.0002 \times d_{ij}^2 + 0.0141 \times d_{ij} + 0.1354) + \sum_{i=1}^{r_s}\ n_{is} \times \frac{d_{i4}}{12{,}732} \times t_4/(-0.0002 \times d_{i4}^2 + 0.0141 \times d_{i4} + 0.1354\ \ ) \times 0.02)$$

In assembly 1A129 all holes are located on surface 1, so only one run is needed. The number of rows is 14, and three sizes of drill bits are used. Thus r_f = 14 and n_{dd} = 3.

$$C_D = (4.65 + (14-1) \times 0.4 + \sum_{r=1}^{14}(n_r - 1) \times 0.1 + L/20{,}000 + \sum_{i=1}^{14} n_{i1} \times \frac{d_{i1}}{12{,}732} \times t_1/(-0.0002 \times d_{i1}^2 + 0.0141 \times d_{i1} + 0.1354)) \times (0.46 + 0.34 + 0.01 + 0.21 \ + 0.31)/1 + \sum_{k=1}^{3} p_{DBk} \times n_k \times \frac{d_k}{12{,}732} \times t_1/(-0.0002 \times d_k^2 + 0.0141 \times d_k + 0.1354) + (\sum_{i=1}^{14} n_{i1} \times \frac{d_{i1}}{12{,}732} \times t_1/(-0.0002 \times d_{i1}^2 + 0.0141 \times d_{i1} + 0.1354)) \times 0.02)$$

Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	∑
t_1	15	15	15	15	15	15	15	15	15	15	15	15	15	15	
d_{i1}	18	18	18	18	14	14	18	18	14	14	18	18	22	22	
n_r	2	2	2	2	2	2	2	2	2	2	2	2	2	2	28
n_{i1}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	28
$(n_r\text{-}1)x0.1$	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.40
n_{i1} x d_{i1}/12,732 x t_1 / (-0.0002 x d_{i1}^2+0.0141 x d_{i1}+0.1354)	0.13	0.13	0.13	0.13	0.11	0.11	0.13	0.13	0.11	0.11	0.13	0.13	0.15	0.15	1.79

Table 15. Drilling time of individual rows

d_k	14	18	22	∑
t_1	15	15	15	
n_k	8	16	4	
n_k x d_k/12,732 x t_1 / (-0.0002 x d_{i1}^2+0.0141 x d_{i1}+0.1354)	0.,45	1.05	0.30	1.79

Table 16. Drilling time with individual drill bits

L = 6 407 mm
p_{DB1} = €0.09/min, p_{DB2} = €0.14/min, p_{DB3} = €0.16/min

$$C_D = (4.65 + (14-1) \times 0.4 + 1.4 + 6\ 407/20{,}000 + 1.79) \times (0.46 + 0.34 + 0.01 + 0.21 \ + 0.31)/1 + 0.09 \times 0.45 + 0.14 \times 1.05 + 0.16 \times 0.30 + (045 + 1.05 + 0.30) \times 0.02)$$

C_d = (4.65 + 5.20 + 1.4 + 0.32 + 1.79) x 1.33 + 0.24 + 0.04 = €18.04

Drilling = €18.04

Fabrication of parts, using the cutting process for plates t < 30 mm, Function (58)

$$C_{PF} = C_{SM} + L \times 0.000363 + 3.96 + L_{CuA}/(6.76 \times t^2 - 368.84 \times t + 6{,}178.64) + L_{CuA}/(17.84 \times t^2 - 973.74 \times t + 16{,}311.60)$$

Material

Basic costs of material and add-ons are obtained from Appendix 9.2. It is assumed that total quantity < 5,000 kg, quantity per thickness < 3,000 kg, and no ultrasonic test is required. Note that the total amount of part 1L169 is 4 pcs.

1L6 C_{SMp} = 1 x 0.23 x 0.025 x 0.38 x 7850 x (1.169 + 0.035 + 0.012 + 0. 064 + 0.094) = €23.50
1L169 C_{SMp} = 4 x 0.12 x 0.010 x 0.368 x 7850 x (1.169 + 0.035 + 0.012 + 0. 064 + 0.094) = €19.00
1L714 C_{SMp} = 1 x 0.18 x 0.020 x 0.405 x 7850 x (1.169 + 0.035 + 0.012 + 0. 064 + 0.094) = €15.68
Material, parts = €58.18

Blasting
1L6 L_A = 380 mm C_B = 1 x €0.14
1L169 L_A = 368 mm C_B = 4 x €0.52
1L714 L_A = 405 mm C_B = 1 x €0.15
Blasting, parts = €0.81

Cutting, edges and holes

1L6 L_{CuA} = 2 x (230 + 380) + 6 x 2π x 13 = 1,710 mm t = 25 mm C_{CU} = 1 x €5.95
1L169 L_{CuA} = 2 x (120 + 368) = 976 mm t = 10 mm C_{CU} = 4 x €4.39
1L714 L_{CuA} = 2 x (180 + 405) + 6 x 2π x 15 = 1,736 mm t = 20 mm C_{CU} = 1 x €5.55
Cutting, parts = €29.06

Fabrication of parts = €88.05

Assembling, Function (74)

$$C_{PA} = (1.59 \times n_{tw} + L_{fw}/1{,}000 \times (0.4988 \times a^2 - 0.0005 \times a + 0.0021) + L_{bw}/1{,}000 \times (0.249 \times b^2 + 0.0096 \times b - 0.0506) + n_p \times 0.5 + n_b \times 0.75) \times (0.46 + 0.01 + 0.03 \ + 0.04)/1 + (L_{fw} \times a^2 + L_{bw} \times b^2/2) \times 7.85 \times 10^{-6} \times (1.91 + 0.44) + (L_{fw}/1{,}000 \times (0.4988 \times a^2 - 0.0005 \times a + 0.0021) + L_{bw}/1{,}000 \times (0.249 \times b^2 + 0.0096 \times b - 0.0506) \times 0.01))$$

1L6:
n_w = 1, L_{fw1} = 908 mm, a_1 = 8 mm, L_{fw2} = 740 mm, a_2 = 3 mm, value of other variables is 0.

C_{PA} = (1.59 x 1 + 908/1,000 x (0.4988 x 8^2-0.0005 x 8 + 0.0021) + 740/1,000 x (0.4988 x 3^2-0.0005 x 3 + 0.0021) x (0.46 + 0.01 + 0.03 + 0.04) + (908 x 8^2 + 740 x 3^2) x 7.85 x 10^{-6} x (1.91 + 4.44) +(908/1,000 x (0.4988 x 8^2-0.0005 x 8 + 0.0021) + 740/1,000 x (0.4988 x 3^2 - 0.0005 x 3 + 0.0021) x 0.01= 22.10 €

1L169
n_w = 1, L_{fw1} = 1,216 mm, a_1 = 3 mm,

C_{PA} = (1.59 x 1 + 1,216/1,000 x (0.4988 x 3^2-0.0005 x 3 + 0.0021) x (0.46 + 0.01 + 0.03 + 0.04) + 1,216 x 3^2 x 7.85 x 10^{-6} x (1.91 + 4.44) + 1,216/1,000 x (0.4988 x 3^2 - 0.0005 x 3 + 0.0021) x 0.01= €4.46

1L714
n_w = 1, L_{fw1} = 720 mm, a_1 = 6 mm, L_{fw2} = 740 mm, a_2 = 3 mm

C_{PA} = (1.59 x 1 + 720/1,000 x (0.4988 x 6^2-0.0005 x 6 + 0.0021) + 740/1,000 x (0.4988 x 3^2-0.0005 x 3 + 0.0021) x (0.46 + 0.01 + 0.03 + 0.04) + (720 x 6^2 + 740 x 3^2) x 7.85 x 10^{-6} x (1.91 + 4.44) +(720/1,000 x (0.4988 x 6^2-0.0005 x 6 + 0.0021) + 740/1,000 x (0.4988 x 3^2 - 0.0005 x 3 + 0.0021) x 0.01= €11.55
C_{PA} = 22.10 + 4 x 4.46 + 11.55 = €51.49

Assembling = €51.49

Post-treatment, Function (77)

$$C_{PT} = (L_{PT} \times 0.0005 + L_{UT} \times 0.06 + L_{MT} \times 0.015) \times (0.46 + 0.03 \ + 0.04)/1$$

L_{PT} = 2x2x(250+6,407) + 2x(370+6,407)+2x(230+380)+4x2x(120+368)+2x(180+405) = 46,476 mm

L_{UT} = 0 , L_{MT} = 0

C_{PT} = €12.54

Post treatment = €12.54

Coating, Function (93) EP-painting system and Function (99) for drying

$$C_P = 4.39E - 06 \times A$$

$$C_{Dy} = 1.7 \times L_A \times W_{Amin}$$

A = 2x2x250x6,407+2x370x6,407+2x230x380+4x2x120x368+2x180x405 = 11,822,060 mm^2
L_A = 6.452 m, W_{Amin} = 0.250 m

CP = 0.00000439 x 11,822,060 = €51.90
Cdy = 1.7 x 6,452 x 250 = €2.74

Coating = €54.64

In transporting cost calculation, when the ratio of weight to volume (531kg / 0.67 m3= 793) exceeds 264, Function (103) will be used as follows

W_A = 531 kg, d = 250 km

C_T = 531 x (0.00004 x 250 + 0.0048) = €7.86

Transporting = €7.86

In erection, Function (110) will be used when the assembly is a beam, and the following values are chosen:
l_s = 15 m, n_{b1} = 6 pcs, n_{b2} = 6 pcs, L_A = 6 452 mm, N_c = 25 tonnes, h_s = 10 m.

$$C_E = (63 \times l_s/972 + 0.5 \times (n_{b1} + n_{b2}) - 0.86 + L_A/30{,}000) \times (2.60 + 0.5 + 0.1 + 0.0153 \times Nc + 0.758 \ + \ 0.0146 \times h_s - 0.0277 \ ) /0.36$$

C_E = (63 x 15 / 972 + 0.5 x (6 + 6) - 0.86 + 6,452 / 30,000) x (2.6 + 0.5 + 0.1 + 0.0153x25 + 0.758 + 0.0146x10 - 0.0277) / 0.36 = 78.37 €

Erecting = €78.37

The total costs of the material, manufacturing, transporting and erecting of assembly 1A129 = 597.75 + 91.74 + 33.26 + 6.99 + 72.40 + 15.70 + 18.04 + 88.05 + 51.49 + 12.31 + 54.64 + 7.86 + 78.37 = €1,124

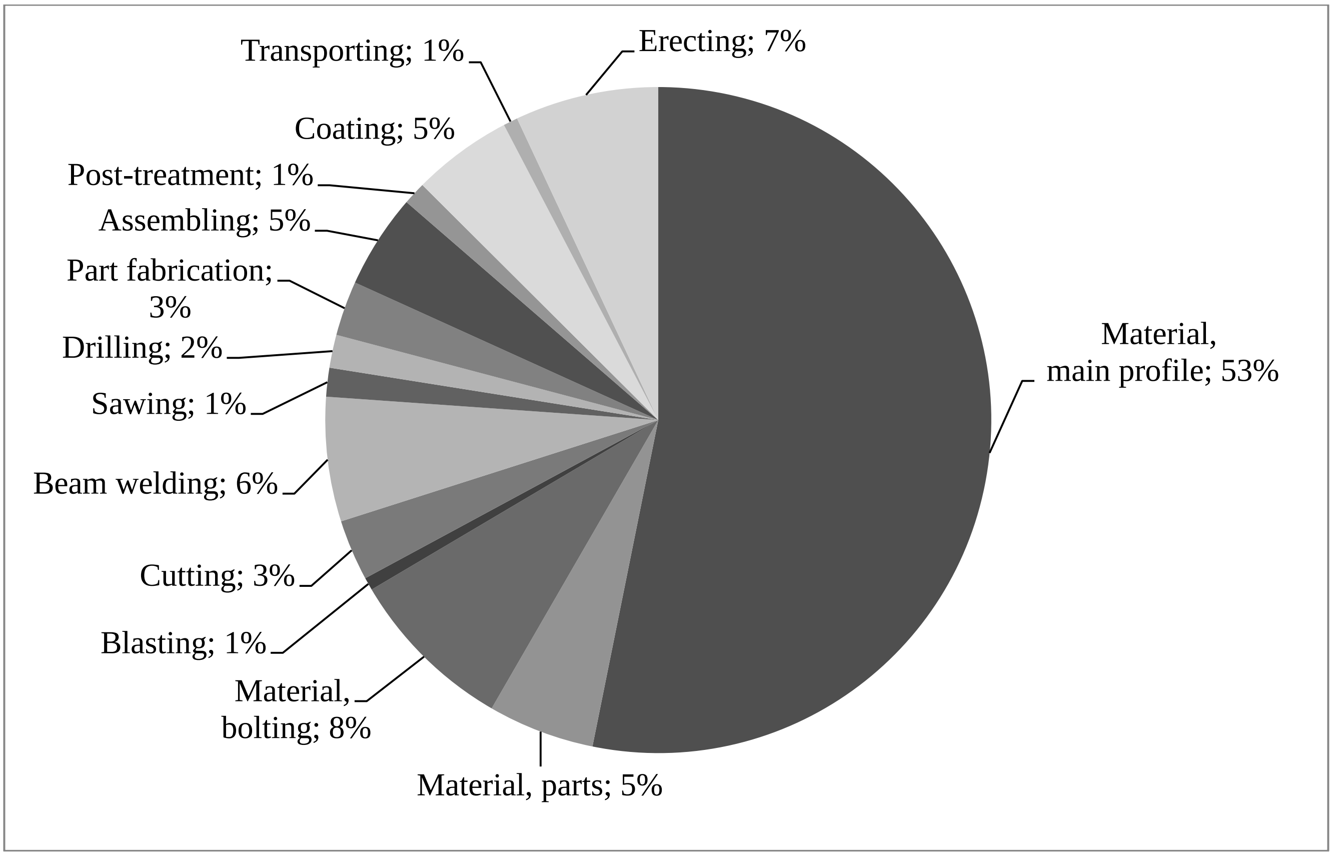
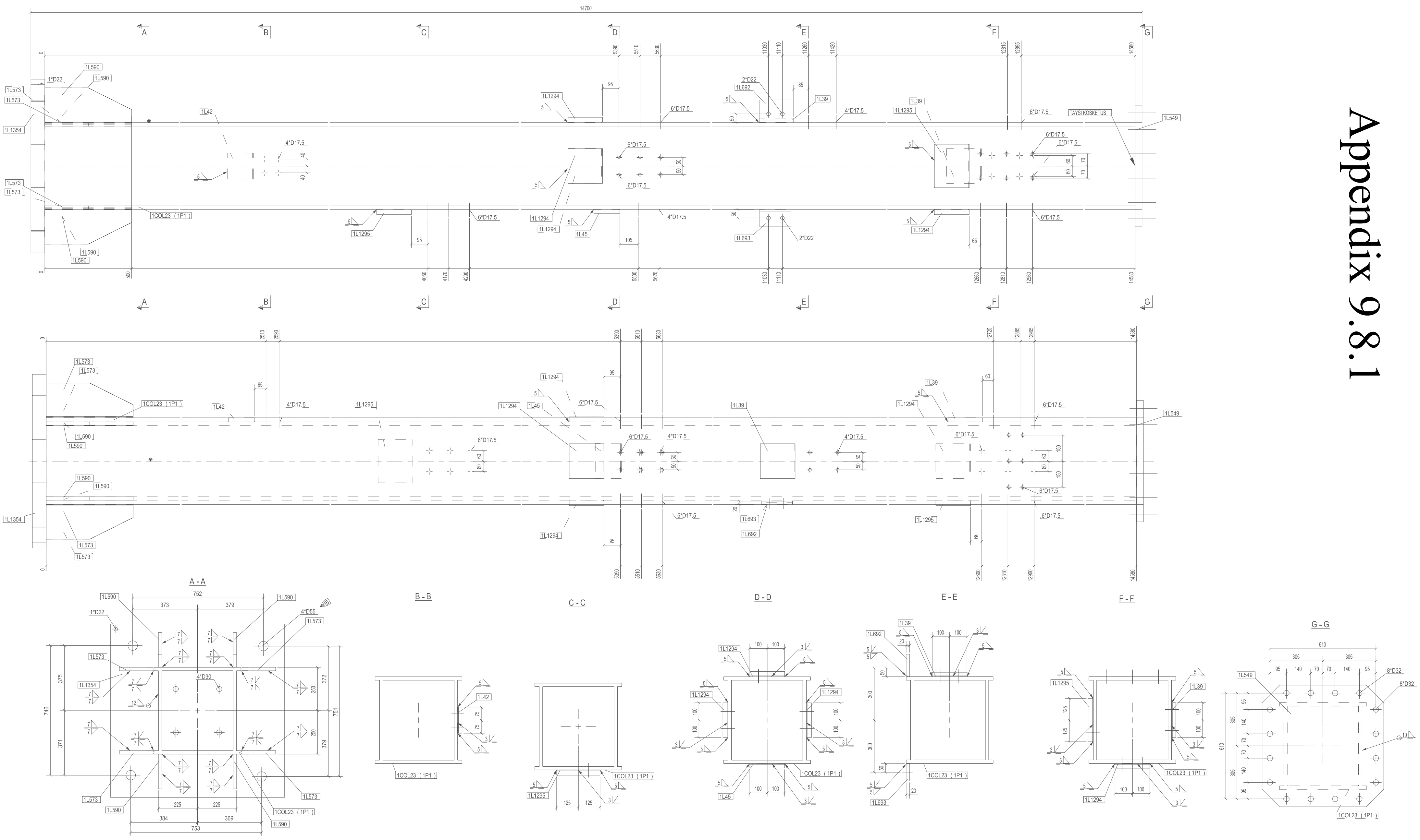


Fig. 63. Distribution of costs of assembly 1A129.

Appendix 9.8 Drawings of the test assemblies

9.8.1 UPG1
9.8.2 UPG2
9.8.3 UPG3
9.8.4 UPG4
9.8.5 UPG5
9.8.6 UPG6
9.8.7 UPG7
9.8.8 UPG8

Appendix 9.8.1



PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L39	PL25X200	S355J2	200	0.2	7.8	2
1L42	PL25X150	S355J2	150	0.1	4.4	1
1L45	PL25X200	S355J2	150	0.1	5.9	1
1L549	PL40X700	S355J2	700	1.0	147.6	1
1L573	PL20X200	S355J2	500	0.8	13.1	4
1L590	PL20X200	S355J2	500	0.8	13.2	4
1L692	PL20X180	S355J2	130	0.1	3.6	1
1L693	PL20X180	S355J2	100	0.0	2.8	1
1L1294	PL30X200	S355J2	200	0.4	9.4	4
1L1295	PL30X250	S355J2	200	0.3	11.8	2
1L1354	PL80X1000	S355J2	1000	2.3	628.0	1
1P1	WB500-20-20X500-25	S355J2	14580	30.6	4395.0	1
			TOTAL:	36.6	5369.2	

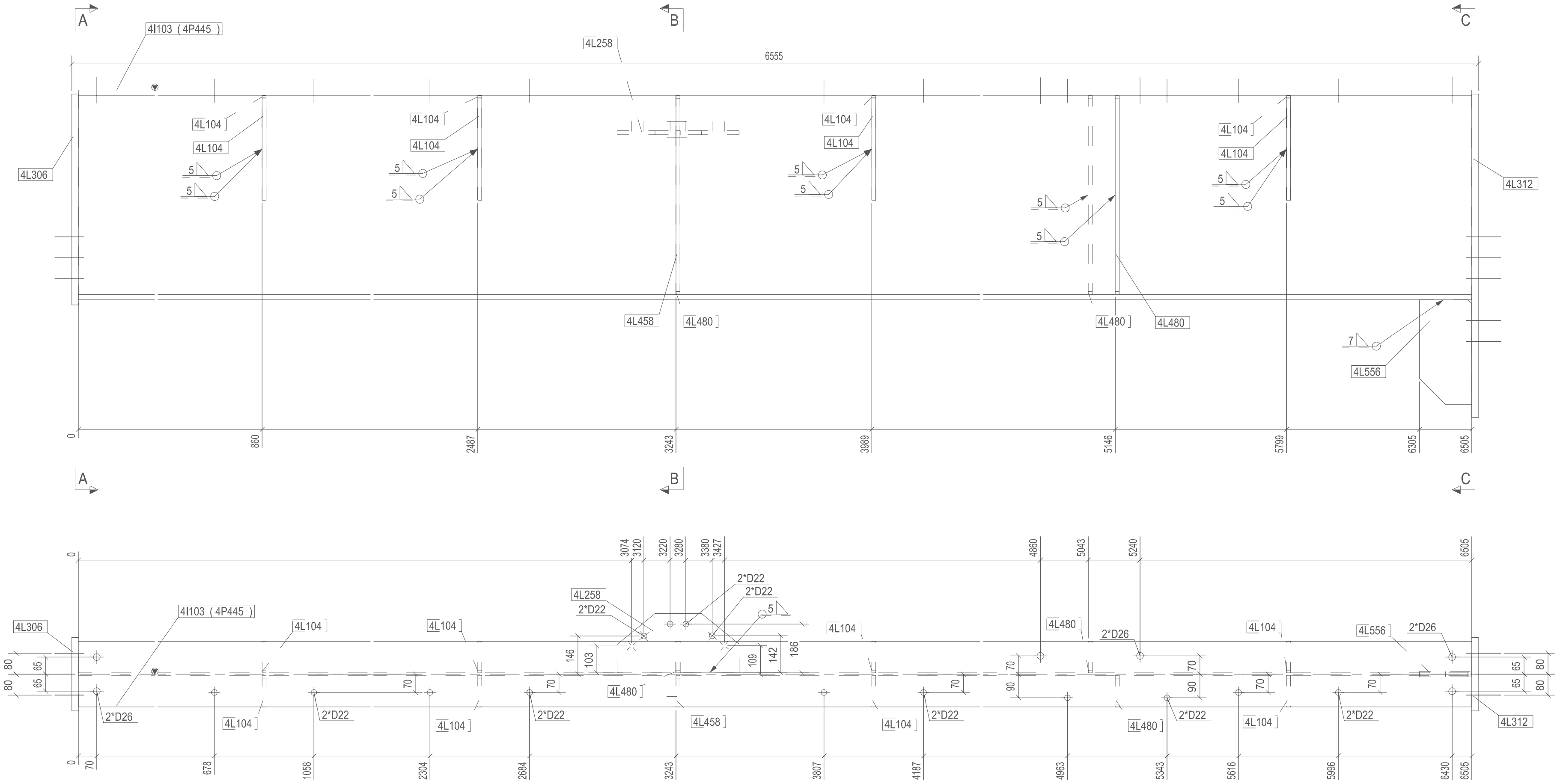
Technical requirements during fabrication

Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, If not specified elsewere EN 29692	Welding class C, EN25817

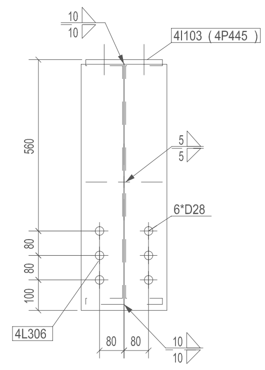
UPG 1

Appendix 9.8.2

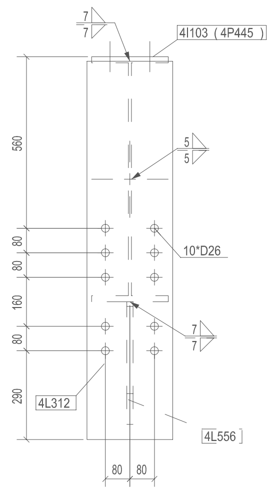
UPG 2



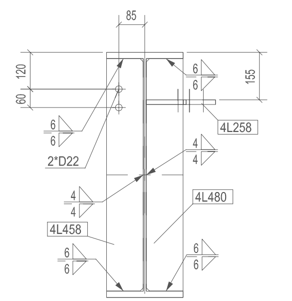
A - A



C - C



B - B



PART LIST

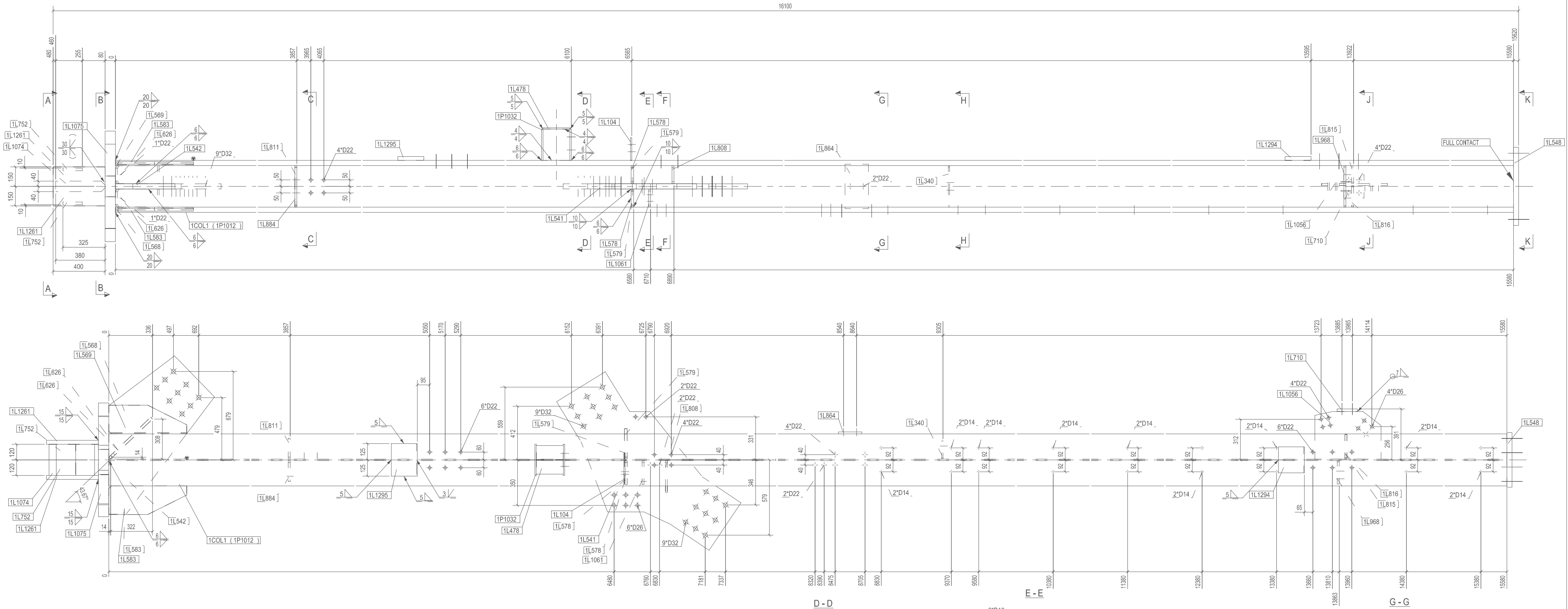
PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
4L104	PL15X120	S355J2	400	0.9	5.6	8
4L258	PL15X226	S355J2	466	0.2	10.2	1
4L306	PL25X280	S355J2	805	0.5	44.2	1
4L312	PL25X280	S355J2	1235	0.8	67.9	1
4L458	PL15X120	S355J2	758	0.2	10.7	1
4L480	PL15X120	S355J2	758	0.6	10.7	3
4L556	PL20X200	S355J2	400	0.2	11.8	1
4P445	WI800-10-20X250	S355J2	6505	16.9	898.7	1
			TOTAL:	20.3	1120.7	

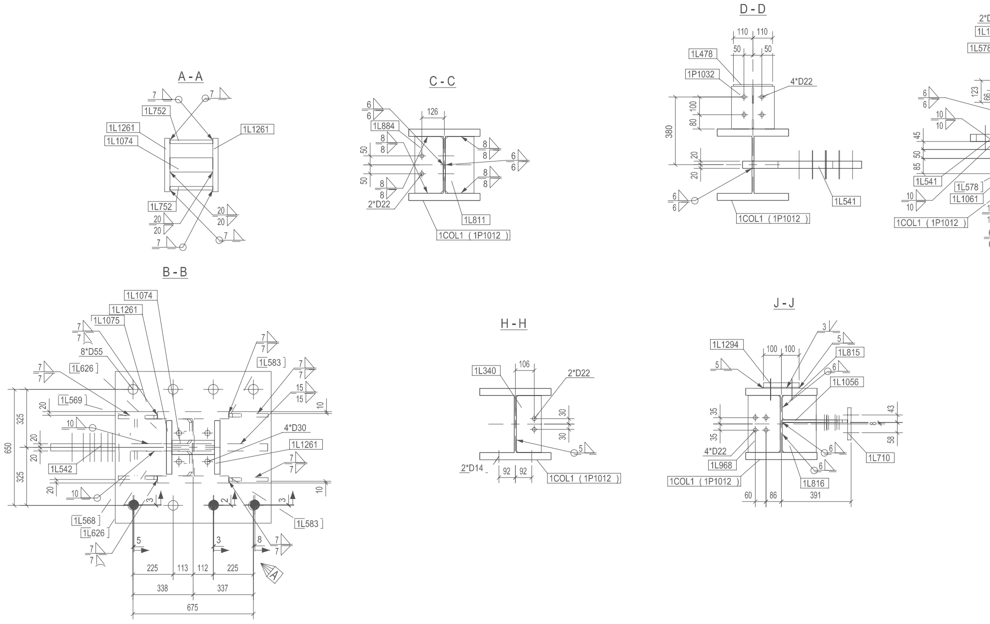
Technical requirements during fabrication

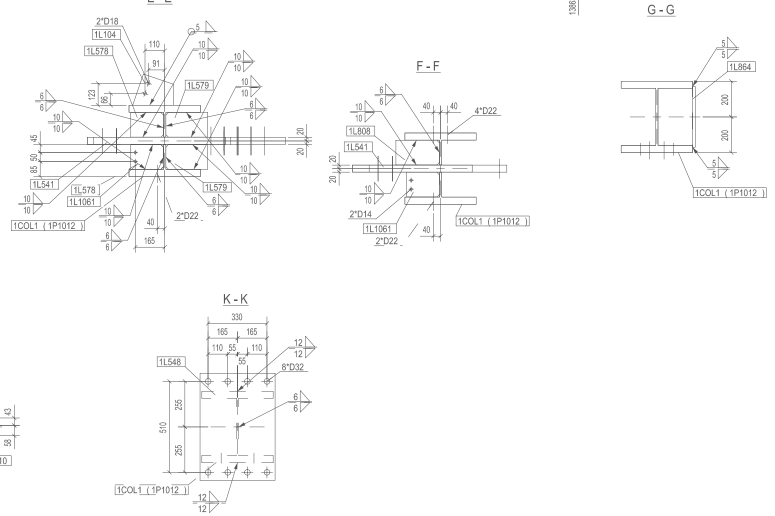
Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewere EN 29692 a 4 / 4 a	Welding class C, EN25817

Appendix 9.8.3

UPG 3







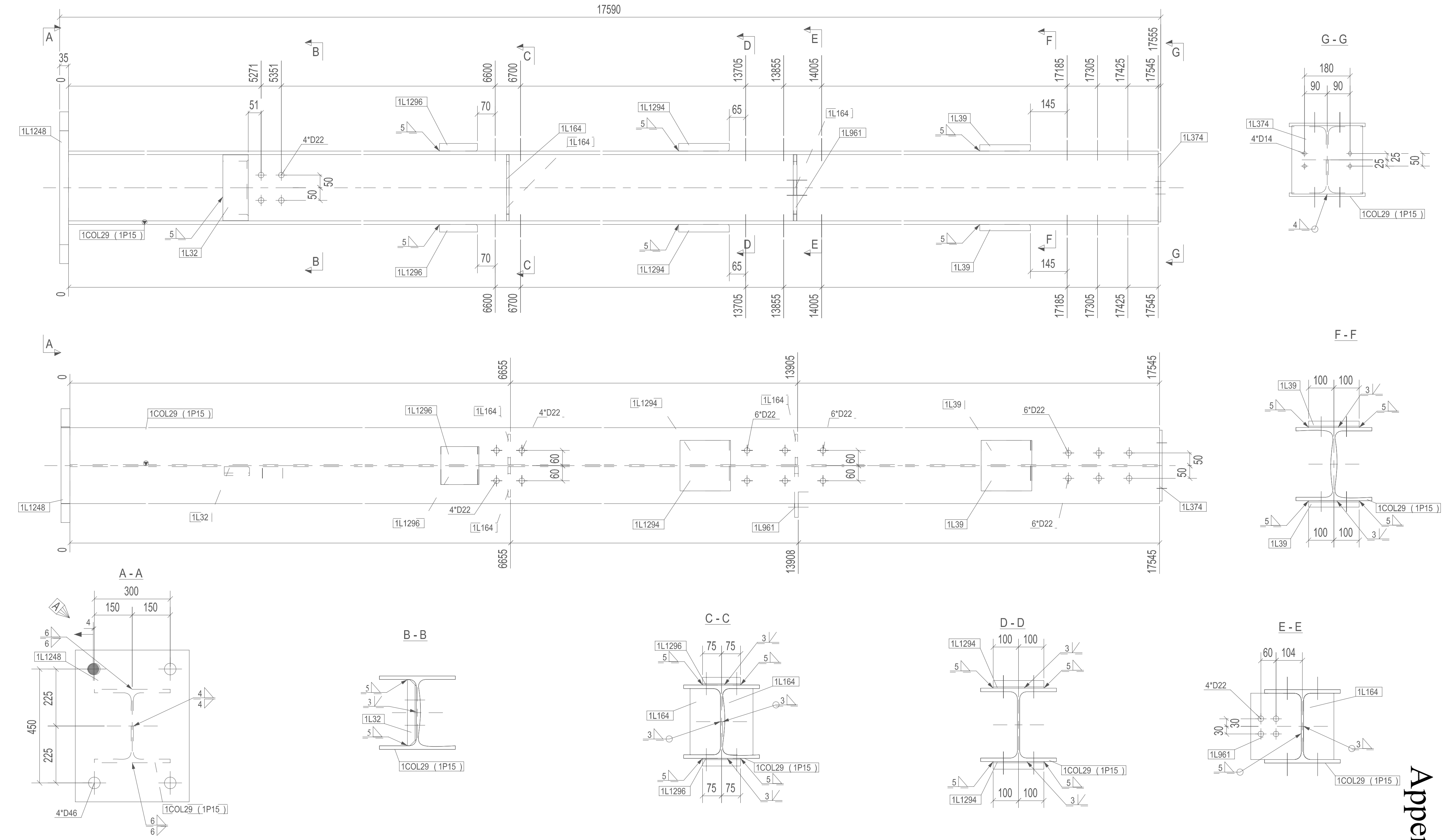
PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L104	PL10X175	S355J2	229	0.1	2.4	1
1L340	PL10X140	S355J2	318	0.1	3.5	1
1L478	PL10X220	S355J2	210	0.1	3.6	1
1L541	PL40X1612	S355J2	884	1.8	258.8	1
1L542	PL40X813	S355J2	1217	1.2	168.8	1
1L548	PL40X420	S355J2	600	0.6	79.1	1
1L568	PL20X220	S355J2	600	0.2	17.0	1
1L569	PL20X220	S355J2	600	0.2	17.0	1
1L578	PL20X138	S355J2	184	0.1	4.0	2
1L579	PL20X138	S355J2	234	0.2	5.0	2
1L583	PL20X220	S355J2	600	0.5	17.2	2
1L626	PL20X138	S355J2	446	0.3	9.6	2
1L710	PL20X180	S355J2	156	0.1	4.4	1
1L752	PL20X150	S355J2	240	0.2	5.7	2
1L808	PL15X138	S355J2	244	0.1	3.9	1
1L811	PL15X160	S355J2	318	0.1	6.0	1
1L815	PL15X136	S355J2	190	0.1	3.0	1
1L816	PL15X166	S355J2	190	0.1	3.7	1
1L864	PL15X180	S355J2	340	0.1	7.2	1
1L884	PL15X160	S355J2	318	0.1	6.0	1
1L968	PL15X180	S355J2	318	0.1	6.7	1
1L1056	PL15X365	S355J2	509	0.4	20.8	1
1L1061	PL15X138	S355J2	184	0.1	3.0	1
1L1074	PL80X240	S355J2	380	0.3	55.6	1
1L1075	PL80X850	S355J2	875	1.8	467.1	1
1L1261	PL30X300	S355J2	400	0.6	28.3	2
1L1294	PL30X200	S355J2	200	0.1	9.4	1
1L1295	PL30X250	S355J2	200	0.1	11.8	1
1P1012	WI400-12-40X400	S355J2	15580	37.4	4378.4	1
1P1032	HEA240	S355J2	240	0.3	13.8	1
			TOTAL:	47.4	5690.2	

Technical requirements during fabrication

Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewere EN 29692 a 4 / 4 a	Welding class C, EN25817

Appendix 9.8.4



UPG 4

PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L32	PL35X260	S355J2	100	0.1	6.6	1
1L39	PL25X200	S355J2	200	0.2	7.8	2
1L164	PL10X120	S355J2	262	0.2	2.4	3
1L374	PL10X280	S355J2	270	0.2	5.9	1
1L961	PL15X200	S355J2	262	0.1	6.1	1
1L1248	PL35X450	S355J2	600	0.6	74.2	1
1L1294	PL30X200	S355J2	200	0.2	9.4	2
1L1296	PL30X150	S355J2	150	0.1	5.3	2
1P15	HEA300	S355J2	17545	30.1	1463.6	1
			TOTAL ::	31.8	1608.9	

Technical requirements during fabrication

Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extent of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extent of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewhere EN 29692 a 4	Welding class C, EN25817

Appendix 9.8.5

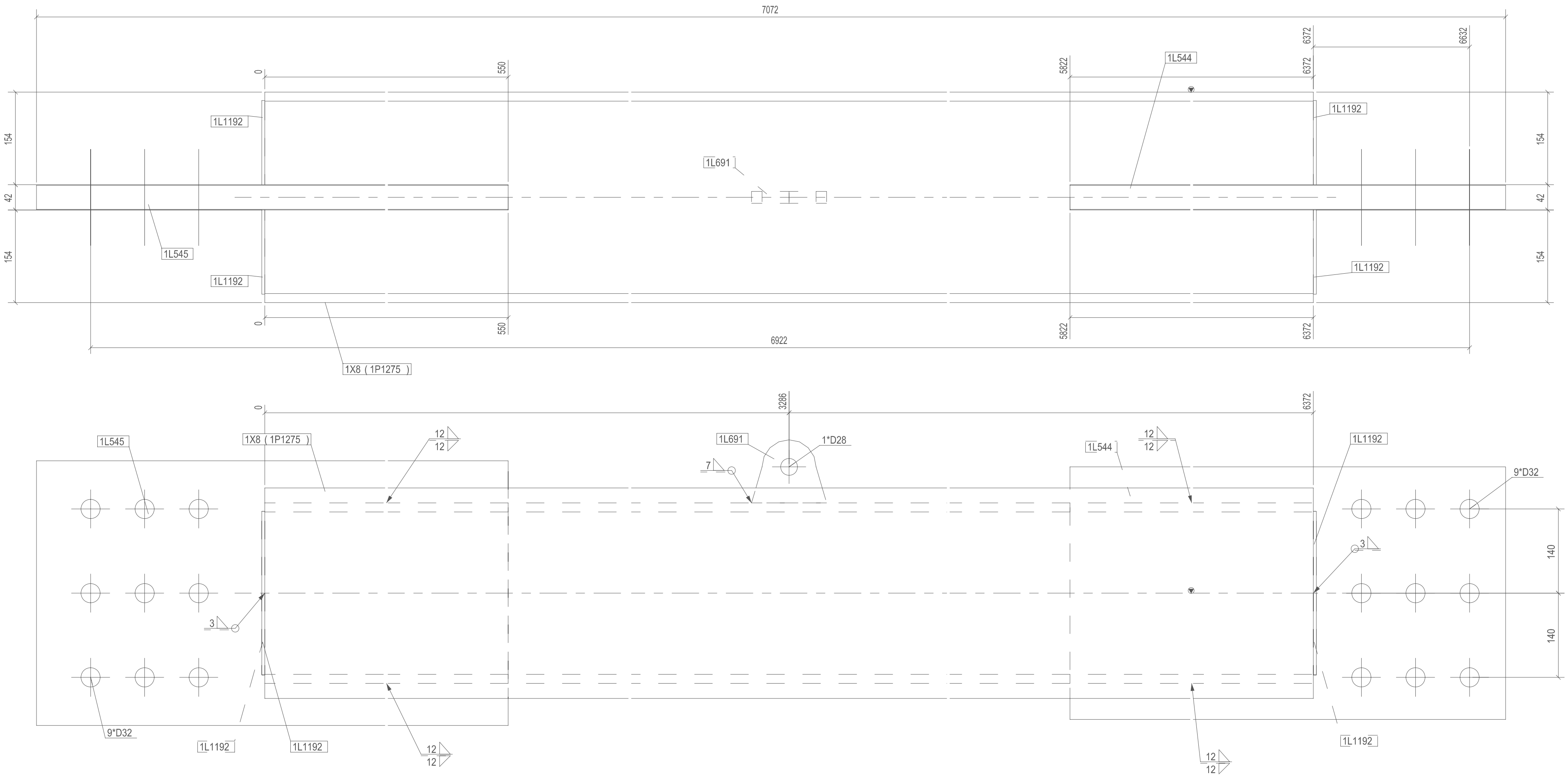
UPG 5

Technical requirements during fabrication	
Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewere EN 29692 a 4 / 4 a	Welding class C, EN25817

PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L69	PL10X140	S355J2	225	0.1	2.5	2
1L1184	PL5X50	S355J2	110	0.1	0.2	4
1P573	CFRHS120X120X5	S355J2H	2178	1.0	39.2	1
			TOTAL :	1.2	45.0	

Appendix 9.8.6

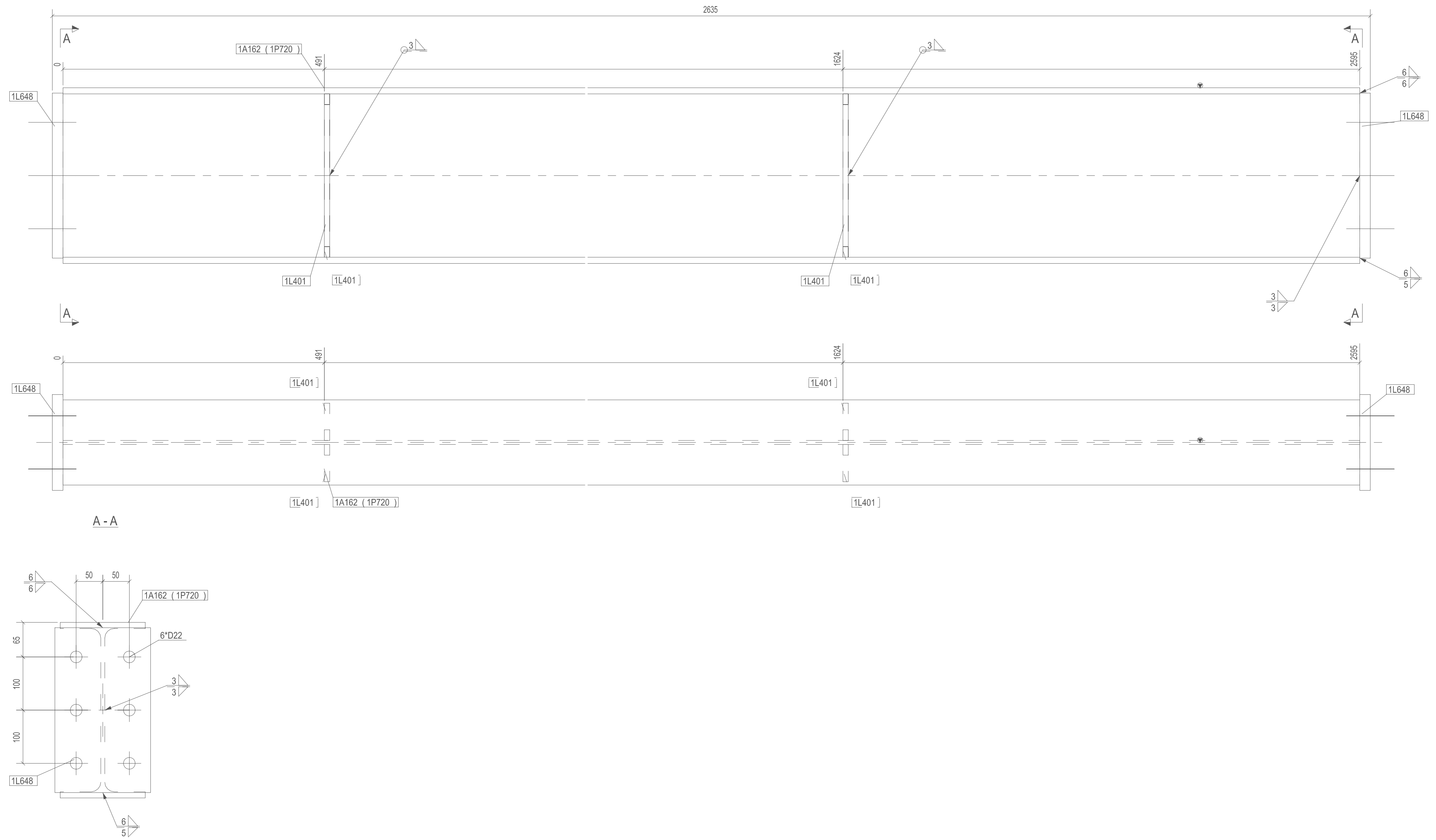


UPG 6

PART LIST						
PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L544	PL40X420	S355J2	870	0.8	114.7	1
1L545	PL40X440	S355J2	930	0.9	128.5	1
1L691	PL20X105	S355J2	125	0.0	1.5	1
1L1192	PL5X140	S355J2	272	0.3	1.5	4
1P1275	WB350-15-15X350-25	S355J2	6372	9.6	994.5	1
			TOTAL :	11.7	1245.2	
R						
	R					0

Technical requirements during fabrication	
Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewere EN 29692 a 4 4 a	Welding class C, EN25817

Appendix 9.8.7



UPG 7

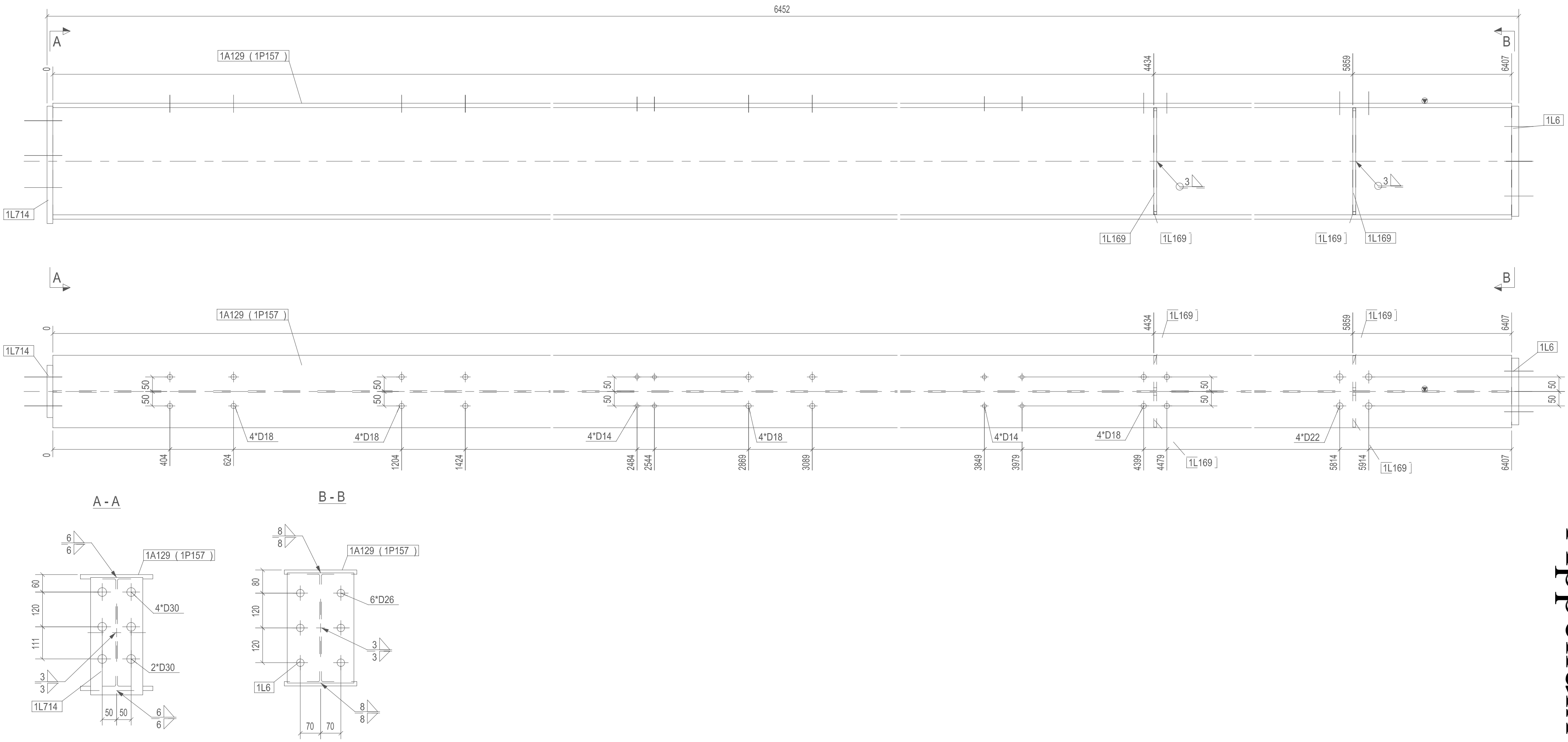
Technical requirements during fabrication	
Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elsewere EN 29692 a 4 / 4 a	Welding class C, EN25817

PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L401	PL10X70	S355J2	307	0.2	1.7	4
1L648	PL20X180	S355J2	310	0.3	8.8	2
1P720	IPE330	S355J2	2595	3.3	121.9	1
			TOTAL:	3.7	146.1	

Appendix 9.8.8

UPG 8



Technical requirements during fabrication	
Project plan, document number	Fabrication tolerances ENV1090-1, section 11
Standard related to fabrication ENV1090-1	Additional requirements for tolerances Project plan and quality specification
Class of surface cleaning ISO8501-3, P3	Inspection of welds, general requirements ENV1090-1 + project plan and quality specification
Surface treatment SFS-EN-ISO12944-5	Additional weld inspections, extend of NDT, fillet welds Project plan and quality specification
Additional requirements for surface treatment 180/2 - FeSa2½	Additional weld inspections, extend of NDT, butt welds Project plan and quality specification
Colour code RAL7016	Inspection of material during fabrication Project plan
Welds of fabricated profile According to fabrication drawing	Requirements for hole forming ENV1090-1, section 6.6 + project plan
Size of weld, if not specified elseware EN 29692 a 4 / 4 / a	Welding class C, EN25817

PART LIST

PART	PROFILE	MATERIAL	LENGTH [mm]	AREA [m2]	WEIGHT [kg]	pcs
1L6	PL25X230	S355J2	380	0.2	17.2	1
1L169	PL10X120	S355J2	368	0.4	3.5	4
1L714	PL20X180	S355J2	405	0.2	11.4	1
1P157	WI400-6-15X250	S355J2	6407	11.5	488.9	1
			TOTAL :	12.3	531.3	

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