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Introducing Welding Manufacturability in a Multidisciplinary Platform for the Evaluation of Conceptual Aircraft Engine components

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Abstract. Computer simulations play an important role for evaluating designs in an early stages leading to that more informed decisions can be taken and thereby reducing the risk of costly re-design. In this paper, a platform currently in operation at aeronautical company for doing extensive automated multi-objective design parameter studies on conceptual designs of aircraft engine components is studied. In the paper, an extension of the capability of the platform into making a rule-based evaluation of the welding manufacturability of the conceptual designs is proposed. The extension is tested by a prototype system at the air-craft manufacturer showing the relation between the design parameters and the manufacturability of the components. The results are presented as a manufacturability index showing what trade-offs with other performance criteria of the engine that can be made. It is shown that the manufacturability evaluation can be integrated in the knowledge value stream and supports a set-based concurrent engineering approach in the company.

Keywords: Manufacturability, CAx, Robotic welding, Set-Based Concurrent Engineering, platform, Multi-objective

1 Introduction

The aircraft engine industry needs to show an ever increasing performance in new products (Vallhagen, Isaksson et al. 2013). Today, cost and sustainability issues are much in focus for airline companies, so manufactures of aircraft engines must present products with reduced fuel consumption, less weight, less environmental impact and at the same time preferably to a reduced cost. Often, meeting the demands for increased performance is possible, however the price is that it becomes increasingly difficult to manufacture the products. The increased performance means higher temperatures and structural loads. To withstand the extra stresses, more advanced alloys are needed and these are known to be notoriously difficult to process. Further, the geometries themselves tend to become more complicated with the increased demand on engine performance, due to e.g. optimization of the flow-path for lower pressure loss.

For these reasons it is desirable to have a good view on how well the proposed design compiles with the intended manufacturing process in an early stage of design. This is to prevent proceeding with designs that later will turn out to be too difficult and expensive to manufacture.

To make these predictions, some of the details about the manufacturing process have to be known in the very early stages of design, when principle solutions are discussed with the customer and the business contract is prepared. This will ensure that the manufacturability aspect is not left to a late stage in the design process, when the room for change is much smaller.

As described in this paper, the studied aircraft engine component manufacturer, evaluates conceptual designs in an early stage of product development considering the performance on structural, thermal and fluid-dynamics performance and assessment of the geometric tolerance distribution in a multi-objective manner. This is performed in an automated environment based on the CAD system Siemens NX. This environment is in this paper referred to as an integrated Computer Aided Engineering (CAE) environment. The environment allows studies of early designs by varying the parameters on surface CAD-models. Further, the CAE environment acts as a decision support tool, building knowledge on the effect of parameter settings of the conceptual models before it is progressed to detailed design. The tool is used to build knowledge and manage trade-offs which enables the company to support their knowledge value streams and to work with a Set-Based Concurrent Engineering (SBCE) approach.

The aircraft engine component manufacturer has a need to include more data for assessment of manufacturability in the studies in order to include more aspects of the product life cycle. It will be an early stage prediction on how suitable different parameter settings are from a manufacturability point of view. Thus, a trade-off can be made between the previously mentioned robustness, thermal, structural and fluid-dynamical aspects and the manufacturability of the design. The automated approach that is applied when conducting the studies enabling the company to work in a set-based manner, evaluating sets of solutions and parameter spaces.

One of the challenges is how to evaluate the manufacturability in a rapid way so that hundreds of different parameter variations on the same concept can be evaluated within a reasonable time. It must be done automatically in a short period of time.

Manufacturability refers to how a product can be produced to a minimal cost and at a maximal reliability. However, there are several influencing factors, as described by (Vallhagen, Madrid et al. 2013). Manufacturability can for instance refer to the complexity of the geometries, how well the different parts can me assembled, how difficult the materials are to form and so on (Bralla 1999, Boothroyd 2011). An automated evaluation based on CAD-models for all manufacturability aspects on the component is not expected to be feasible at the present time due to the many influencing factors. Therefore, to begin with, the most influential factors will be addressed and that is the welding of the structure. Several different methods for robotic welding are available in the workshop of the company and they all have different characteristics when it comes to which materials, geometries and thicknesses of plates that they can handle. The objective is to gain knowledge on the applicability and performance of the different methods in an early stage of design. How this is accomplished in a speedy automated way so that different parameter settings readily can be compared for manufacturability is the question that this paper will answer.

The main contribution of this paper is showing that manufacturing knowledge on robotic welding can be made available for re-use for rapid welding manufacturability evaluation in a multidisciplinary context in the early stages of design. This is done by making amendments to the existing platform allowing welding manufacturing knowledge to be formatted and managed in the platform.

The remainder of the paper is organised as follows: The method employed is described in the next chapter followed by a literature chapter which cover relevant aspects of technology and product platforms and how knowledge is represented in them. Knowledge management (KM) and organisational issues in the multidisciplinary context is discussed. The section also elaborates on SBCE and its role in platform building and the knowledge value stream. In the following chapter 4, the case of application at an aircraft engine manufacturer is described, beginning with the industrial context and then detailing the manufacturability example. It is followed by a discussion highlighting relevant considerations of the presented extension. This leads up to the conclusions section and finally future work is suggested.

2 Method

This paper was written as part of a larger research project with a duration of three years involving four companies not just in aerospace but also in the automotive and the production equipment sectors. Three senior faculty staff and three PhD students are currently involved in the project as well as a number of company professionals.

The overall objective of the research project is to increase the companies' abilities to respond to fluctuating requirements from customers, so that they can "tune in" their product development processes to be more responsive to the fluctuating requirements. The assumption is that this will have an effect on how they devise their product and knowledge platforms.

The project follows the Design Research Methodology (DRM), (Blessing and Chakrabarti 2009). This methodology emphasises setting clear and measurable objectives for the desired To-Be state in the companies envisioned for some time after the research project has terminated. These objective are called success criteria (SC). They point out specific areas in which the companies will improve their abilities.

To enable the achievement of the desired SC:s in the company there are enablers (EN) formulated. The EN:s are conditions that are thought to be necessary for the fulfilment of the SC:s. Examples include systems, processes and software.

There are relations between the EN:s and SC:s in that each of the EN:s contributes to the fulfilment of the SC to a varying degree. These relations can be visualized by for example matrix methods.

With guidance from DRM, the research project has involved the companies i workshops and consecutive interviews. The objectives have been to find the SC:s and EN:s and also to find the companies priorities among the SC:s and to find how the SC:s and EN:s are related to each other. Professionals from the companies, between one and three persons from each company, have written on Post-IT notes what they perceived as the most important SC:s and EN:s at the beginning of the project. They did this for about one hour. In the session, 50 or so notes were gathered. After the workshop, faculty staff organised the SC:s into headings. This work followed to some extent the method described by (Ficalora 2010). A period of time after the workshop, the companies were asked to prioritize among the 15 different SC:s organised into 5 categories. The method of prioritising forced them to distinguish some of the SC:s as more important than others. The result was that the companies ranked "reuse knowledge" as the most important SC. The second most important was "Time to respond to quotation" and thirdly "Time spent in project".

Follow up interviews were made at the aerospace company studied in this paper. It became clear that the most important enabler for them was to make a prediction of the manufacturability already in the conceptual stage. Consequently, the project was concentrated on addressing this at the aerospace company.

3 Literature

Sub suppliers in industry are seeking ways to conduct product development in more efficient ways and at the same time offering highly customised products. A way to achieve efficient customisation is the use of a platform definition (Simpson, Jiao et al. 2014). The component based product platform is often described as either modular or scalable. However, there will often be a demand for knowledge about future requirements and interfaces in order to create enough variants of a product to gain back the extra expenses that has been put on developing the product platform. This creates concerns for the sub suppliers developing products to be integrated in the customer's product where the interfaces and requirements perhaps change or remain unknown for part of the development phase. One way to manage this is to extend the definition of a product platform to include more of the company "assets" than just highly concretised components, (Johannesson 2014). Examples of such company assets are established and documented methods of verifying a design suggestion. Since investments has been made in developing the method, it is regarded as a company asset.

(Högman and Johannesson 2011) explores the use of a technology platform that consist of methods which involves knowledge about the design and manufacture of the products. (Levandowski, Raudberget et al. 2014) uses the configurable component concept to model a platform in early stages of development. The modeling technique is based on SBCE and the hierarchy of functional requirements and design solutions. SBCE, as opposed to a traditional point based approach, is a method where sets of solutions is developed in parallel (Sobek II 1999). In a point based approach, a concept is chosen early in development and then iterated until reaching a feasible solution. With SBCE, a wider spectrum of the design space is explored. The focus is to eliminate bad or unfeasible solutions when enough knowledge about the solution exist as opposed to the early selection of a design solution. Positive effects of applying SBCE in industry has been observed by (Raudberget 2012).

The knowledge value stream has been said to be, like SBCE, part of lean product development. According to (Kennedy 2008) the knowledge value stream consists of capture and reuse of knowledge about markets, customers, technologies, product and manufacturing capabilities. The knowledge should be generalized and visualized to flow across projects and organizations.

This paper continue to build on the model for describing the platforms, started in (André, Stolt et al. 2014). If the design knowledge is captured, structured, saved and can be retrieved, it can be reused in future development project as a natural part of the platform definition. This is graphically shown in Fig. 1, where the continuous build-up of knowledge value steam is shown in the diagonal. Is represents the continuous extension and updating of the platform as experiences from the products emerges or new technology is being developed. The platform contains representations of knowledge such as design guidelines, models, process and manufacturing knowledge to be reused in product development projects. Note that the knowledge build-up is ongoing while the PD projects, shown in the lower part of figure 2, have a start and an end. However, to realize this, means of capturing, representing and reusing the knowledge in a pre-planned way must be developed.

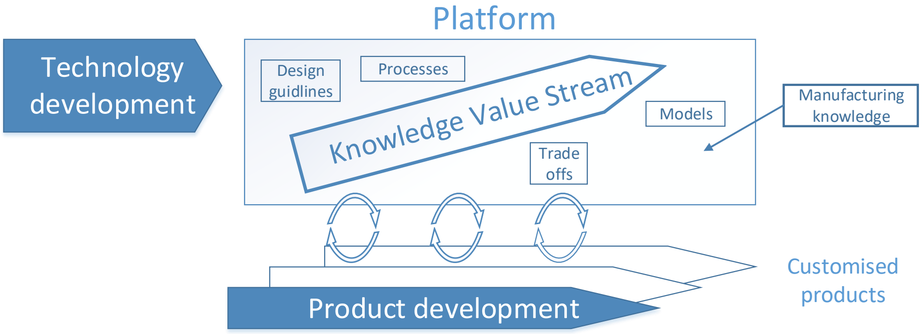


Fig. 1 Representing the knowledge to be re-used.

The knowledge can be represented in for example guidelines, process descriptions, models and best practice methods. Examples also include executables such as excel sheets, scripts and applications to facilitate the knowledge retrieval and possibly automated reuse. From the technology development new verified methods, tools and technology solutions emerges. These company assets are used in the different PD projects.

The extent of the platform varies in companies. It is perhaps limited to one discipline or it can be multidisciplinary involving several types of knowledge representations and models. The models in the platforms are often based on computer aided technologies, CAx, where the x is replaced with the technology such as Engineering (CAE) or Process Planning (CAPP).

Merging the different CAx models into one platform creates a multidisciplinary environment. For the efficient capture and reuse of knowledge, several issues related to the construction, use and maintenance of the platform occurs. Examples includes adapting the information to the intended user. Depending on the role in the organisation the needs vary as for example the granularity and the precision by which the information needs to be presented.

The multidisciplinary CAx environment makes it possible to visualise information for several different disciplines and to merge results from simulations in different domains. However, there are challenges in interpreting the results and making a balanced trade-off between them so that informed design decision can be taken (Shao, Liu et al. 2016) (Amouzgar 2015) (Stolt, André et al. 2015). This is mainly because there are likely couplings between the objectives with different degrees of importance. Here, the DSM (Design Structure Matrix) can be used to structure the dependencies (Nomaguchi, Saito et al. 2015).

There are at least two reasons for platforms to become increasingly multidisciplinary: One is that the work is done concurrently involving several different disciplines such as design and manufacturing working on the same models simultaneously. The second is that the products themselves are becoming more multidisciplinary such as the introduction of electronics and software in mechatronic products. In an industrial product development context, there is usually a system already in operation at the company for storing and versioning of documents such as a PDM system.

(Bergsjö 2014) highlights the importance of managing the knowledge in multidisciplinary CAx environments. For this, a close integration with the PDM system is necessary. Bergsjö reports case studies from three different companies and how they integrate the PLM system with their CAx environments with a focus on their motivations and requirements. The product and process knowledge that is available in the PLM systems needs to be distributed in the right user format. The companies in the study employ a service oriented architecture (SOA) to retrieve information from the PLM system into the CAx application.

During the production phase, there is also a lot of data being generated in production. This is valuable information for product development that should be continuously incorporated into the platform to develop the knowledge. (Dhuieb, Belkadi et al. 2015) proposes a Digital Factory Assistant to be used by the workers in the production to report production data via hand held devices. They also show how to incorporate the data into the PLM system.

In addition to production data, simulating the products also creates valuable data for the extension and refinement of the platform.

(Saarelainen, Buda et al. 2014) addresses the open loops where there is a lack of feedback of simulation data. The authors have investigated by interviews what the main drivers are for closing the open loops. Examples of important drivers include reuse, traceability and reuse. The PLM perspective is also supported by closing the open data-loops.

More complex products consisting of several components and sub-systems typically have interfaces to connect between the components and sub-systems. These interactions must be managed in the platforms so that the design teams responsible for different disciplines and subsystems can interact efficiently as elaborated by (Rahmani and Thomson 2011). They propose a formalisation model of the interfaces, allowing a more efficient interaction between the design teams. The formalisation model can also perform a consistency check securing that no part of the interface remains unmanaged by any of the design teams.

(Red, Marshall et al. 2013) discuss today’s limitations of the CAx tools which only allow single user interaction with the models. They argue that to further develop the CAx environments, several different users should be allowed to work on the same models simultaneously. They propose a regional decomposition of the models allowing different types of users to edit the models at the same time. They also show that the regional decomposition is possible in today's CAD systems. The paper acknowledge that the collaborative CAx environment needs to expand to more than a single organisation. This raises issues on data security and avoiding disclosing sensitive information. (Teng, Mensah et al. 2016) shows how to manage access control in a trans-organisational collaborative environment using role-based access control.

4 Case of application

The company studied distinguishes clearly between the technological and product platform (André, Stolt et al. 2014). The company has a development process with the aim of developing methods and verifying them so that they can be included in the company's technology platform. To keep track of the readiness of the methods, the TRL scale (Technology Readiness Level) developed by NASA is used. Examples of methods included in the technology platform involve FEA and CFD analysis, explaining e.g. the most appropriate type of mesh and how it should be applied and what type of elements should be used for the particular types of analysis.

Since the aeronautical industry have strict demands on verification, it is not allowed to use any methods apart from the approved ones described in the technology platform.

When the aeronautical company is creating a new engine design it follows the process depicted in Fig. 2. Conceptual ideas are created together with the other suppliers of aero engines and components and the aircraft manufactures. This will give hints on what the expected requirements on the new generation of engines will be and which technologies that are expected to be used. Surface CAD-models of the concept is constructed. They are planned for variation of the parameters so that the design space can be covered without any update failures of the models.

To build knowledge on the effect of the parameter settings in the early stages of design, extensive automated parameter studies are made in the CAE environment. Having gained a rough understanding using the CAE-environment on how the parameters should be set to achieve the wanted trade-off between the performance, structural strength and manufacturability, decisions on how to set the parameters of the concept is made. In the next step, which lies outside the CAE-environment, the design is further elaborated with more precise simulations of the engines performance including detailed simulation of the production process. This includes e.g. offline–programming and path planning of the welding robots and the detailed

Fig. 2 The design of a new aero-engine.

sequencing and clamping of the sub-assemblies. The final stage is the testing and verification of the design which is made on physical parts. It is done first on a flying test-bench and eventually on the actual aircraft.

The studies in the CAE environment is done before any business contract has been written. The main objective of the studies is to gain knowledge about the concept. Firstly, this will lead to that the trade-offs in the design are more thoroughly understood. It will also allow the manufacturer to respond quicker to changes when the contracts have been signed and the actual product development has begun. Often, as the development of the aircraft progresses, the initial requirements change. Suppliers who can respond to these changes quickly are highly appreciated. It is therefore important for the supplier to continuously build up the general knowledge on the product and its manufacturing processes and just not focus on the development project closest at hand.

4.1 Production setup

The components that are considered in this paper are static frames in the aero engines. They transfer the loads from the engine to the pylon located under the wing of the airplane. These components also form the airflow through the engine counteracting the rotation of the air produced by the rotating fans. The components are produced by welding three different parts together as seen in the left of the below fig. 3. All parts shown in the figure are fictitious for demonstration purposes. The actual parts are manufactured by casting, machining or sheet metal forming.

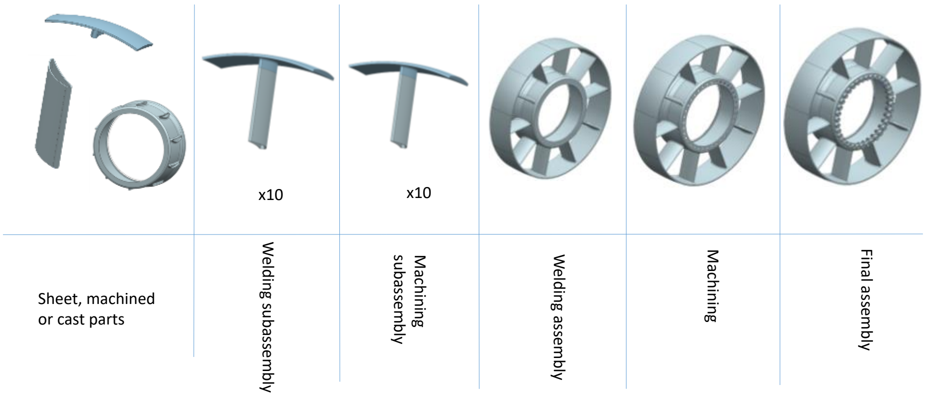


Fig. 3 The design of a new aero-engine.

Firstly, the three parts are welded together to a welding subassembly (fig. 3). These sub-assemblies are named sectors. In the fig. 3 example there are 10 of them. The 10 sectors are machined to prepare them for welding and to give the correct surface smoothness. All the sectors and the cast hub are thereafter welded together to a complete component. This is followed by a machining operation. The part is inspected before it is finally assembled. These operations are done in a highly automated workshop where most of the operations are carried out by industrial robots. The workshop can perform TIG (Tungsten Inert Gas), laser, plasma and Electron

Beam (EB) welding and a number of machining and inspection operations. Fixtures are and jigs are built to enable the robotic processing.

4.2 CAE Environment

The CAE environment consists of scripts and other tailored methods for running all analyses in automated mode and also retrieving and visualizing the results as shown in fig. 4.

The structural, thermal, geometric robustness, producibility, and the fluid-mechanical performance is evaluated. Due to the high number of evaluations (in the order of hundreds) that must be done, the process of generating models and meshes with varying parameter settings and evaluating them is fully automated so that the results can be reviewed within one or a few days.

When a conceptual design is ready, a parametric CAD-model of it is made. It is in an early stage of design, but all critical issues regarding the architecture of the engine, choice of materials and (roughly) how to manufacture the engine has been defined, albeit they are likely to change as the product development project unfolds. All detailed design, production planning and optimisation remains.

The CAD-model that is made for the CAE-environment studies does not represent the whole engine. Instead, it is single components like the turbine frame described in section 3.2.

By naming low level geometric entities in the CAD-model such as surfaces, edges and vertices they can be identified as for example welds and materials. This procedure is referred to as “tagging”. Those tagged entities are identified by programmed scripts hosted by the CAD-program so that automated operations such as rule-based manufacturability assessment can take place. Also, the order in which the parts of the component are assembled is kept track of in the system.

In the CAD-model, geometric parameters like lengths and angles can be varied in an associative way. Varying these parameters has an impact on the performance of the engine and its manufacturability. For example: If the number of vanes is increased the flow through the engine is impaired and the weight increases. However, the structural strength is increased. The studies in the CAE-environment are aimed at gaining an understanding of the nature all these dependencies, so that a starting point for the final design can be established. One example of studies is finding which of the geometric parameters has the greatest influence on e.g. the airflow through the engine.

The studies make it possible to explore the concept and to understand which trade-offs that can be made. Some extra weight can perhaps be accepted if the service interval can be extended. Likewise, it is perhaps worth sacrificing some manufacturability if the pressure loss through the engine can be reduced.

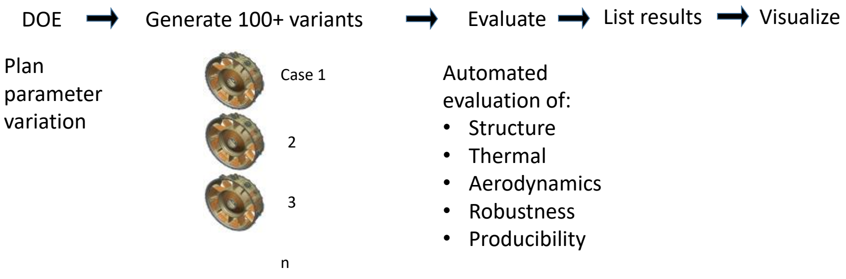


Fig. 4 The CAE-environment.

Through Design of Experiments (DOE) a number of different settings of the associative CAD-model parameters before mentioned can be generated. There will be one hundred or so variants of the same CAD-model. Every such variant is referred to as a “design case” The variation is planned so that the variants will be distributed in the parameter space evenly. For planning the variation DOE methods like Box-Behnken or Latin Hypercube, see e.g. Cavazutti (Cavazzuti 2013) are used, ensuring that the whole design space is represented.

All the generated CAD-models are subsequently evaluated. This includes making FEA meshes, applying loads and running the analysis. Thereafter, the results are saved and listed. It is challenging for the design engineers to interpret the extensive results lists, so methods such as parallel graphs are being used to visualise the results.

There are several difficulties with the described process: Firstly, running a large number of automated analysis in sequence takes several days of calculation time. If one analysis goes wrong the process can stop and no results will be retrieved. There are exception handlers in the system that makes it possible to carry on to the next design case so that the process can go on, missing only the failed design case. Secondly, the system produces large amounts of data that has to be trawled for interesting cases and dependencies for visualization. Thirdly there is a challenge of keeping the knowledge applied by the system up to date and to keep track of the analyses history.

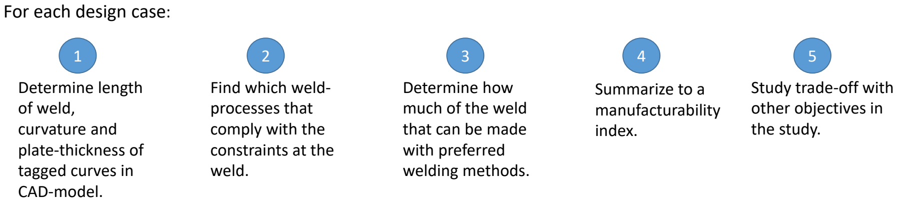
4.3 Working principle of the manufacturability module

Manufacturability has traditionally been discussed from a machining point of view. Features in CAD models are identified interactively and automatically by feature recognition such that a process plan for their manufacture can be generated Shah (Shah 1995). These process plans form the basis for planning toolpaths and making predictions on the manufacturing costs.

However, evaluating manufacturability is not restricted to automated process planning of machining. Using Manufacturability Analysis System (MAS) (Shukor and Axinte 2009) many other aspects of manufacturability can be analysed.

There have been numerous attempts on evaluation of geometries for weld processes to find the cost of welding a particular geometry represented in CAD. Some examples: (Maropoulos, Yao et al. 2000), (Chayoukhi, Bouaziz et al. 2008), (Elgh and Cederfeldt 2008). These are based on the automated or interactive evaluation of CAD-

models. Ordinary CAD models holds the geometric information only. This type of CAD models can be said to be augmented with various manufacturing information.
From the CAD-models, process plans are created describing how much weld that will be needed and also the geometric conditions in for example accessibility. From the planning of weld-methods and paths the weld-cost of welding can be calculated.
The objective in this early stage of design is not to get an absolute monetary value on the welding cost, but rather making a comparison between different design cases. One example of what the study is expected to reveal is: If the space is narrowed down in the vicinity of a weld, will it be possible to access with the standard robotic weld gun? If not, selecting a less preferred weld-method will be necessary and thus lowering the manufacturability for that design case. Fig. 5 shows the different steps in the evaluation of a design case:



For each design case:

1. Determine length of weld, curvature and plate-thickness of tagged curves in CAD-model.
2. Find which weld-processes that comply with the constraints at the weld.
3. Determine how much of the weld that can be made with preferred welding methods.
4. Summarize to a manufacturability index.
5. Study trade-off with other objectives in the study.

Fig. 5. The steps in evaluation of a design case.

Step1: As mentioned, all welds have been tagged with names when the CAD-model was created. This means that the model can be searched for all curves that represent welds by names. For each of the welds, the plate-thickness can be determined as well as the curvature in a number of points around the weld curve and the minimum distance to the nearest geometry (accessibility hindrance) from the weld in the x, y and z directions with respect to the weld gun. The z-direction is the longitudinal direction of the weld gun. Also the materials in the surfaces adjacent to the curve has been defined in the CAD-model and is read from it.

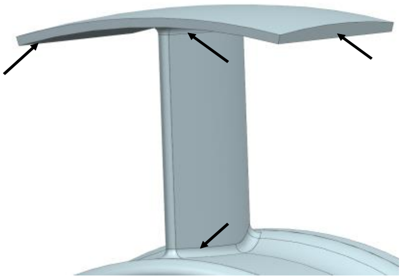


Fig. 6 A sector with some tagged welds indicated by arrows to be evaluated.

As described in section 3.2 the components are typically built in sectors that are pre-assembled and subsequently welded together to circular geometries. Fig. 6 shows a CAD-model of one such sector with four weld-curves indicated by arrows.

Step2: The conditions at the weld are compared with the capabilities and constraints of each of the weld-methods. The limitations for plate-thicknesses, curvatures, materials and reachability depends on what type of welding equipment that is used, the materials and the welding speed. To get an estimate on which plate-thicknesses that each weld method is capable of handling, the CES (www.grantadesign.com/products/ces/) has been used. It gives the following ranges: EB 0,3 - 50 mm, Laser 0,25 - 20mm, TIG 0,7 - 8mm, Plasma 0,075 - 6 mm. Since the limits includes extreme variants of the process encompassing all types of equipment, the ranges are narrowed down to exclude the extremes. The thickness-ranges are seen in table 1 below.

The table 1 also show the minimum curvature, materials and the reachability. The reachability is derived from the sizes of commercially available weld guns for robotic welding. The dimension in the z-direction is assumed to be 300mm since small robotic weld guns can be found on the market corresponding to these dimensions. The dimensions in the x and y direction are about to 70x70 mm. Similarly, for robotic laser welding an estimate of the dimensions of the weld gun is (x,y,z) =(100, 200, 450mm) obtained from a supplier of such equipment.

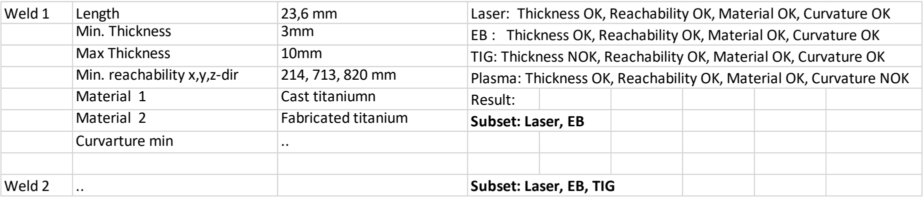
In order not to get a too narrow section that can melt down and give a bad result there is a requirement on the curvature. This is expressed as a minimum radius related to the size of the weld pool. The size of the weld pool is much related to the process conditions, so no absolute values can be given in table 1.

Table 1. Constraints per weld-process.

Constraints per weld process:				
	Curvature	Plate-thicknes	Material	Rechability x, y, z
Laser	..	1mm - 10mm	Fe, Al, Ni, Ti	100, 200, 450
Electron beam	..	2mm-30 mm	Fe, Al, Ni, Ti	..
TIG	..	1mm-3mm	<list>	300, 70, 70
Plasma	..	2mm-8mm	<list>	..

For each weld, a subset of feasible welding methods is derived by examining which processes that comply with all constraints as seen in the below table 2. The table shows that for weld 1 Laser and EB is possible. Weld 2 is not shown in detail in the table but feasible methods are Laser, EB and TIG.

Table 2. Finding feasible methods per weld.



Weld 1	Length	23,6 mm	Laser: Thickness OK, Reachability OK, Material OK, Curvature OK
	Min. Thickness	3mm	EB : Thickness OK, Reachability OK, Material OK, Curvature OK
	Max Thickness	10mm	TIG: Thickness NOK, Reachability OK, Material OK, Curvature OK
	Min. reachability x,y,z-dir	214, 713, 820 mm	Plasma: Thickness OK, Reachability OK, Material OK, Curvature NOK
	Material 1	Cast titaniumn	Result:
	Material 2	Fabricated titanium	**Subset: Laser, EB**
	Curvarture min	..	
Weld 2	..		**Subset: Laser, EB, TIG**

Step 3 and 4: When the subsets of feasible methods have been derived, a selection of the most preferred ones must be made. This is done by ranking them from weld preference. The ranking list has been put together by (Heikkinen and Müller 2015) by letting manufacturing engineers assign figures to the degree of preference.

In the degree of preference, the cost and robustness of the method as well as its performance from a sustainability perspective is included. The ranking is the following: Laser welding is the most preferred with 15 points, TIG is the second best with 14 points, Plasma-welding has 12 points and finally EB welding has 10 points. This preference needs to be weighed together to a single figure on the manufacturability (M) in percent. The model used considers how much of the total weld length can be made by the preferred method:

$$M = 100 \cdot \left(\frac{L_{Laser}}{L_{tot}} \cdot \frac{P_{laser}}{P_{highest}} + \frac{L_{TIG}}{L_{tot}} \cdot \frac{P_{TIG}}{P_{highest}} + \frac{L_{Plasma}}{L_{tot}} \cdot \frac{P_{Plasma}}{P_{highest}} + \frac{L_{EB}}{L_{tot}} \cdot \frac{P_{EB}}{P_{highest}} \right) \quad (\mathbf{1})$$

Thus a design case where all the welding can be made by laser welding will have manufacturability 100%.

If it from the CAE environment evaluation turns out that it was not possible to use laser in the whole weld, say as an example that the constraints evaluation showed that out of 50 m weld, 30 m could be made by laser, 10 m could be made by TIG, 5 m by plasma, and 5 m by EB, the manufacturability would instead be M=93%:

$$M = 100 \cdot \left(\frac{30}{50} \cdot \frac{15}{15} + \frac{10}{50} \cdot \frac{14}{15} + \frac{5}{50} \cdot \frac{12}{15} + \frac{5}{50} \cdot \frac{10}{15} \right) = 93\% \qquad (\mathbf{2})$$

Step 5: Now the manufacturability is listed for every design case. All other aspects of the design case is considered at the same time. The below table 3, shows the results of run. It has been simplified and contains fictitious figures. The table illustrates the multi objective nature of the run.

Table 3. Results of a run in the CAE environment.

Design Case	Expected Life in hours	Factor buckling	Robustness	Pressure loss (bar)	Manufacturability %
1	500	0,82	1%	0,1	95
2	520	0,83	1,3%	0,3	93
3	492	0,845	1,2%	0,2	92
..					

This forms a decision support, finding interesting settings of the parameters for the bests trade-offs in the design cases of the multi-objective study. Some of the more promising of them can be singled out for more detailed analysis. The results can be shown as surface plots such that a trade-off for the best parameter setting can be found.

4.4 Evaluation of CAE environment

The manufacturability evaluation demonstrator was discussed with two professionals from the company's production, daily involved in production planning, cost calculations and follow-up of production. They have several years of experience in these positions in the company. It involves making detailed planning of robotic welding and inspection in for example flexible manufacturing cells including off-line programming of welding sequences. They were interviewed separately and their response was consistent in that the manufacturing module is much needed in the early phases. However, there had been too few products evaluated to make any conclusive statements on the added value of it. The manufacturing index was believed to be difficult to interpret. Instead the system should highlight potential problems such as number and locations of violations of the space requirements for the weld gun. By presenting this information, the production engineers can assess the difficulties in handling those problems when planning the production set-up.

5. Discussion

This paper describes the studied aerospace company's approach towards including manufacturability knowledge in a platform definition. The modelled manufacturability knowledge is described in a way that enables integration of an automated multi objective evaluation tool. With this approach a parameter space can be evaluated in an early stage exploring several concept sets. Knowledge about the designs are built and can be communicated. This supports both SBCE and the knowledge value stream in the company. The introduction of manufacturability evaluation has been performed with a subjective method, involving ranking by manufacturing engineers. The research is still in early phases and more elaboration on the influencing factors are expected to be done. The presented method does not include the assembly order and clamping of the parts to be welded. Also operations like cleaning the plates and casts, making inspections and doing rework when faulty welds has been found is not included although they contribute considerably to the manufacturing cost.

The accessibility is in practice a complex problem. The robot must be able to position the welding gun or other tool without any part of the robot or tool colliding with the work-piece or the jigs and fixtures. The specification in detail of now this should be carried out is normally done by off-line programming where the whole production facility such as the robot cell has been modelled in software such as DELMIA V5 (http://www.3ds.com). This computer model allows the actions of the robot to be planned in detail. It is also aimed at finding the most efficient path for the tool minimizing the processing time. Normally, this is not done until the final design is available. Even a rough path planning requires the intervention of a human operator in every design case which for time and resource restrictions is not feasible. Instead one design case should be studied in detail, resulting in an envelope volume representing the tool path. This volume is used in all the other design cases. In the current work this envelope has been estimated only considering the size of the tool. There will likely be undetected collisions or un-necessary large margins in the current system due to that the actual movements have not been considered.

Further, in the early stages the production set-up is generally not defined. Later the fixing elements and jigs in the production can be altered. When they are altered they may constitute hindrance in the planned tool path. For these reasons, it is important to have an ongoing dialog with the production department as the manufacturing processes are developed in parallel with the actual component. The analyses will need to be made again on an updated version of the planned production setup.

Further, it is believed that the key to more precise prediction of the manufacturability is to include more elaborate process plans for each design case. These will contain influential items with high impact on the cost and sustainability which can be assessed using well established methods such as LCA (Life Cycle Analysis) and LCC (Life Cycle Costing).

6. Conclusions and future work

The results from the study suggest that the use of a platform definition containing descriptions of knowledge for reuse purposes is a promising way forward. In order to use a set-based approach, creating and analysing several designs, automation becomes crucial. Automated evaluation of manufacturability based on CAD-models has previously been extensively researched. However, this paper has highlighted the need of a quick and autonomous tool for early stage feasibility studies and process planning. Some initial steps have been taken but the continuation of the research needs to address making accessibility predictions without interactive path planning as well as sequencing the production process so that process plans can be automatically created. From these more detailed predictions of manufacturability as well as cost and sustainability estimation is expected to be made. The inspection of the welds has also been identified as crucial for the manufacturability. Future work will address the prediction of geometric suitability for x-ray and penetrant inspection.

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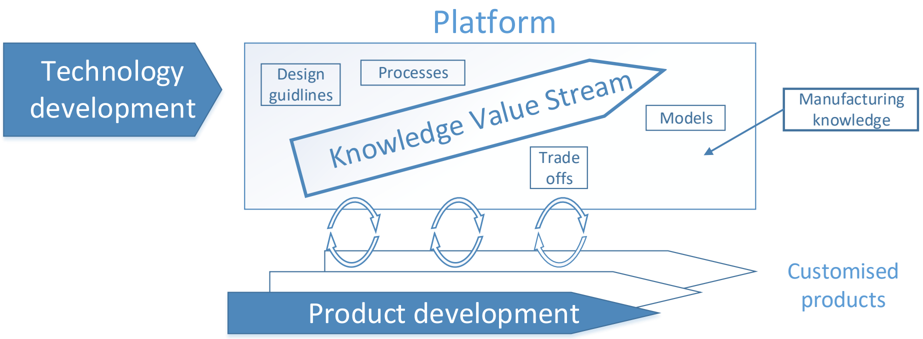


Fig. 3 Representing the knowledge to be re-used

Fig. 4 The design of a new aero-engine.

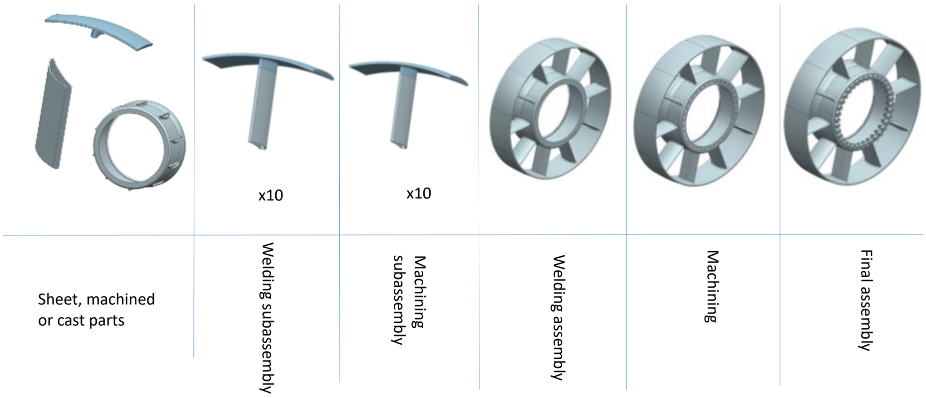


Fig. 3 The design of a new aero-engine.

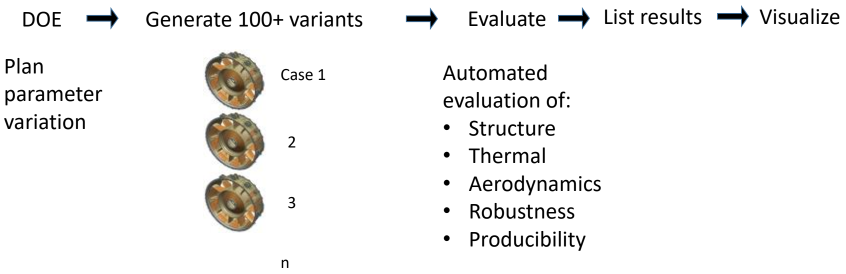
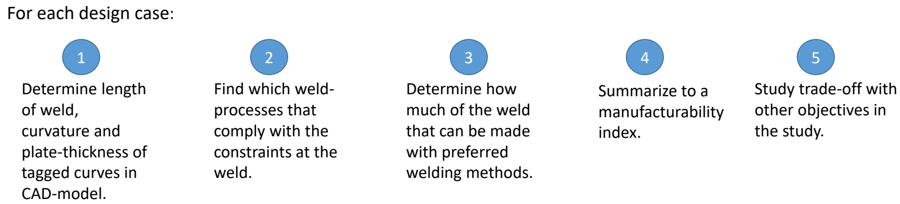


Fig. 4 The CAE-environment.


For each design case:

1. Determine length of weld, curvature and plate-thickness of tagged curves in CAD-model.
2. Find which weld-processes that comply with the constraints at the weld.
3. Determine how much of the weld that can be made with preferred welding methods.
4. Summarize to a manufacturability index.
5. Study trade-off with other objectives in the study.

Fig. 5. The steps in evaluation of a design case.

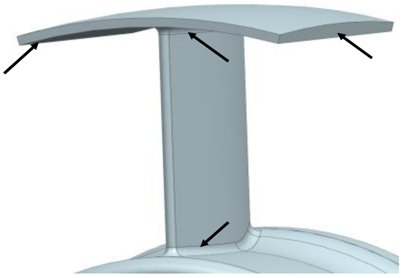
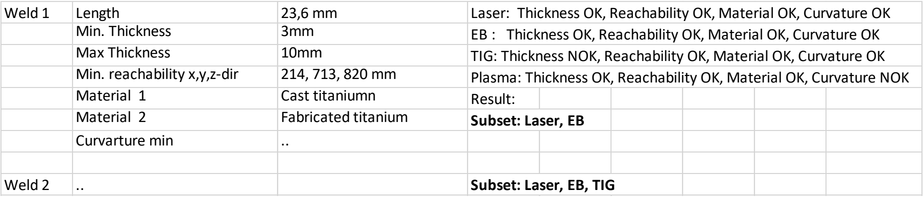


Fig. 6 A sector with some tagged welds indicated by arrows to be evaluated.

Table 2. Constraints per weld-process.

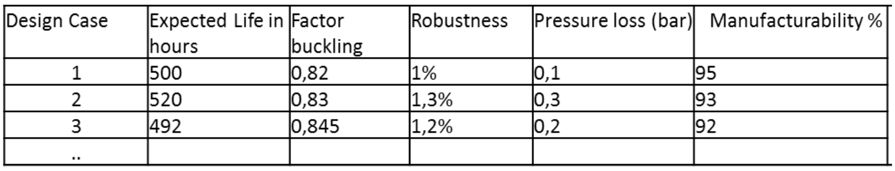
Constraints per weld process:				
	Curvature	Plate-thicknes	Material	Rechability x, y, z
Laser	..	1mm - 10mm	Fe, Al, Ni, Ti	100, 200, 450
Electron beam	..	2mm-30 mm	Fe, Al, Ni, Ti	..
TIG	..	1mm-3mm	<list>	300, 70, 70
Plasma	..	2mm-8mm	<list>	..

Table 2. Finding feasible methods per weld.



Weld 1	Length	23,6 mm	Laser: Thickness OK, Reachability OK, Material OK, Curvature OK
	Min. Thickness	3mm	EB : Thickness OK, Reachability OK, Material OK, Curvature OK
	Max Thickness	10mm	TIG: Thickness NOK, Reachability OK, Material OK, Curvature OK
	Min. reachability x,y,z-dir	214, 713, 820 mm	Plasma: Thickness OK, Reachability OK, Material OK, Curvature NOK
	Material 1	Cast titaniumn	Result:
	Material 2	Fabricated titanium	**Subset: Laser, EB**
	Curvarture min	..	
Weld 2	..		**Subset: Laser, EB, TIG**

Table 3. Results of a run in the CAE environment.



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