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Manufacturability Analysis for Welding – A Case Study Using Howtomation© Suite

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Abstract. This paper is a summary of master thesis written in the fall of 2015 in the department of Product Development in Jonkoping University in Sweden as a part of a research project with focus on the implementation and management of systems for design automation and design for manufacturing. It includes an implementation with the aim of enhancing a system currently in operation at an aerospace supplier. The system is used for multi-objective design analysis in the early phases of product development. The analysis involves both the performance of the jet engines components as well as their manufacturability. The work is focused on the weldability assessment, based on available weld methods and the weld capabilities of the company. A number of rules for analysing the weldability are proposed. To keep this knowledge transparent, traceable and updatable it is managed by a novel software called Howtomation© Suite which is a forward chaining inferencing engine. The proposed framework enables a weldability index and welding cost guide to be derived, helping the designers choose appropriate weld method in early design stages.

Keywords. Design Automation, Knowledge Based Systems, Engineer to Order, Knowledge Base, Knowledge Object, Manufacturability Analysis, Manufacturing cost Analysis.

Introduction

According to S. K. Gupta *et al.* [1], Manufacturability analysis means evaluating the manufacturability of a proposed design with a given set of available manufacturing operations. Welding is one of the most commonly used joining technics. It is important to evaluate manufacturing feasibility of weld components during early design stages to avoid costly redesign and development delays [2]. One of the common requirements for customized products such as aerospace engineer-to-order (ETO) products is that the product designers have to consider a broad range of new design solutions [3]. The concepts of concurrent engineering (CE) allows the designers to make a wide variety of considerations such as manufacturability, assembly sequence, etc. during early stages of a product development process [2]. Design Automation, Knowledge based engineering, Design for Manufacturing (DfM) [4][5] are some of the techniques used in the manufacturing industry to meet the requirement in terms of product customization, product development time, manufacturability evaluation, cost estimation etc. The realization of individually engineered products can be made possible by the adoption of an automated engineer-to-order (ETO) [6] approach for quotation, development, and the production preparation processes [7][8][9][10]. The concepts of DfM allows the designer to consider manufacturing aspects such as materials selection and weld

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methods, weld sequence, assembly methods, necessary tools and fixtures for assembly, testing methods, etc. for the development of a product. The framework allows, up to 70% of a product's manufacturing cost to be estimated at the design stages [11]. It is important to have the ability to estimate the manufacturing cost of a component given its customer specification.

After doing interviews with the aircraft component manufacturer, it was understood that component manufacturing feasibility is also important, apart from the component functionality. Manufacturing feasibility analysis is required to avoid redesigns, reduce manufacturability cost and mainly to reduce part development time. The aerospace manufacturer is in the process of creating an automated tool that can assess the manufacturing feasibility of a component using existing product and process knowledge. The results of that investigation must enable the recognition of manufacturing difficulties and suggest methods suitable to manufacture and also determine an approximate manufacturing cost in the early design stages. The primary objective of this research work [12] is to develop an automated system which can perform a quick assessment of how well suited for welding a particular design is. This system will employ available industrial knowledge and give suggestions to the designers on how to improve the weldability of the design. It will also approximate the welding cost of that design. This is important in ETO companies to quickly go from the customer requirement specification to a quotation with most the competitive pricing.

1. Literature Review

Researchers have made some efforts to develop an automated computer software for evaluating manufacturability and to make cost estimations for welded components. Examples include Maropoulos *et al.* [13]. They made an attempt with a software named as "CAPABLE". It is a welding analysis software based on feature recognition technology. Yongjin Kwon *et al.* [2] have done similar work with the Sheet Metal Welding Advisor (SMWA) using customized C++ codes. The problem to use these developed techniques are knowledge transparency, details traceability and system upgradability. These are some essential maintainability aspects of a software tool for use in an industrial environment over a considerable length of time. The term transparency is a condition that all functions of a software must be disclosed to users [14]. The term traceability means that the user can find the version and amendment details of the current evaluation procedure including the references of the evaluation results. The term upgradability refers to the possibility to improve the existing system with a minimum of effort.

There are some commercial software's such as DFMPro [15] which is capable of evaluating the manufacturability of a design from its CAD model. DFMPro is also a ruled based analysis system which can evaluate the manufacturability of a design with a set of defined rules. The rules are maintainable and upgradable. The disadvantage with DFMPro is that the standard version if the system is not capable of weld evaluation for the time being.

Liu HongJun *et al* [16] have developed a method to evaluate manufacturability of an Aero-engine blade. The method is based on production rules and constraint-based machinability evaluation techniques. Kashid *et al.* [17]have developed an expert system for doing manufacturability assessment and process planning of sheet metal parts based on a production rule-based expert system approach. Rule-based analysis and constraint-based evaluation techniques have been utilized in this research work to develop an automated Weldability analysis system.

Vishal Naranje *et al*. [18] have developed a system for checking manufacturability, based on knowledge based system (KBS). Technical knowledge had been acquired from different sources of knowledge acquisition and framed in the form of production rules of 'IF-THEN' variety and then coded using AutoLISP language. Similar logic has been applied to this development work to make constraint-based weld evaluation with MS-Excel environment.

Jose M. Sanchez *et al.* [19] has developed a microcomputer-based Design Producibility Rating Tool (DPRT) to measure the producibility of simple metal components. The index has been derived from different design, material and manufacturing factors related to the level of design production difficulty. Weldability index has been introduced here with similar concepts to rank the weld methods for selecting most feasible method to a weld joint.

Joel Johansson, one of the co-authors of this paper has developed an automation software called as Howtomation©. It is a software developed with .net application. He has applied the Howtomation© suite to automate the heated runner systems for injection moulding of plastic material [7]. In addition to managing knowledge, it also has the capability of transferring information from one application to another. Examples include the CATIA, MS-Excel, MathCAD and Solidworks environments. The information transfer is realized by using 'Knowledge objects' and 'Parameters' objects. It acts as an inference engine to the developed weldability analysis system and making it possible to automate the entire process.

The producibility of fabricated Aero engine parts has been investigated by [20][21][22]. The authors have investigated how producibility aspects can be brought upstream, making the designs more suitable for manufacture by fabrication. In this paper a subset of this, namely the welding producibility is in focus

2. Weldability analysis system

The approach employed for development of weldability analysis system is similar to the one described by Shukor *et al.* [23]. The Manufacturability Assessment System (MAS) is a three step analysis system, which evaluate the weldability of a design from its CAD model with the available knowledge of the weld methods of the company. The basic approach of weldability analysis is shown in Figure 1. The details of the various subsystems shown in the Figure 1 will be explained later in this section. Component material and geometry details can be extracted from the proposed design's CAD model with a *Details extraction system*. The weldability will be analysed with constraint-based *Weldability evaluation system* based on defined weldability rules which are similar to the Vishal Naranje's [18] production rules with 'IF-THEN' logic. A *weld method's knowledge base* can be developed with available weld methods and descriptions of the capabilities of an individual weld method. Here presented as weld-process data sheets for each weld method. The *Execution system* can do the weldability analysis with the developed rules. The developed weldability analysis system also enables the calculation of weldability of a design based on weld difficulty and presented as *Weldability Index (WI).* The output part consists of a *Result's post processing system*, in which results from the analysis system will be summarised and the estimated cost to perform the welding operations will be presented.

2.1. Weldability Index

Weldability index is an index value which defines the weldability of a joint for a chosen weld method. Determining the weldability index is one way to rank all feasible weld methods to a weld joint. The weldability index (WI) refers to the level of difficulty of the weld. This method is an improved version of the CIM systems Industrial Automation company (Texas, USA) Producibility Rating tool called DPRT. During the weld evaluation process, the level of difficulty will be identified based on the details received through the design parameters, and will be rated based on set of standards defined in the weld method's knowledge base. The difficulty will be rated between 0.01 to1.00. But, if the criteria are not suitable to weld then the difficulty will be infinite. For all influencing factors the difficulty values will be averaged and an overall difficulty will be determined. Subtracting the overall difficulty from one, the weldability index will be determined. The result of this evaluation defines weld feasibility in terms of WI. In case of manufacturing conflicts between the design and welding, WI value becomes negative which indicates as infeasibility. The calculation procedure has been explained by following three steps:

1. Define difficulty level (DL) to each influencing factor
2. Calculate Difficulty Index (DI)

$$DI = \frac{\sum_{i=1}^{i=n} DL_i}{n}, \quad n = no.of\ influencing\ factors \tag{1}$$

3. Calculate Weldability Index (*WI*)

$$WI = 1 - DI \tag{2}$$

2.2. Cost modelling

The welding cost will be estimated based on chosen weld method, joint filler material (based on component material), length of weld, number of weld runs and the average weld speed of a chosen weld method. Different costing technics are available and used by the individual industry. Marginal costing techniques has been used for this work in which all the costs, related to a weld method are allocated to the cost heads. These cost heads are divided into two groups; one is 'fixed cost' and the others is 'variable cost'. Fixed cost is the cost paid by a company to keep the weld facility but is not dependent on the level of utilisation of the equipment. A suitable depreciation method can be used to allocate the fixed cost part to the weld cost per unit length. Variable cost is the cost that varies with equipment utilisation per unit weld length. Weld cost per unit length can be identified by adding the fixed cost and the variable cost. Furthermore, in the case of jigs and fixtures, common jigs and fixtures will be depreciated and will be add to the cost. But the cost of exclusive jigs and fixtures have to be added separately. The requirement of exclusive jigs and fixtures will be identified based on weldability failures in terms of tool accessibility.

2.3. Details extraction system

Different techniques can be used to extract geometry and material details from the CAD model. Feature recognition technique is used in some commercial packages [15].

Parameters tagging is another way to extract geometric and material details from the CAD model. In the work described here, the tagging technique has been used. As seen in Figure 2, the parameters are created in the CAD environment and the model measurements are to be tagged to these parameters. A VBA (Visual Basic for applications) code can be introduced to automate this activity in the CATIA environment.

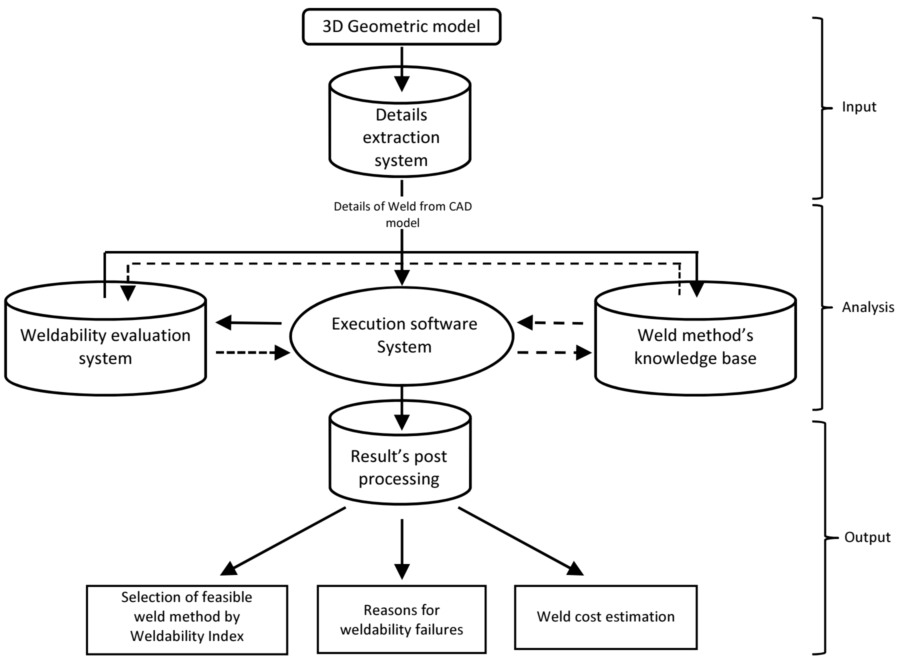

Figure 1. An approach to evaluate the weldability of a part from its CAD model.

2.4. Weldability evaluation system

In order to evaluate the weldability, a set of verified rules are required to analyse the weldability of a design. The rules are used to analyse the proposed design in different aspects, such as; material feasibility, shape, tool accessibility and etc. These rules have been extracted from various sources such as scientific literature, welding data handbooks, Weld equipment operation manuals, industrial standards or best practices, company own design procedure and other valid data. Usually the available rules are documented in the form of simple text. For example: Tanigawa *et al.* [24] have defined that the allowable initial gap of 0.2 mm and the allowable linear misalignments are 0.7mm for laser welding. In order to verify the weldability of a component with these definitions, an evaluation is needed. The developed weldability evaluation rules are similar to the Vishal Naranje's [18] production rules with 'IF-THEN' logic with Liu HongJun's [16] constraint-based technique. The rules have been developed in MS-Excel due to availability and maintainability considerations.

The extracted information from the CAD model is sent to the MS- Excel based rules. Subsequently, the rules will be evaluated by referring to the *Weld method's knowledge base*. The rules are managed by the system allowing version control.

Required rules will be connected to the *Execution system* based on evaluation requirements.

2.5. Weld method's knowledge base

A weld method's knowledge base is a data bank for all available weld methods and their capabilities. Examples of capabilities includes allowable weld materials, allowable thickness range, required filler material, type of welds, positions and so on. The details are documented for each available weld method separately. The capabilities of each weld method are subjected to the weld machine size and available weld technology. The descriptions of the weld methods, that is the weld data sheets are updated with time and new weld machines will replaces the old machines. For that, the developed weld method's knowledge base has been established such that it is upgradable according to the changes. Before use of this tool on manufacturing level, an appropriate knowledge base has to be prepared in the form of 'weld method data-sheets' for each available weld method with their capabilities.

2.6. Execution system

The role of an execution system is to execute a task *i.e.* doing weld analysis automatically. The execution system will integrate all weldability analysis' subsystems. The execution system has been prepared in the Howtomation© suite [7]. Once the execution system has been developed in the Howtomation© suite, the subsystems can be attached to this execution system easily. The execution system consists of three parts INPUT, ANALYSIS and OUTPUT. The *Details extraction* is connected to the INPUT part. The INPUT part observes the design information and sends it to the ANALYSIS system which consists of *Weldability evaluation system*. The ANALYSIS system will evaluate the weldability of a design with a set of predefined rules and gives the evaluation results in terms of the weld difficulty and the reasons for these difficulties. The results are conveyed to the OUTPUT part. The OUTPUT part consists of a *Result's post processing system*, which process the results taken from each evaluation rule for each weld method for each weld joint and gives a summary of the weld analysis including WI and approximated 'cost of welding'. Figure 5 shows a view from the execution system.

2.7. Result's post processing system

The purpose of result's post processing system is to make a summary of results from the analysis results in a defined format. After the *Weldability evaluation,* the details of information such as; weld difficulty, reasons for poor weldability, weld method, object or joint name, rule number and overall rule validity result will be transferred to the OUTPUT part. During the post processing the information will be summarized according the weld method and weld joint. The weldability index is calculated based on weld difficulties and the cost calculation is based on weld length, number of runs and filler material.

3. Illustrative Model

The developed weldability analysis system has been applied to evaluate weldability of a jet engine component. An illustrative example of a fictitious engine component with details extraction is provided. This CATIA Part file has been attached to the input part of the execution system (Figure 5). The input part of the execution system is in turn connected to the analysis part, which consist of weldability evaluation system in the form of rule checks.

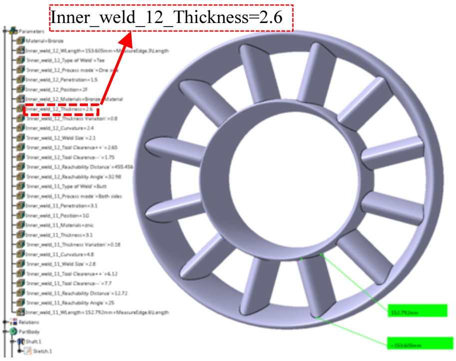

Figure 2: Illustrative model for weldability evaluation.

Different weld checks can be seen in the analysis part. Each of the MS-Excel evaluation files are connected to these objects in Howtomation, allowing them to be executed in an order determined by the inference engine. The evaluation rule checks are based on 'IF-Then' logic by comparing the inputs received in the MS-Excel evaluation file with the selected weld method's weld method data-sheet.

As an example - if the material is not suitable to weld or if the thickness is out of feasible range, then the result becomes "not OK" for the thickness feasibility check. The reason will be shown to the user in the results section. The reasons are: 'Material is unfeasible for weld' or 'The plate thickness is out of feasible range'. If the thickness is feasible then it will calculate the 'difficulty' based on the level mentioned in the knowledge base (weld method data-sheet). The process is visualised by showing colours in the icons. Figure 5 shows a screen shoot from Howtomation.

Object Name	Weld Method	Weld Feasibility	Cost	Weldability Index
Inner_weld_11	TIG	ok	305.75	0.432461538
Inner_weld_11	LaserBeam	not ok	1222.59	-3.07692E+12
Inner_weld_12	TIG	not ok	307.38	-3.84615E+12
Inner_weld_12	LaserBeam	not ok	1382.70	-5.38462E+12

Figure 3: Summary of results.

The evaluation results from each rule check icons in the analysis system are connected to the output part. After the analysis of the evaluation rules, the results, reasons and the difficulty levels, which are based on given

Object Name	Weld Method	Rule .No	Rule Detail	Feasibility	Remarks	Decision
Inner_weld_11	TIG	WMM001.A01159	The component "material" must be suitable to the weld method	Yes	Material is weldable	ok
		WMG001.A01159	The "Plate thickness" should be lower than the weld method capability	YES	The Plate thickness is feasible to weld. The plate thickness is 3.1. The maximum allowable thickness is 45 and the minimum thickness required is 2	
		WMS001.A01159	The Required "weld penetration" is lower than the weld method higher value	YES	Required weld penetration is Possible because the required penetration is 3.1 and the weld method can do maximum of 8 and the minimum of 3	
		WMS002.A01159	The "Thickness Variation" is allowable to the weld method	YES	Defined thickness variation is suitable because the part thickness variation is 0.18 and the weld method maximum possibility is 0.2	
		WMG003.A01159	The required "Weld Thickness" must be higher than the chosen weld method's minimum value	YES	The weld size is suitable to weld because the part weld size is 2.8 and the weld method maximum possible weld size is 7 and the minimum are 2	
		WAG003.A01159	The "Curvature" is possible to the weld method	YES	Defined curvature is suitable to weld because the required curvature is 4.8 and the weld method's maximum allowable curvature is 5	
		WAG007.A01159	The "Tool Clearence"must be enough for the weld gun movement	YES	The tool clearence is suffecient because the required clearence is 6 and the possible clearence is 7.7	
		WAG007.A01159	The "Tool Clearence"must be enough for the weld gun movement	YES	The tool clearence is suffecient because the required clearence is 6 and the possible clearence is 6.12	
		WAG004.A01159	The "Reachability angle" must be sufficient to reach the weld gun	YES	The reachability angle is suffecient because the required reachability angle for the weld method is 12 and the possible angle is 25	
		WAG005.A01159	The "Reachability Distance vertical" must be must be sufficient to reach the weld gun	YES	Reachability distance is Suffecient because the maximum possible Reachability distance is 15 and the available Reachability distanceis 12.72	
		WAG002.A01159	The "Process mode" most be compatible to the weld method	YES	The Process mode is possible to weld	
		WMG002.A01159	The "Weld type" is feasible to the weld method	YES	The weld type is suitable	
		WAG001.A01159	The "Weld position" must be compatible to the weld method	YES	The weld position is suitable to the selected weld method	
Inner_weld_11	LaserBeam	WMM001.A01159	The component "material" must be suitable to the weld method	Yes	Material is weldable	not ok
		WMG001.A01159	The "Plate thickness" should be lower than the weld method capability	YES	The Plate thickness is feasible to weld. The plate thickness is 3.1. The maximum allowable thickness is 45 and the minimum thickness required is 2	
		WMS001.A01159	The Required "weld penetration" is lower than the weld method higher value	YES	Required weld penetration is Possible because the required penetration is 3.1 and the weld method can do maximum of 8 and the minimum of 3	
		WMS002.A01159	The "Thickness Variation" is allowable to the weld method	NO	Defined thickness variation is not suitable to the selected weld method because the part thickness variation is 0.18 and the weld method maximum possibility is 0.02	
		WMG003.A01159	The required "Weld Thickness" must be higher than the chosen weld method's minimum value	YES	The weld size is suitable to weld because the part weld size is 2.8 and the weld method maximum possible weld size is 7 and the minimum are 2	
		WAG003.A01159	The "Curvature" is possible to the weld method	NO	Defined curvature is not suitable to the selected weld method because the required curvature is 4.8 and the weld method's maximum allowable curvature is 1	
		WAG007.A01159	The "Tool Clearence"must be enough for the weld gun movement	NO	The tool clearence is not suffecient to the selected weld method because the required clearence is 22 and the possible clearence is 7.7	
		WAG007.A01159	The "Tool Clearence"must be enough for the weld gun movement	NO	The tool clearence is not suffecient to the selected weld method because the required clearence is 22 and the possible clearence is 6.12	
		WAG004.A01159	The "Reachability angle" must be sufficient to reach the weld gun	YES	The reachability angle is suffecient because the required reachability angle for the weld method is 22 and the possible angle is 25	
		WAG005.A01159	The "Reachability Distance vertical" must be must be sufficient to reach the weld gun	YES	Reachability distance is Suffecient because the maximum possible Reachability distance is 15 and the available Reachability distanceis 12.72	
		WAG002.A01159	The "Process mode" most be compatible to the weld method	YES	The Process mode is possible to weld	

Figure 4. Results from each rule check icons for each weld method.

inputs will transfer to the output part. The output part is attached with the result's post processing system which makes a summary of results with weldability index, weld cost and the weld feasibility from the analysis results in a defined format (Figure 3). In case of manufacturing conflicts between the design and welding a negative WI value indicates as infeasibility. Then the designer can verify the infeasibility parameters with the reasons (Figure 4). This work gives a solution to the manufacturing industries to consider manufacturing infeasibilities in design stages.

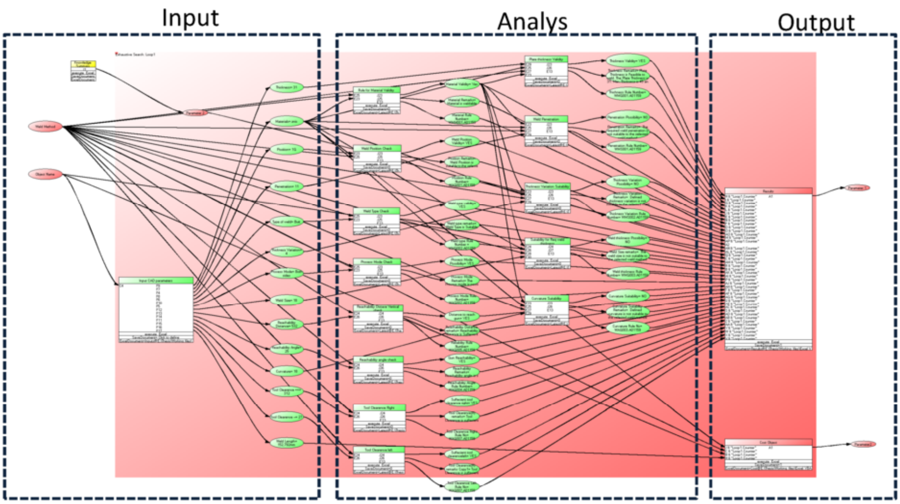

Figure 5. Execution system for weld analysis.

4. Discussion

This work demonstrates successful implementation of knowledge base engineering concepts for developing weldability analysis system. Process transparency and detail traceability have been achieved. The advantage of using Howtomation© suite is that a user can see the work in progress on the screen and is able trace the details of the weld evaluation. All the subsystems are integrated and automated with the execution system developed in the Howtomation suite. These discrete subsystems are prepared in such a way that they are easily maintainable and upgradable as technological improvements are being made. The weld evaluation rules have been made so that the rules can be updated with different versions and it is possible to extend the rules for manufacturability evaluation of other processes than welding. The weld method's knowledge base is kept separate so that weld methods can be added and removed easily. The existing weld methods are also readily updated by revising the process data sheets.

There are some foreseen limitations in the implementation of the system in the industrial environment. The system is unable to detect the uncompleted input information which will result in manufacturing unfeasibility. As emphasized by other researchers, there is a difficulty to do automation for welding gun interference for 3D natured welding paths. Further, the details of the extractions of tagged features are also not fully automated. It needs some manual intervention to identify the type of weld joint (Ex: tee, lap, etc.), weld direction with gravity direction and so on. It increases the preparation time of the CAD model and multiplies with the number of weld joints in the model. However, for a single manufacturing concept, the input model preparation can be automated with VBA code. The rule preparation, making different rule versions and the rule addition and deletion needs some programming skills from the staff who will operate the system. The constraint-base evaluation is limited to six degrees of freedom variables. For higher degree variables, another constraint solver has to be used. As a part of the future works, these difficulties will be solved along with the introduction of PDM system for rule management and weld sequence optimization.

5. Conclusions

The weldability analysis system has been developed according to the requirements of the aerospace company. It is an advantage for ETO industries to evaluate weld feasibility and approximate weld cost in early design stages. The developed weldability analysis system is an integrated part of an automated multi-objective design analysis system which is an integration of all functional analysis such as; Elasticity analysis, buckling analysis, fracture analysis, thermal analysis, manufacturability analysis and so on. The developed automated weldability analysis system is not only capable of analysing weldability of a design, it is also able to report potential issues back to the designer and selecting the most appropriate weld method. The Weldability index and approximated weld cost can help the selection of the most favourable weld method.

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