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Using engineering documentation to create a data framework for life cycle inventory of welded structures

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Abstract

Welding is considered an energy-intensive manufacturing system and it represents one of the most impacting construction process. The paper aims to define a structured data framework for life cycle inventory of a welding process starting from engineering and design documentation. The use of design documentation allows to perform robust LCA analysis which permits to compare the environmental performances of the most widely used welding technologies early in the design process. The necessary information to fill the data framework can be retrieved by available documentation developed in the preliminary design phase allowing to anticipate the life cycle analysis before the construction phase. A ship hull structure designed to be manufactured by the use of GMAW and GTAW welding processes has been analyzed as case study. The use of data framework facilitates the inventory phase creating a consistent and robust inventory for LCA.

Keywords: LCA; LCI; welding technologies; data framework; documentation;

1. Introduction

Welding is a consolidated joining technology widely used in different industries, such as automotive, shipbuilding, oil and gas and industrial/chemical plants. Welding is considered an energy-intensive manufacturing system, and for this reason, it requires be investigated from the sustainability perspective, which means economic, environmental and social [1]. Metal arc welding processes are intensively used in daily manufacturing activities, and the interest in the environmental impact of consolidated welding technologies is growing over time. They include different technologies such as gas metal arc welding (GMAW), shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), etc. [2]. All these processes are characterized by a large number of parameters which require the adoption of a data framework able to consolidate process inputs and outputs [3]. This is a critical issue in the analysis of life cycle performances of products and large structures manufactured by the use of welding processes. In addition, this task is even more challenging during the design phase when the available data is limited but corrective actions can be put on place [4]. The definition of an efficient and robust data collection passes through the analysis of engineering product documents which are usually stored in different repositories (PLM, CAD, etc.) and available in different formats [5].

Focusing on the environmental issue related to the welding processes, different research topics have been investigated: (i) environmental comparison of welding technologies through life cycle assessment (LCA), (ii) environmental analysis of products manufactured by the use of welding processes, and (iii) data collection for environmental assessment of a welding process. Concerning the environmental comparison of welding

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technologies, the literature is limited. Sproesser et al. (2015) [6] compared metal arc welding variants to join a plate of 20 mm-thick structural steel, while Shrivastava et al. (2015) [7] compared the energy and environmental performances of friction stir welding vs. GMAW processes. Both works provide an interesting overview of the analyzed processes and how to use the outcomes to develop design strategies for improving the welding technologies. However, important aspects, such as the quantification of the welding attributes (e.g. bevels, filler materials, fumes, etc.) for each technology, are missing. Concerning the environmental analysis of products manufactured using welding processes, the literature is quite broad. For example, Ardente et al., 2005 [8] analyzed the SMAW process for the manufacturing of a solar thermal collector, while Zhang et al., 2008 [9] investigated GMAW process adopted the manufacturing process of a hydraulic press slider. All these works provide interesting insights even if the models and the indicators adopted to achieve the results are different and heterogeneous. Concerning the data collection for environmental assessment of a welding process, some examples can be transferred from other sectors/industries, such as vessel manufacturing [10] and buildings [11], even if a data framework is missing for this technology.

The current work attempts to overcome the research gap highlighted by the literature analysis with the following objectives: (i) to create a structured model and a data framework for life cycle inventory of a generic welding structure, and (ii) to analyze complex and large structures with the aim of developing a decisional support metric for the selection of the most sustainable technology for asset/structure construction. It is worth noting that all the necessary information to fill the mentioned data framework can be retrieved by available documentation developed during the preliminary design phase. Furthermore, the adoption of the data framework allows to anticipate the life cycle analysis before the construction/manufacturing phase. The use of project documentation guarantees high accuracy during the environmental analysis, while results are more robust and less sensitive to the uncertainty related to the use of general/background data.

The paper is structured as follow: after this introduction, Section 2 presents the LCA model adopted for the analysis of welded structures and Section 3 proposes the LCI data framework. Section 4 shows how the proposed framework can be adopted in the analysis of yacht hull. Finally, Section 6 summarizes the outcomes of this study and presents selected proposals for future work.

2. Life cycle model

This section provides an insight of the life cycle model used to assess environmental performances of metal arc welding technologies. The LCA model has been built on the basis of the LCA framework proposed by the standards (ISO 2006a, ISO 2006b). LCA framework includes four steps: (i) goal and scope definition, (ii) inventory analysis (LCI), (iii) life cycle impact assessment method (LCIA) and, (iv) interpretation of results. Concerning the goal and scope definition, the functional unit modelled for the system assessment are described in section 2.1 while the system boundaries are described in section 2.2. Concerning LCI, a brief description of inputs/outputs required for the analysis is reported in section 2.3. Lastly, the adoption of LCIA method and the selection of the most suitable environmental indicators for this study is argued in section 2.4.

2.1. Functional unit definition

According to [12], the first step of LCA (goal and scope definition) should be defined at the beginning of the study. Since the attributional LCA (aLCA) system modelling approach has been chosen for the technology comparison, inputs and outputs need to be referred to the functional unit, reference flow and system boundaries of the product system. For a welded structure, the functional unit is defined as: *"the manufacturing, use and disposal of a welded structure able to guarantee the engineering requirements (according to a specific standard) in terms of strain, stress, corrosion allowance in the expected lifetime of T-years"*. The functional unit refers to a specific lifetime, and *T* represents the lifespan of the product specified at the beginning of the project. A project lifetime (*T*) is a prerequisite to compare different design alternatives and welding processes. The reference flow is the welded structure, and it includes the constituent materials and the type and amount of welding (length) necessary for the construction. The specific standard adopted for the realization of welding process is a design requirement defined at the beginning of the project. The functional unit allows to make a consistent comparison of welding processes and welded structures in accordance with the recommendation reported in the ISO standard [13].

2.2. System boundaries definition

Concerning the system boundaries of a welded structure the life cycle phases included in the analysis are: (i) materials extraction, (ii) manufacturing, (iii) use and, (iv) end-of-life (EoL). In this case, the material selection and the related welding technology have an influence on the useful life of the system (e.g., corrosion allowance of some materials are longer than other materials) [14] [15] and it affects the possibility to recover or not the constituent materials at the EoL. Two life cycle phases have been neglected from the analysis: (i) the transport phase, and (ii) the maintenance phase.

2.3. LCI

LCI is considered the most time-consuming phase of life cycle analysis. LCA results are strongly affected by the quality of inventory and the level of detail. A characterization of input/output data are necessary to define a common platform (data framework) for the inventory. Appendix A reports an extract of the necessary input and represents the mathematical description of the inventory (data framework structure), including: (i) the items involved in the inputs definition, (ii) the equations used for the assessment of each item, (iii) a description of necessary parameters (data required), (iv) the data type and, (iv) the data source (document). The framework is based on available data deriving from project documentation. A description of the data framework is reported in section 3.

2.4. LCIA

The environmental impacts have been calculated according to the following life cycle impact assessment (LCIA) methods: (i) ReCiPe midpoint [16], (ii) ReCiPe endpoint [16] and, (iii) Cumulative Energy Demand (CED) [17]. Table 1 reports the chosen impact categories. Since this study is directed towards the environmental impact quantification of welding processes as well as the manufacturing of complex/large structures realized by the adoption of welding processes, energy, materials and natural resources are of primary importance. SimaPro 8.05.13 (Prè Sustainability) has been used as the LCA software tool for the analysis, and the EcoInvent database (version 3.1) has been used as a supporting inventory database for background data.

Table 1 Impact categories

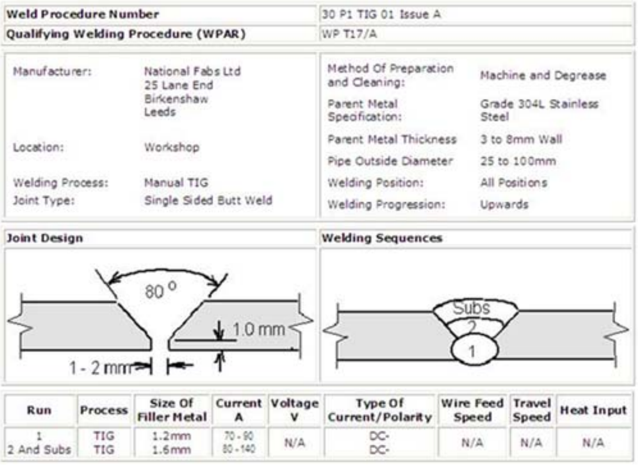
Impact category	Unit	Abbreviation
Climate change	kg CO2 eq	CC
Ozone depletion	kg CFC-11 eq	OD
Human toxicity	kg 1.4-DB eq	HT
Photochemical oxidant formation	kg NMVOC	POF
Particulate matter formation	kg PM10 eq	PMF
Metal depletion	kg Fe eq	MD
Fossil depletion	kg oil eq	FD
ReCiPe end-point	Pt	END-POINT
Cumulative Energy Demand	MJ	CED

3. Life cycle data framework

This section provides a detail description of: (i) the type and structure of engineering documentation used to retrieve input/output information (section 3.1) and, (ii) the structure of the data framework developed to integrate primary and secondary data, respectively retrieved from engineering design documentation and literature (section 3.2).

3.1. Project documentation

Required data described in the LCI section are available as design information stored into project documents. The use of project documents has two aims: standardize and harmonize the quality of data among different environmental analyses and reduce the data input uncertainties for a more robust environmental analysis. The following documents are used for the welding technology life cycle assessment: (i) CAD model, (ii) welding map, (iii) welding procedure specifications (WPSs), (iv) base material certificate/datasheet and, (v) filler material certificate/datasheet. A 3D CAD model is the design document which allows to virtually represent the product under development. By exploring the 3D CAD model, the following information can be retrieved: (i) size and geometry of welding beads, and (ii) lengths of welding beads [18]. Usually, the use of 3D CAD model is coupled with the welding map where the types of WPS used in the product are reported. The welding map is a schematic representation of the assembly which reports labels of WPSs in the exact position where they need to be applied. The WPS is the formal document describing welding procedures and how the process has to be realized (Fig. 1). The WPS contains all the necessary information that welders have to respect for making sound and quality production welds as per the code/standard requirements (e.g. ISO, DNV, ASME). By exploring the WPS document, the following information can be retrieved: (i) type of welding process (ii) qualified welding positions, (iii) welding parameters for each pass (current, voltage, speed, heat input, etc.), (iv) base material, (v) filler material, (vi) pre-heat temperature and method, (vii) shielding gas (if required), (viii) purging gas (if required), (ix) flux type (if required), and (x) bevel size and geometry. Base material and filler material certificates are two documents provided by the material manufacturers. The aim of both certificates is to ensure the quality of the supply in terms of chemical composition and mechanical performance considering dedicated tests performed on the same batch from which the material has been produced.



Weld Procedure Number	30 P1 TIG 01 Issue A
Qualifying Welding Procedure (WPAR)	WP T17/A

Manufacturer:	National Fabs Ltd 25 Lane End Birkenshaw Leeds	Method Of Preparation and Cleaning:	Machine and Degrease
		Parent Metal Specification:	Grade 304L Stainless Steel
Location:	Workshop	Parent Metal Thickness	3 to 8mm Wall
		Pipe Outside Diameter	25 to 100mm
Welding Process:	Manual TIG	Welding Position:	All Positions
Joint Type:	Single Sided Butt Weld	Welding Progression:	Upwards

Joint Design

Welding Sequences

Run	Process	Size Of Filler Metal	Current A	Voltage V	Type Of Current/Polarity	Wire Feed Speed	Travel Speed	Heat Input
1 2 And Subs	TIG TIG	1.2mm 1.6mm	70 - 90 80 - 140	N/A	DC- DC-	N/A	N/A	N/A

Fig. 1. Example of a WPS.

3.2. Data framework

The LCI requires the definition of a structured data framework for the collection of the above mentioned parameters starting from available project documentation. It is worth to recall that the project documentation is available in the early design phase before the manufacturing phase starts. The use of the data framework allows to anticipate the life cycle analysis before the beginning of the construction phase. The data framework identifies the sources from which it is possible to retrieve the available data and provide the mathematical relationships necessary to obtain all input and output flows through the system boundaries. The framework has been defined with the same structure independently from the analyzed welding technology. In case of welded structure analysis the following documents represents the mandatory items for the life cycle analysis: (i) WPS (primary data), (ii) CAD model (primary data), (iii) welding map (primary data), (iv) material certificates both for base material and filler material (primary data), (v) literature documentation such as papers, and scientific literature (primary data), (vi) EoL option (scenario) and, (vii) LCA database such as Eco-Invent (secondary data). Fig. 2 represents the proposed data framework, including the required parameters for the inventory and the related project documentation where those parameters are retrieved.

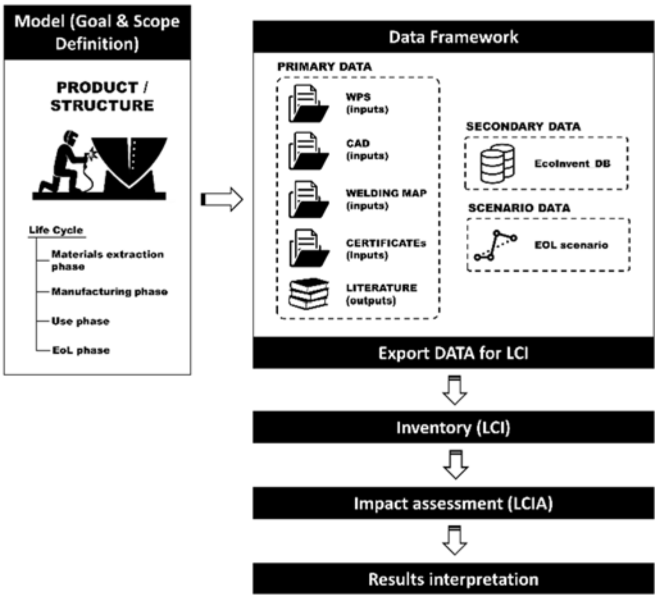


Fig. 2. Data framework

4. Case study: the hull structure

A ship hull is a structure made up of various metal blocks and plates welded together. Fig. 3 shows a section frame of the hull model analyzed in this study.

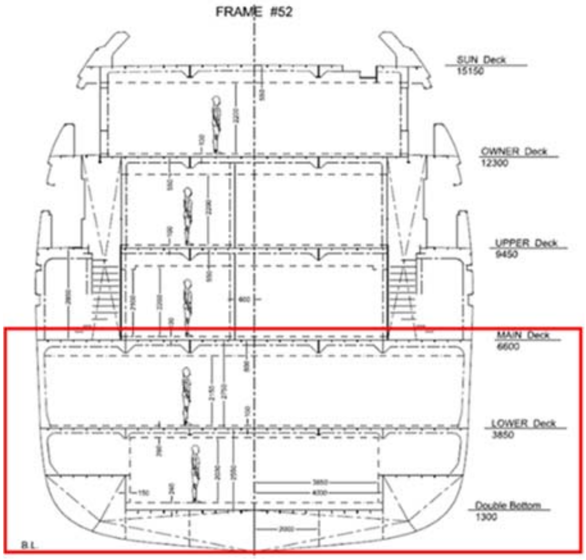


Fig. 3 Section frame of the hull

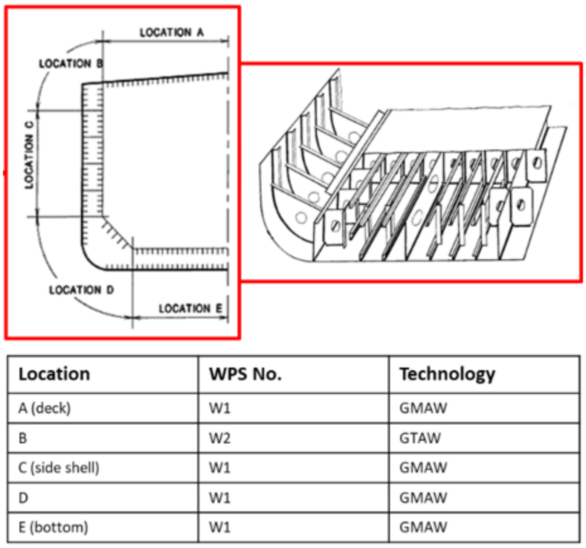
Based on the project requirements (e.g. 20 years of useful life), two different types of hull has been engineered: (i) the *CS-Hull* - manufactured with metal arc welding processes and by using low-grade carbon steel with an average metal plate thickness of 6 [mm] and, (ii) *AL-Hull* - manufactured with metal arc welding processes and by using aluminum alloy with an average metal plate thickness of 9 [mm].

The construction of both hull types requires the fulfillment of the requirements reported in the Lloyd's Register (LR) standards for welding. A combination of two different technologies has been chosen for shipbuilding: GTAW and GMAW. In both cases, the EoL option has been defined on the bases of the current standards applicable in this field such as the Hong Kong international convention [19] and the EU regulation on ship recycling [20]. The recycling rate has been set on 75% based on the current literature available in this field [21]. Table 2 reports the aggregated inventory data for the life cycle assessment of the CS-Hull and AL-Hull structure.

Table 2 Inventory data for the CS-Hull and AL-Hull structures

	CS-Hull	AL-Hull
Hull material	LR Grade AH36	Alloy 5083 H 321
Hull thickness [mm]	6	9
Hull total weight (approx.) [ton]	130	40
Welding length (approx.) [m]	12000	12000
Welding energy consumption [kWh]	25913.00	4218.11
Shielding gas consumption [kg]	14909.13	3048.68
Filler material consumption [kg]	14069.24	4498.39
Slag (filler material) [kg]	281.39	89.97
Welding fume emission [g]	1.11E-01	9.64E-02

The project documentation has been used to retrieve all the necessary information for the fulfillment of the proposed data framework. An example of a CAD model and a welding map for a specific hull section is reported in Fig. 4.



Location	WPS No.	Technology
A (deck)	W1	GMAW
B	W2	GTAW
C (side shell)	W1	GMAW
D	W1	GMAW
E (bottom)	W1	GMAW

Fig. 4 CAD model and welding map for a specific hull section

The adoption of the proposed data framework allows to have the same structure for the inventory and to replicate the life cycle analysis for each proposed configuration (*CS-Hull* vs. *AL-Hull*) with the same data and with the same level of detail. The parameters have been retrieved by consulting the project documents developed for each configuration and the data framework allows to calculate each item for input (base material, filler material, welding energy, etc.) and output (slag, fumes, etc.) by using the proposed equations. From the data framework, all the mentioned items have been exported for the life cycle inventory and then, by using the impact assessment (LCIA) methods (ReCiPe and CED), environmental impact indicators have been assessed. A comparison of the two hulls has been reported in Fig. 5. The graph shows a notable dominance of the *AL-Hull* environmental impacts for most of the environmental indicators such as: CED, CC, POF, PMF, FD and end-point. In particular, the environmental load of the *AL-Hull* represents approx. 60% compared with the *CS-Hull*. In contrast with this results, OD and MD show a remarkable dominance of the *CS-Hull*. Also for the HT indicator, the value of the *CS-Hull* is higher than the *AL-Hull* one.

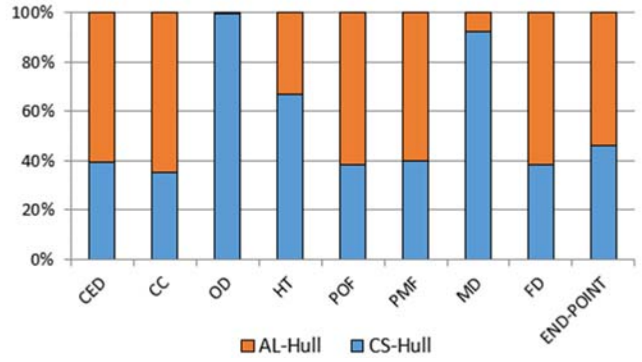


Fig. 5 Hulls manufacturing comparison

By using the data framework structure and its classification it is possible to make a deeper analysis of both projects. In the case of *CS-Hull*, a notable dominance in terms of the environmental burdens (CED, CC, OD, POF, PMF, MD, FD and end-point) of the base material is noticed. In all the mentioned indicators, the impact related to the base material required for the *CS-Hull* plates represents approx. 50% of the environmental load, while the manufacturing phase is approx. 25% of the environmental load (see Fig. 6).

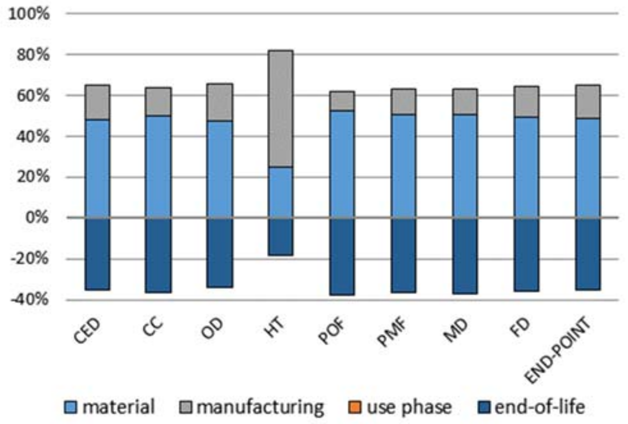


Fig. 6 Environmental impacts of CS-Hull

On the other hand, for the *AL-Hull* project, the impact related to the base material required for the *AL-Hull* plates represents more than 60% of the environmental load while the contribution of manufacturing phase is limited up to 10%.

5. Conclusions

The present study illustrates how a data framework enables to standardize the LCI of welding structures by identifying the data required and providing the mathematical relationships necessary to obtain the necessary data early in the design process. The results analysis of the reported case study shows the impact of the welding manufacturing process in comparison with the other items included in the life cycle analysis such as the raw materials and the recovery rate at the EoL. In particular, the share of welding process impact is strongly related with the base materials used for the welding plates. Furthermore, since large metal structures, such as a ship hull, require huge quantity of material, the environmental load for this life cycle phase is greater than all the other ones.

In conclusion, the study proofs how the use of project documentation allows to create a consistent and robust inventory for the life cycle assessment of large and complex structures providing an efficient decision making tool for the analysis of design alternatives in terms of environmental burdens. The proposed approach can be adopted as a standard for the engineering judgment in the development of welded structures as well as in the comparison of alternative welding processes early in the engineering and design phases. Future perspectives will be focused on economic and social aspects for a holistic assessment oriented to sustainability.

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APPENDIX A – Extract of the necessary input for the inventory (data framework structure)

INPUT	Equations	Data Required	Data Type	Data Source
Filler material				
Filler material type	-	Filler material type (chemical composition)	String	WPS
Filler material consumption [kg] ($C_{fil.mat.}$)	$C_{fil.mat.} = \frac{A \times \frac{\rho_{fil.mat}}{10^9} \times L}{\frac{DE}{100}}$	Cross section area [mm^2] (A)	Numeric	WPS, CAD
		Welding length [mm] (L)	Numeric	CAD
		Filler material type [kg/m^3] ($\rho_{fil.mat}$)	Numeric	Filler material certificate
		Deposition efficiency [%] (DE)	Numeric	Literature
Welding energy				
Welding energy [kWh] ($E_{wel.}$)	$E_{wel.} = \frac{\sum_1^n \frac{i_k \cdot V_k \cdot 60}{v_k}}{3{,}6 \cdot 10^6} \times \frac{L}{10^3}$	Welding current [A] (i_k)	Numeric	WPS
		Welding voltage [V] (V_k)	Numeric	WPS
		Welding length [mm] (L)	Numeric	CAD
		Welding speed [m/min] (v_k)	Numeric	WPS
		Welding time [min]	Numeric	Welding length, welding speed
		Number of passes [ad.] (n)	Numeric	WPS
Pre-heat				
Pre-heat (gas) type	-	Pre-heat type (gas or coil)	String	WPS
Pre-heat (gas) consumption [kg] ($C_{preheat}$)	$C_{preheat} = \frac{m \cdot C_p \cdot \Delta T}{LHV}$	Weight of heated area [kg] (m)	Numeric	Base metal material, base metal thickness
		Specific heat [J/kg °K] (C_p)	Numeric	Base metal material
		Base metal material	String	WPS, base material certificate
		Base metal thickness [mm]	Numeric	CAD
		Preheating area [mm^2]	Numeric	Preheating area is supposed 0,15 cm wide for each side of the bevel.
		Pre-heat temperature [°K] (ΔT)	Numeric	WPS
		Lower heating value of gas [J/kg] (LHV)	Numeric	Literature
Pre-heat (coil), energy required [kWh] ($E_{preheat}$)	$E_{preheat} = \frac{m \cdot C_p \cdot \Delta T}{3{,}6 \cdot 10^6}$	Weight of heated area [kg] (m)	Numeric	Base metal material, base metal thickness
		Specific heat [J/kg K] (C_p)	Numeric	Base metal material
		Base metal material	Numeric	WPS, CAD, base material certificate
		Base metal thickness [mm] (t)	Numeric	CAD
		Preheating area [mm^2]	Numeric	Preheating area is supposed 0,15 cm wide for each side of the bevel.
		Pre-heat temperature [°K] (ΔT)	Numeric	WPS
...				