KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

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EVALUATION OF PRODUCIBILITY ASSESSMENT TOOLS USING SET-BASED APPROACH IN MULTI-DISCIPLINARY AEROSPACE DESIGN

Final project for Master’s degree

Supervisor
Assoc. Prof. Dr. Rūta Rimašauskienė

KAUNAS 2017

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Production Engineering (code 621H70004)

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(Title and code of study programme)

Evaluation of producibility assessment tools using set-based approach in multi-disciplinary aerospace design

DECLARATION OF ACADEMIC HONESTY

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1. Darbo tema: *„Aviacinių prototipų pagaminamumo rodiklių vertinimas kompleksiniame tarpdisciplininio projektavimo kontekste“ (lietuvių k.). „Evaluation of producibility assessment tools using set-based approach in multi-disciplinary aerospace design“ (anglų k.).*

Patvirtinta 2016 m. gruodžio 8 d. dekano įsakymu V25-11-20

2. Darbo tikslas: *Ištirti ir įvertinti aviacijos prototipų pagaminamumo rodiklius praktiškai analizuojant turboreaktyvinio variklio galinės struktūros gamybos aspektus ir pademonstruojant pagaminamumo vertinimo sistemos rezultatus.*

3. Darbo struktūra: ***Teorinė dalis:*** *tiriamojo objekto apibrėžimas aviacijos pramonės kontekste, tarpdisciplininis projektavimas, suvirinamumo vertinimo sistema, galinė turboreaktyvinio variklio struktūra, tiriamieji klausimai, ekspertinių sistemų inžinerija, vienalaikė inžinerija, dizaino eksperimentas, gamybos vertinimo sistema, gamybos kaštų ir laiko modeliavimas.* ***Metodologija:*** *projektavimo ir tyrimo metodas, veiksmo tyrimo metodas, veiksmų įgyvendinimo ciklai, koreliacijos matrica, kokybinis tyrimo vertinimas.* ***Tiriamoji dalis:*** *sistemos analizės paruošimas, pagaminamumo rodiklių vertinimas, duomenų apdorojimas, gamybos proceso planas, rezultatų vizualizacija ir demonstravimas.* ***Vertinimo dalis:*** *rezultatų, metodologijos ir tyrimo klausimų aptarimas.* ***Priedai:*** *klausimynas, gautų ir panaudotų rezultatų duomenys, koreliacijos matrica.*

4. Reikalavimai ir sąlygos: *pademonstruoti pagaminamumo nustatymo galimybes, naudojant kompanijos pateiktus struktūrinius modelius ir pasitelkiant joje naudojamas komercines ir vidaus programas. Tyrimo metu naudotos konfidencialios informacijos darbe neminėti.*

5. Darbo pateikimo terminas 20___m. ____ mėn. ___ d.

6. Ši užduotis yra neatskiriama baigiamojo darbo dalis.

Išduota studentui __Donatui Kveseliui______

Užduotį gavau__Donatas Kveselys_____ __________
(studento vardas, pavardė) (parašas, data)

Vadovas___________________________ __________
(pareigos, vardas, pavardė) (parašas, data)

Kveselys D. Aviacinių prototipų pagaminamumo rodiklių vertinimas kompleksiniame tarpdisciplininio projektavimo kontekste. *Gamybos inžinerijos*, Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Mokslo kryptis ir sritis: Gamybos inžinerija, Technologijos mokslai

Reikšminiai žodžiai: *Aviacijos variklių pramonė, DFM, dizaino eksperimentas, ekspertinių sistemų inžinerija, EWB, pagaminamumo rodikliai, pagaminamumo vertinimo sistema, tarpdisciplininis projektavimas, TRS/TEC/TRF, vienalaikė inžinerija*

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SANTRAUKA

Šis baigiamasis darbas – tai projektavimo platformos automatizavimo tyrimų tęsinys, kurio bendras tikslas yra pademonstruoti vystomos pagaminamumo nustatymo sistemos galimybes aviacijos produktų kūrimo stadijoje. Projektas atliktas globalioje aviacijos produktų gamybos įmonėje „GKN Aerospace“, Švedijoje. Sistemos analizė atlikta tiriant galinę turboreaktyvinio variklio struktūrą (TRS) tarpdisciplinio projektavimo kontekste, siekiant įvertinti produkto suvirinamumą.

Aviacijoje produkto vystymo ir konceptualizacijos stadijoje atliekami kompleksiniai vienalaikiai tyrimai atsižvelgiant į kartu naudojamas termodinamikos, konstrukcinės analizės, aerodinamikos ir kitas disciplinas. Gautų parametrų duomenys koreliuojami ir, pasitelkiant optimizavimo įrankius, nustatomas optimalus produkto dizainas. Šis baigiamasis darbas prisideda prie galutinio tikslo pilnavertiškai integruoti pagaminamumo nustatymo sistemą kaip papildomą tarpdisciplinininių studijų sritį, kuri padėtų produkto vystymo procese, įvertinant jo gamybos aspektus.

Parengta sistema panaudota 29-iems parametriškai varijuojantiems TRS kompiuteriniams modeliams (prototipams), kurie buvo sugeneruoti dizaino eksperimentų principu. Visų modelių geometriniai parametrai, pvz., kraštinių ilgis, storis, kreivis, surinkti automatiškai ir modifikuoti skirtingų suvirinimo grupių apibrėžimui. Šie rezultatai leido dalinai nustatyti gamybos proceso planą ir preliminarų produkto projektavimu paremtą papildomą gamybos laiką. Galiausiai visi turimi duomenys buvo sujungti su kitų projektavimo disciplinų rezultatais ir vizualizuotos jų parametrų sąsajos.

Atliekant projektą susidurta su sistemos parengimo problemomis dėl ribotų galimybių valdyti kompiuterinius modelių junginius, tokius kaip TRS. Taip pat buvo sprendžiamos problemos, susijusios su pagaminamumo rodiklių pagrįstumu, dalinai automatizuoto duomenų apdorojimo vystymu ir produkto projektavimo savybių susiejimu su jo gamybos aspektais. Pagaminamumo sistemai pademonstruoti plačiai pasitelktos komercinės ir įmonėje sukurtos programos kartu su nuolatine produkto vystymo skyriaus pagalba, susiduriant su esminėmis kliūtimis.

Naudota veiksmo tyrimo metodologija leido sukurti rezultatui orientuotą sprendimą, koncentruojantis į skyriaus projekto vadovo nustatytas problemas. Adaptuotas ciklinis tyrimo metodas padėjo valdyti projekto eigą atsižvelgiant į gaunamą grįžtamąjį ryšį. Įgyvendinti keturi tarpusavyje susiję veiklos ciklai, t.y. duomenų apdorojimo vystymas, gamybos procesų plano tyrimas, tarpinių rezultatų vizualizacija ir galutinės sistemos demonstravimas. Projektas įvertintas atsižvelgiant į produkto vystymo ir gamybos specialistų nuomonę, aptariant naudotą metodą ir rezultatus.

Atliktas darbas lėmė sistemos patobulinimą, nustatė pagaminamumo vertinimo galimybes ir svarbiausius gamybos aspektus. Sistama parodė perspektyvius rezultatus, kurie gali padėti rasti kompromisą tarp produkto dizaino ir pagaminamumo.

Kveselys D. Evaluation Of Producibility Assessment Tools Using Set-based Approach In Multi-disciplinary Aerospace Design. Master’s thesis in *Production Engineering*, Kaunas University of Technology, Faculty of Mechanical Engineering and Design.

Research area and field: Production Engineering, Technology Sciences

Key words: *Aero-engine industry, DFM, Design of Experiment, Knowledge Base Engineering, EWB, producibility indicators, Producibility Assessment System, multi-disciplinary design, TRS/TEC/TRF, set-based concurrent engineering*

Kaunas, 2017. 63 p.

SUMMARY

This thesis is a continuation of design automation studies focusing on impact research of currently under developed producibility assessment system at a global aerospace products supplier GKN Aerospace Sweden. A case study was carried at the company on Turbine Rear Structure (TRS) component’s design of a jet engine with the main objective to evaluate weld producibility assessment tools and to demonstrate system’s performance in multi-disciplinary design environment. The context of this thesis is a set-based product design development where several studies, i.e. thermal, structural, aerodynamic etc. are carried concurrently to gather knowledge between their parameter relations. The thesis contributes to the goal of fully integrated producibility assessment in multi-disciplinary studies to support product development process.

Completed assessment setup was used on 29 parametrically varied TRS case study models which had been generated using Design of Experiment sampling methods. All models were run through the system to extract their geometry metrics, i.e. edge length, thicknesses, curvature etc. Afterwards, extracted data was processed into producibility indicators defining different weld groups. Final data allowed initial production process plans’ assessment and preliminary prediction of additional design driven manufacturing time. All obtained data was integrated with multi-disciplinary study results and various response surfaces were generated.

The problems encountered during the thesis execution involved systematic analysis setup to extract and verify CAD geometry data, assessment of meaningfulness of producibility metrics, development of semi-automated data post-processing module and relating product design to its manufacturing aspects. Commercial and in-house developed software were used extensively to demonstrate the results of the system with the help of continuous company support to mitigate indispensable bottlenecks along the way.

Action Research methodology was used to develop solution focused approach by addressing problems identified by project supervisor. Iterative research structure was adapted with repeated study refinement loops. The established method implementation consists of four interdependent action cycles, i.e. development of data post-processing module, investigation of process plans, intermediate data visualization and final demonstration of the system. The results of the system were evaluated by collecting feedback of product development and manufacturing specialists.

The work has led to systematic improvements, determined assessment limitations and most relevant weld producibility aspects. The presented system in action showed promising results to support product design decisions considering both performance and producibility.

CONTENTS

1. INTRODUCTION

Aerospace industry product development is highly complex and takes a long time to realize. Consequently, there is a need to speed up development processes and shorten production lead times, which makes aerospace industry embody more automotive type characteristics. Increasing demands and necessity to reduce product development and manufacturing time puts high stress on those segments. One of the companies experiencing such effect is a major aircraft engine components supplier GKN Aerospace with product portfolio ranging from civil to military aircrafts. Its products can be found on planes like Boeing 787 “Dreamliner” [1].

The company recognizes that substantial part of components’ development complexity rises from the multi-disciplinary studies where different engineering fields come into place and must be evaluated concurrently due to their parameters’ inter-dependency. For example, the most aerodynamic solution may be difficult or even impossible to manufacture with tools available at the time. How does one decide on the most suitable design is a trade-off which should be assessed with various multi-variable optimization techniques. To address the situation, Research & Technology (R&T) department at GKN Aerospace Sweden has introduced a system called EWB or Engineering Workbench. It seeks to integrate different modules like structural, thermal, aerodynamic, geometrical analyses and evaluate them concurrently. This system is executed on several component variants which are parametrically created from a single CAD base-line model, following design of experiment principles.

Obtained data allows the user to explore the design space instead of initially settling on a single design concept. Such set-based engineering approach allows more optimum design selection and provides valuable knowledge between different parameters’ relation determining the design. However, EWB is still under development and new modules have to be developed and introduced.

It is known that depending on the industry the biggest part of committed costs occurring throughout the whole product life cycle originate from production. Nevertheless, the highest cost influential decisions are made during the early stages of product development [2]. Consequently, the most straightforward way to tackle these cost drivers is to address them concurrently. Recognizing this situation GKN Aerospace has expressed desire for producibility assessment to be integrated into their EWB. Here, the company aims to address manufacturability related issues in the early development stages of product design this way preventing higher incurred manufacturing costs or re-design loop-backs.

The most recent works within the researched topic are partially developed Producibility Assessment System (PAS). Heikkinen & Müller, 2015 [3] described how such system should be structurally integrated allowing robustness and flexibility and Max Jacobsson, 2016 [4] further developed weld producibility assessment system which allows the user to extract geometrical data from CAD models considering several producibility metrics. In the context of this thesis PAS is also referred to as weld producibility assessment system. Latter available weld producibility system still lacks various metric definitions and, although developed with the aim to maintain flexibility and robustness, has not been formally validated on other component welds aside from the ones that it was designed on.

This master thesis addresses PAS with a focus to evaluate current system’s performance on a different group of design cases and developing semi-automated data post-processing tool for easier results interpretation and visualization. The main aim of the thesis is to evaluate producibility assessment indicators through demonstration of the system in action with actual data. This is achieved by working on the already attainable metrics and using them to communicate producibility in the context of other EWB disciplines.

The following objectives summarize the scope of the thesis:

1. Determine current PAS state by error identification and amendments to establish correct analysis setup.
2. Capture producibility assessment metrics and their implications on process plans.
3. Implement producibility data post-processing module to prepare for assessment integration with other multi-disciplinary studies.
4. Demonstrate system’s performance in multi-disciplinary environment analyzing data response.

Approach towards each of the above objectives is further discussed in the chapters below.

2. THEORETICAL BACKGROUND

This section explains theoretical background of the project. It is mostly focused on preceding works directly linked to the topic to establish thesis perspective, review research object environment and further discuss relevant definitions and concepts.

2.1. CASE STUDY OBJECT

This thesis is a continuation of the previously carried and ongoing research at the aerospace company. The research is quite broad and is generally focused on automation in product development processes. The studies cover design platform concept for Engineering to Order (ETO) businesses [5] and automated producibility assessment within such platforms by the example of weld producibility assessment system investigating different manufacturability metrics and system's implementation [6-7].

The thesis can be defined with Design Research and Methodology (DRM) framework, which was developed by Blessing and Chakrabarti, 2009 [8]. DRM is used for extensive research scope allowing to measure impact of the carried studies. In the broader research context, this thesis stands in a prescriptive study phase of the DRM which consists of four methodological stages (Fig.1). Here the research has already been established, descriptive study performed with success criteria defined and impact model partially completed. It is further explained how the thesis fits theoretical framework of DRM in section 3.1.

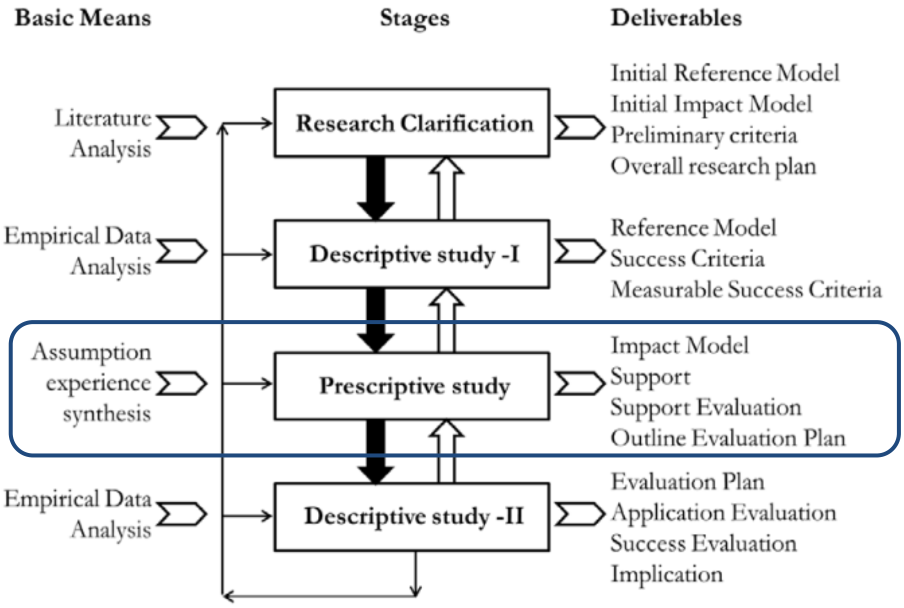


Figure 1: Project's scope (selected) within Design Research process framework [8]

Initial studies investigated 4 case companies, one of which is in an aerospace field, and concluded that there is a need for integrated producibility assessment platform. The platform was expected to mitigate problems in later product development and visualize effects of changed requirements and their fluctuations [5]. Consequently, as part of the broader ongoing researches this thesis is focused to address the latter expressed needs and contribute to the general study.

2.1.1. GKN Aerospace

Globally GKN Group employs 55 000 people, out of which 17 000 belong to the Aerospace division, and has operations in more than 30 countries. Besides Aerospace the company also has divisions in Driveline, Land systems and Powder metallurgy [9].

It is worth mentioning that out of all new large commercial aircrafts 100% have components produced by GKN Aerospace. The company also cooperates with several field businesses such as Rolls-Royce, General Electric, Boeing and others [10]. With a wide portfolio in civil and military usage components, the company places high standards on quality delivered and continuously ensures maintenance of their products, which is so essential in the aerospace industry.

This project is carried in the division’s headquarters in Trollhättan, Sweden. Previously the affiliate was known as Volvo Aero but after being bought in 2012 was renamed to GKN Aerospace. Today the company has the broadest engine product portfolio with key segments in intermediate, turbine exhaust, compressor/diffuser cases and other parts. Some of the main technological processes include advanced machining and automation capabilities, high speed machining, surface and heat treatment, electron beam, laser, tungsten inert gas, plasma and resistance welding [11].

2.1.2. Computer Aided Design environment

In its products’ development, the R&T department employs a heavy use of Siemens NX software, which is a high-end capability CAD/CAM/CAE integrated software with design automation orientated language extensions like Knowledge Fusion (KF) and Journal.

KF is defined as an object orientated language which lets engineering knowledge to be added to the tasks by creating rules executed in the software [12].

Journal is a way that NX user sessions can be automated because it has an option for the activity to be recorded as a macro in another programming language like Visual Basic (VB). It allows to expand and customize the activity based on the user needs.

Weld producibility assessment system uses both KF to prepare design cases for specific data extraction and journal to run the whole process in a non-interactive background mode and to store collected data in an excel file. However, there is an option for the analysis to be run in an opened NX user interface for easier task tracking, which comes in handy when script execution errors have to be fixed.

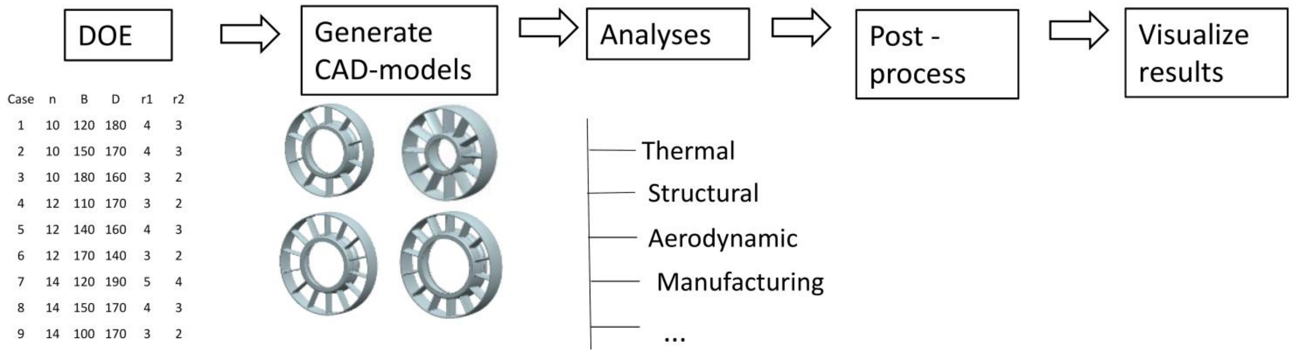
This thesis work led to significant exposure to the commercial and in-house developed software during which some familiarization had to be acquired to successfully execute the work.

2.1.3. Engineering Workbench

Product development process at GKN is highly affected by the Set-Based Concurrent Engineering (SBCE) methodology which gave rise to the in-house developed platform called Engineering Workbench or EWB. This tool is used to improve product development process in design space exploration by integrating thermal, structural, aerodynamic and geometrical studies. At the time of the thesis execution EWB did not include producibility assessment module as it is still very underdeveloped but at least partial introduction as a result of this thesis is highly desirable.

The key characteristic of EWB is that it gathers all the design and performance parameters from separate modules and allows carrying parametric CAE studies. The detailed EWB process is quite complex but broken into main parts can be described in just several sequential steps leading to the results (Fig. 2). Here, a correct CAD baseline model is prepared tagged for parametric analysis. Then using Design of Experiment (DoE) it is planned which model parameters should be varied and how to sufficiently represent design space. DoE dictates assigns controlled parameters, e.g. number of assembly building blocks, edge lengths, face thicknesses etc. Based on DoE, several CAD-models or Design Cases (DCs) are automatically generated. At this point all DCs are automatically analyzed in multi-disciplinary context for thermal, structural, aerodynamic and other results. Gathered data is used in the post-processing step, after which parameter response can be investigated to narrow design space for optimum solution.

Collected results are helpful in building knowledge on parameters' influence across various disciplines allowing product performance predictions and supporting further design development.



Case	n	B	D	r1	r2
1	10	120	180	4	3
2	10	150	170	4	3
3	10	180	160	3	2
4	12	110	170	3	2
5	12	140	160	4	3
6	12	170	140	3	2
7	14	120	190	5	4
8	14	150	170	4	3
9	14	100	170	3	2

Figure 2: Principal structure of parametric environment [13]

2.1.4. Weld producibility assessment system

Since the main object of this thesis work is weld producibility assessment system, it is important to understand how it is structured and executed. Although the system has been continuously under development at GKN Aerospace by several contributors this section mostly refers to the recent thesis work of Jacobson M., 2016 [4].

Weld producibility assessment system, or as it is interchangeably referred to by its broader term as just Producibility Assessment System (PAS), is designed utilizing product development principles to increase robustness and flexibility. Here the latter two terms simply imply that the system has to be able to handle different analysis objects or models and at the same time be flexible enough to be built on and thus further elaborated. PAS is structured in a modular way which provides a clear systematic architecture and traceability. It follows a sequential process with no unnecessary dependencies letting the user to modify one part of the system without the need to go and update the others (Fig. 3).

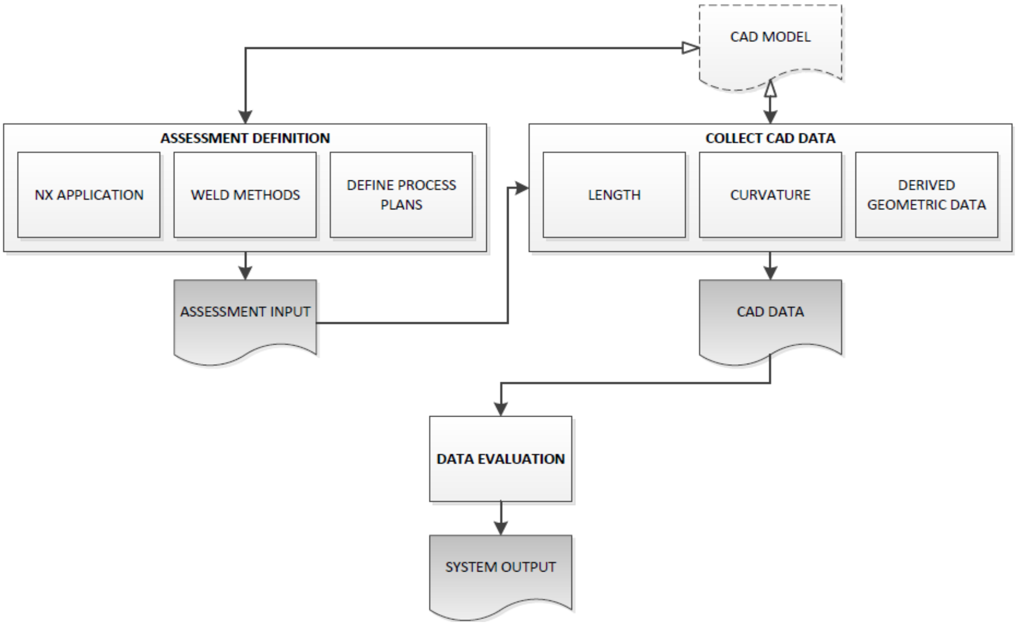


Figure 3: General system architecture of weld producibility assessment [4]

Assessment definition includes weld methods and process plan definitions in excel files. They were established with intent to only provide analysis framework and are not fully defined or updated to be used in an ongoing EWB studies. Anyhow, if fully realized, these definitions would expand analysis knowledge base and help determine the most preferential production methods and processes for a specific design.

The key property of the assessment module is selection of CAD features to be analyzed. A single DC is opened in NX interface and specific attributes are selected with the help of internal KF applications (Fig. 4). The attributes are simply selectable model edges which are regarded as weld edges. Surfaces surrounding the weld edge are constraints and have to be selected in order to correctly evaluate reachability data of the weld. This enables a sort of reachability metric estimation by providing information about weld edge surroundings such as nearest collisions restricting the welding mechanism. These features are then automatically sent to the excel file and additionally grouped to define how they are welded together.

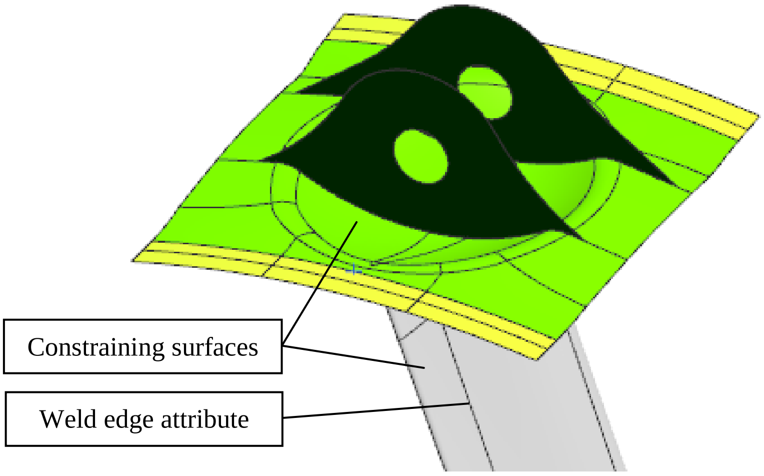


Figure 4: Model feature example

Collect CAD data is the second process part which uses assessment definition input for CAD data extraction. Here, previously mentioned features' file is updated with CAD data through the script which opens each DC, applies specific KF rules and extracts metrics like length, curvature, material ID, thickness, reachability angle and distance. Not all the data is directly available in the NX application and therefore it must be derived by automatically implemented model manipulations, which are the major cause of time extensive process. To simplify the work, no new files are generated at this point as necessary data is retrieved and stored directly into the same input file, which can then be used for data analysis directly.

Data evaluation is the final part of weld producibility assessment system where it is processed by a python script to structure and evaluate it against process plans and weld methods defined in the initial part. Established form of evaluation output provides a complete summary of all features for the entire set of DCs with some of the data expression handles, i.e. summation, max/min values, number of occurrences etc.

Current state of the system raises several requirements for its successful execution stated in the previous research findings [4], i.e.

1. Strict naming convention – feature names are crucial for the system to differentiate between features and identify if an attribute is a weld.
2. Feature sustainability – it is important to make sure that the evaluated features do exist in the geometry.

2.1.5. Turbine Rear Structure

Turbine Rear Structure (TRS), Turbine Exhaust Case (TEC) and Turbine Rear Frame (TRF) are all the names referring to a rear end static component of the jet engine (Fig.5). It supports low-pressure shaft and redirects exhaust flow from low pressure turbine to the exit nozzle [14]. This structural part is used to with PAS because its complexity better corresponds to the system's development level. However, it is recognized that a fully developed automated design integrated with producibility assessment should be able to maintain robustness for a wider range of structural components than just TRS.

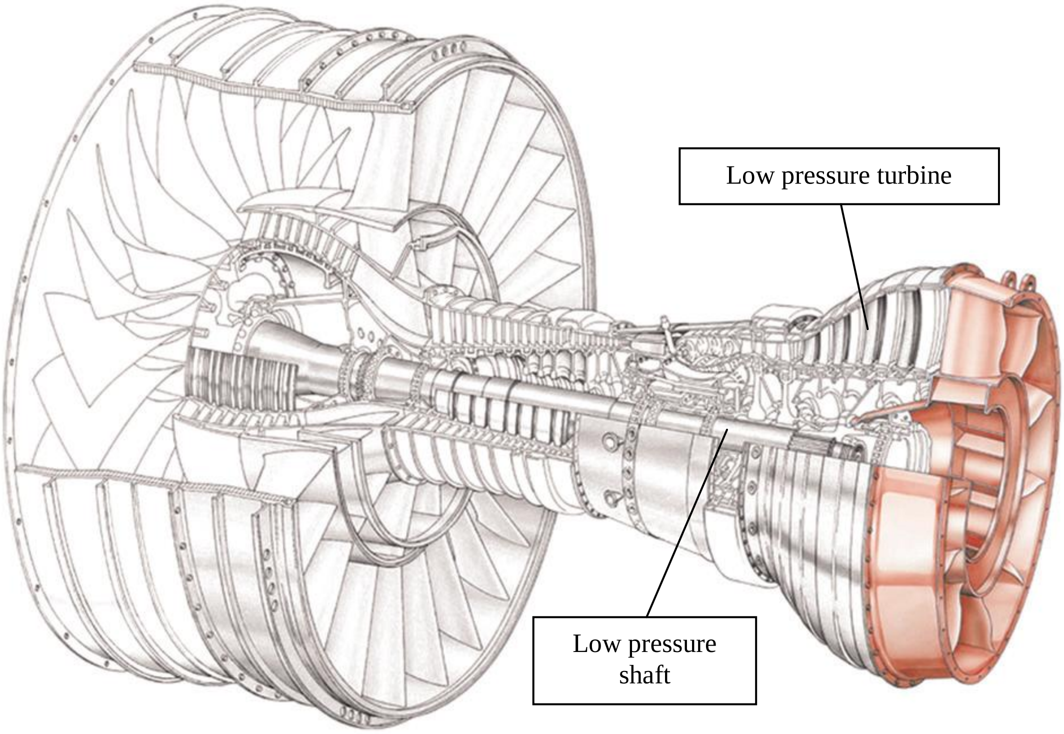


Figure 5: Turbine Rear Structure (highlighted) [15]

TRS is a beneficial option for a case study object because its concept is driven by manufacturing and purchasing rather than product functionality. Nevertheless, it still does not diminish structural requirements to withstand thermal, structural loads as well as to be light and aerodynamic for fuel efficiency [14, 15].

The parts used to assemble TRS are cast, forged or formed from sheet metal. Before the parts are welded together some machining operations are carried in preparation for the assembly and afterwards to deliver with the right geometric tolerances [15]. Finished structures are carefully inspected using various methods focusing on weld seam quality and other features.

2.1.6. Case study research questions

The object of this study is producibility assessment and how its multi-disciplinary analysis can be improved with manufacturability aspects for the proposed set of DCs. The project is performed at the aerospace company and therefore executed in the existing environment of that company where multi-disciplinary analysis system is represented by EWB and weld producibility assessment system is under development. Although implications of this research may be discussed outside the case of execution but the research questions formulated are in the context of models and tools provided by GKN Aerospace Sweden.

Weld producibility assessment system is under-developed and therefore not yet integrated into EWB. Some functionalities are finished but they are not formally validated. Assessment definitions require extensive investigation to accurately determine and define welding process in terms of time and costs. However, such accurate assessments are outside the scope of the thesis. Therefore, the first research question is focused on the data that is already attainable in the system and is formulated as such:

How can already extractable CAD model data be used for weld producibility assessment in a meaningful way?

Performed analysis in the project focuses on a specific gas turbine structure (TRS). This limits investigation of producibility assessment indicators to the context of that structure. Since the key desirable requirement for the system is robustness, system’s applicability on the other structural components is also discussed:

What are the most relevant producibility indicators of TRS to predict manufacturing time and do they maintain robustness in the context of other components?

Well established indicators should allow evaluation of different design cases. However, to be able to conclude any design with an overall producibility evaluation, there must be a way to express different indicators into a unified measurement. For the business, such ultimate measurements are time and costs, which are difficult to predict and acquire. Here, general process plans are investigated to see if the influence of different indicators could be determined and used to find a unified meaningful form of assessment:

How can producibility indicators be summarized for a preliminary but relevant single evaluation value?

2.2. KEY DEFINITIONS AND CONCEPTS

2.2.1. Knowledge-based engineering

To fully grasp the essence of this thesis research environment, several design engineering concepts need to be re-stated and further discussed. It is explained how traditional design engineering differs from Design Automation (DA) below.

Conventionally, a typical design engineering process involves moving from stages of preliminary towards detailed CAD model, which is finalized to meet objective criteria stated in the beginning of product conceptualization phase. Such traditional process can be facilitated with an innovative approach in computer-aided engineering known as Knowledge Based Engineering (KBE). KBE is defined as: "*…a method which captures product and process-based data and helps in building a virtual prototype in a system <…> for building a geometric model along with downstream processes such as material selection for static and dynamic analysis, and manufacturing capability enabling design automation.*" [16].

KBE allows design automation to take place by storing and retrieving design related data. The data can be used to automatically generate new models avoiding repetitive design tasks. Realistically, such concept implementation and use requires substantial support of computer based solution principles. Artificial Intelligence (AI) structures can be utilized, which are further theoretically discussed in Heikkinnen & Müller, 2015 [3] preceding project work. Nevertheless, well implemented knowledge-based systems should not be difficult to modify as the knowledge stored within is defined explicitly [17]. Therefore, one could, to some extent, work with the system without extensive knowledge of the programming language used. That is why some system manipulations and amendments were performed in the execution of this thesis.

Here it is important to understand that KBE, as stated by Rocca, 2012 [18]:

- Automates repetitive and non-creative tasks.
- Supports multi-disciplinary design optimization in all design process phases.

2.2.2. Set-based concurrent engineering

It can easily be shown that product development involving several different objectives in its realization can become a very complex task, especially when parameters defining those objectives are not directly correlated. How does one then have to undergo a development process?

Set-Based Concurrent Engineering (SBCE) is an engineering methodology with the potential to be applied not only in the development but in business activities in general because it seeks to address different process tasks in parallel or at the same time. So by reducing sequential work this concept results in reduced lead times and, consequently, costs.

The problem related to sequential development process is very well represented in the Figure 6, *a*. Here, the impact on the product life-cycle costs as early as in the concept development stage is shown to have the biggest influence as the information about the product in those early stages is mostly lacking. Initial poor judgment can cause re-design loop-backs which drive the costs even higher. In the sequential process, up to several stages may have to be repeated if they end up in that re-design loop. Latter situation is named as “over the wall engineering”. One must consider multiple product development stages concurrently to avoid re-design issues, e.g. manufacturing is addressed as early as in the conceptual studies. This, of course, is no re-design proof method as development is always an iterative process but the number of changes, time and costs can be significantly reduced (Fig. 6, *b*).

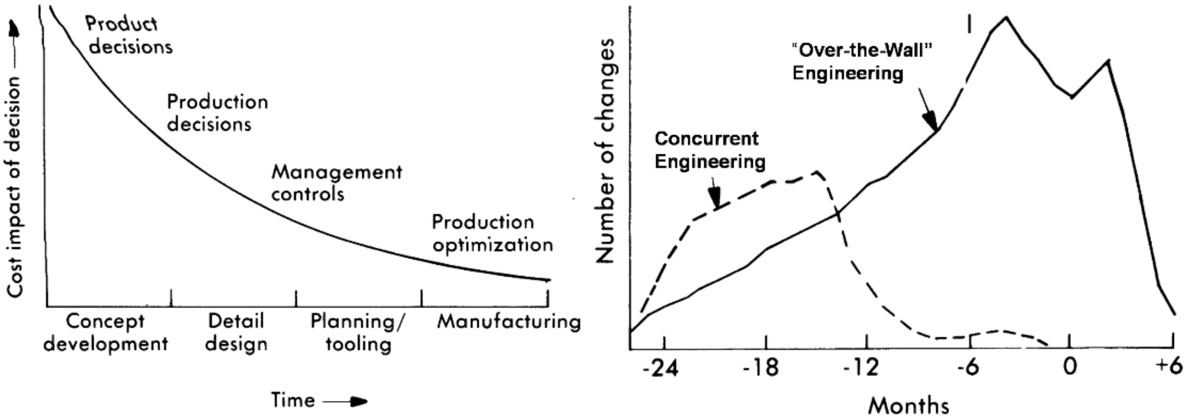


Figure 6: Engineering decision making impact and concurrent engineering benefit [19]

Another aspect of SBCE allowing the processes to be worked on concurrently is a set-based approach. Contrary to the point-based approach, where only single or few Design Cases (DCs) are considered, set-based concept involves exploring a wide design space. The number of infeasible solutions is reduced only as exploration of design space continues. Most importantly, all the design cases are a valuable source for the previously presented knowledge base system, where their information is stored. This allows to go back to them and use the obtained knowledge to look for relations of different parameters. Exploration of the design space lets developers find a more optimum solution and reduce loop-backs since alternative DCs can be selected without significant development efforts at any stage. Subsequently, SBCE studies have shown reduction in probability of design iterations [15].

2.2.3. Design of Experiment

Design of Experiment or DoE is a statistical method to define performance of a system by looking for correlation between input and output variables [20]. This method is the most general approach that one can employ to evaluate a system as it looks at it from a “black-box” perspective.

It means that no assumptions are initially made and the system is regarded as unknown. It is acknowledged that the system is subjected to controllable/uncontrollable factors and can give an output when acted upon by an input (Fig. 7). Varying a set of input parameters, system's behavior can be constructed and mathematical response surfaces can be plotted.

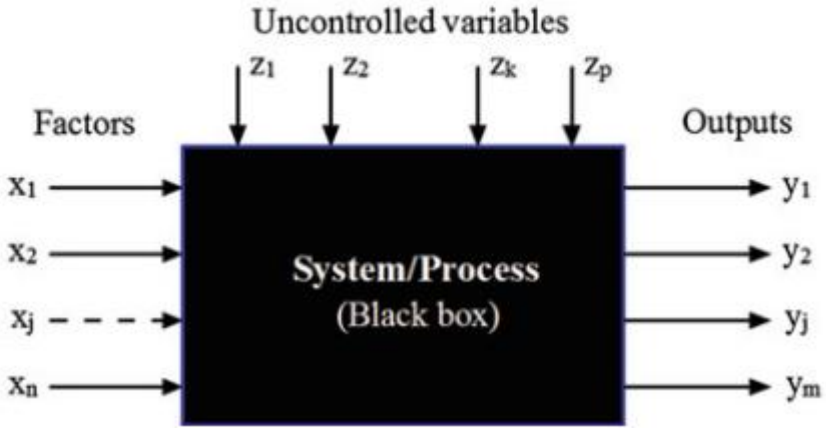


Figure 7: Formal definition of DoE [20]

In the most common scientific sense, the experiments are carried out by selecting one single variable while fixing the rest. Then, with enough certainty, observed response could be concluded to be a direct outcome of that variable. Nevertheless, multi-variable analysis is common in the DoE which then has to employ mathematical statistical models to vary those sets of parameters. In fact the increased variation in the design of computer experiments is an objective as it covers a wider design space and explores it by evenly spreading parameters across it [3].

Without resorting to extensive mathematical explanations of DoE distribution, the key take away of this chapter is to grasp the intent of the concept. It plays an important role in SBCE and is directly used to generate series of design case models by applying DoE on a single parametric base-line CAD model.

2.2.4. Manufacturability Assessment System

Manufacturability Assessment System or MAS is a system of tools which allows predicting or evaluating how manufacturable is a specific product design. Such system is exactly what is desired to be integrated into product development process.

Despite rather intuitive definition, it is important to clarify the distinction between the terms manufacturability and producibility. Vllhagen J. et al. 2013 in his research about producibility and manufacturability methodologies for the development of aerospace engine components said that manufacturability is used in the context of producibility. There is a clear distinction between the two terms. Producibility holds a strong link to product functions and performance, whereas manufacturability only focuses on product manufacturing trying to make it easier with less regard to product performance [21].

Therefore, MAS can be a system on its own as a subset of a broader producibility assessment system, where product performance and other characteristics are considered together with manufacturability. It is also concluded that in an aerospace context product functionality is so critical that there is a strong performance bias [10] which means that manufacturability tends to fall into a category of secondary influential factors. This by no means suggests that it could be neglected as it still is a valuable mean of support to optimize objective design.

MAS usually employs such tools as Design for Manufacturing (DFM) and Design for Assembly (DFA). The concepts solely seek to design the product in a way to improve its manufacturing by reducing the number of assembly parts and modeling the product to allow more preferential manufacturing techniques. In the context of high end technology engine components, tools like DFM and DFA may be more limited due functionality based product design constraints.

It would be best if CAD/CAM systems supported MAS as much as possible which would allow highly automated assessment process. Some modern computer modeling software already have built-in systems with enough flexibility for a user to create, customize and apply DFM rules to their design cases and extract relevant data. The data can be directly used as an assessment or joined with externally available techniques and pre-established knowledge base to analyze it. For example, information like material type, sheet thickness, minimum corner radius shapes and dimensions of holes could be extracted from the models. Then this information is used as inputs to the MAS. Generated outputs can be redesign suggestions, selection of processes and materials, process sequencing setups, planning setups and even foreseeable production costs and times [22].

However, these manufacturability metrics must be internally defined, which requires sufficient knowledge of the involved manufacturing processes. To succeed, developers and production specialists have to cooperate. Afterwards, the knowledge base can be created which contains all the necessary manufacturing rules and figures. It is also important to recognize that MAS must be constantly updated to stay current with the changing manufacturing processes.

2.2.5. Production costs and time modeling

The ultimate objective in producibility assessment for business is defining product prototypes in terms of process time and costs. This is a very challenging objective involving a lot of controllable and uncontrollable factors. Here the most relevant literature is reviewed for welding assessment.

It is found by Miller D.K. (2004) that when it comes to welding costs, there is a number of factors that could be considered, e.g. [23]

- Time for joint preparation.
- Time to prepare the material for welding (blasting, removal of oils, etc.).
- Time for assembly.
- Cost of electrodes.
- Cost of shielding materials.
- Cost of electric power
- …

There are three basic approaches to estimate welding costs, i.e. costs per unit, length or weight. The approach can be chosen based on the manufacturing type. Unit method applies for pieces moving through a workstation, length is used for estimating long different size welds and weight method works for significant volumes of weld material deposition.

Pabolu V. et al. (2016) [6] investigates welding manufacturability of TRS and chooses price per weld length approach to model the costs. The calculations are made based on chosen weld method, joint filler material, length of weld, number of weld runs and the average weld speed. Used modeling approach is relatively detailed and tries to express weld length costs in terms of fixed costs, i.e. equipment, installation, maintenance etc. and variable costs, i.e. manpower, electricity, filler material etc. Such costs modeling method assumes fixed and variable costs to be sub-parts of weld length costs.

However, given discussed weld length approach does not explicitly define the most impactful design aspect affecting the costs. One could not decide that the most effective way to reduce costs is a weld length reduction simply because they are expressed per unit of length. Latter assumption is one dimensional and overlooks complexity of the estimations where product design changes for the same weld length can carry immense hardly predictable manufacturing effect. Therefore, discussed estimation method does not allow robust evaluation for costs and time optimization. Here, product design must be considered as a whole in relation to manufacturing to establish its valid impact evaluation.

3. METHODS AND IMPLEMENTATION

This chapter is focused on method selection and implementation plan to execute the thesis. Two general methods used in the preceding works within the topic are described and compared to set the preference.

3.1. DESIGN RESEARCH METHODOLOGY

As mentioned in the section 2.1, producibility assessment development follows Design Research Methodology (DRM) established by Blessing and Chakrabarti, 2009 [8]. The method aims to clarify research objective by introducing concrete success criteria. Here it is analyzed what are the main factors preventing successful research and how can they be worked on to achieve success.

It has been mentioned that this thesis work is a sub-part of a broader DRM scope consisting of four main executable steps. Several previous works leading up to this thesis used DRM as the main method for their smaller scope research showing that the method can be applied on different scalability levels. Below it is briefly summarized what is the essence of the method to fully grasp the context of this thesis. Later it is argued whether the same DRM should be applied here.

Research clarification

It is important to begin with research clarification as the first DRM step is to define success and introduce measurable criteria. This is a fundamental element of the method identifying the aim of the research, focusing upcoming studies to find what is preventing success, developing support aimed at addressing the most influential factors and allowing its evaluation.

In the broader project scope that this thesis contributes to, it is desired to introduce a functioning producibility assessment system into multi-disciplinary set-based concurrent engineering studies. Some relevant success criteria that are impacted by this thesis are reflected in previously carried case studies by Elgh F. et al., 2016 [5]:

- Time spent in project - measured in time
- Support the designer - measured by designers’ assessment
- Lower number of errors - measured by number of changes in series production

Descriptive study I

In the first descriptive study it is necessary to increase knowledge and understanding of a design determining the most influential factors affecting established measurable criteria. This creates basis for the design support to be developed on.

At GKN, the first descriptive study knowledge has already been gathered by mentioned producibility assessment system research and development contributors. Some of it is available in their publications but additional information was collected from company staff assisting this thesis work.

Prescriptive study

Prescriptive study uses results of the descriptive study to develop an impact model which describes improved situation, systematically develops support and evaluates it. Here it was not required to develop a fully functional and complete impact model design. It only had to be sufficient enough to evaluate support with respect to previously established success criteria. Therefore, prescriptive study is usually a type of demonstrator or prototype which can later assist in a more complete development of the system.

PAS is the impact model and, although under-developed, it is the main working object of the thesis. The project is set in the prescriptive study phase of DRM which activities according to Blessing L., 2004 [24] can be summarized as such:

- Impact model or theory development.
- Systematic support development.
- Support evaluation with respect to its in-built functionality, consistency, etc.

The thesis contributes to all three summary points because it is aimed to assess the current impact model required by the study, implies systematic changes to collect relevant producibility assessment data and supports evaluation of the system as a whole by evaluating used indicators obtained from it.

Descriptive study II

The final study of DRM is focused to evaluate and validate the outcome of the prescriptive study and looks at it from a study purpose point of view. This can lead to some qualitative and quantitative results as established measurable factors should be evaluated.

Method feasibility for the study

DRM is known to be a good fit general approach method when it comes to determining which research to conduct and conclude it with specific measurable criteria evaluation. However, DRM process suggests method application to find and research innovative solutions when the working environment is not well known and requires lots of information collection. As many research methods, DRM is an iterative process during which different studies may be re-evaluated and considered concurrently. The method seems to be scalable if several impact models are determined in the study and considered separately. For example if the PAS was to be complemented with other assessment tools besides weld producibility, they could be researched individually. Nevertheless, Goldkuhl G., 2013 based on other scholars' publications, reviewed that DRM operates on a general level. He noted that the impact model design, although pursued on a specific problem, is later abstracted to a class of problems [25].

On the other hand, this thesis is focused on PAS and attempts to at least partially introduce it to the multi-disciplinary design studies. No new complete system was developed and only the most indispensible amendments were made in the existing system to allow the study.

Consequently, DRM method was not employed in the study as most of the required information is readily available for the defined research objectives yielding Descriptive Study I rather irrelevant, if DRM was to be applied. The most influential factors prohibiting the study are linked to the available weld producibility assessment system and were solved internally without extensive discussion in this thesis.

3.2. ACTION RESEARCH

Methodology employed in the thesis is Action Research (AR) which is concerned about improvement through action [26]. The method is better recognized in social sciences but was applied by Pabolu V. 2015 [6] in weldability analysis system development who chose the method over DRM as well. Nevertheless, AR can be employed in both quantitative or qualitative researches and focuses on local practices without overlooking its contribution to the general study [24]. The method is iterative and involves repetitive reflection on action cycles to verify if produced results or study refinements are needed. AR is a process by which change and understanding can be pursued at the same time [27]. Therefore, it was a sufficient approach for the study as it was not clearly known which indicators and in what form were to be analyzed due to potential delimitations imposed by the system.

Action Research was also discussed in the research methods literature review by Runeson et. al. 2009, who discussed AR application in software engineering stating that the method can be used in combination with case studies to better determine pre-and post-research impact [28]. Finally, AR is simply preferable due to its relevance to the project underlined in method definition: *"the AR approach … is particularly appropriate for solving problems for which past research has provided, at least a starting point and for the time being, a reasonably accepted scientific model supported by evidence. AR can then test the evidence against the model, refine it, or improve on it"* [29].

Above exactly corresponds to the project scope as some previous research has already been made. It was important to focus on the output of the system available evaluating its robustness through a case study and in turn doing some possible and necessary refinements imposed on the system.

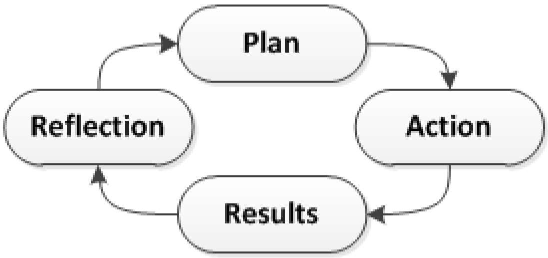


Figure 8: Action research cycle

Although typical AR steps consist just of four parts, i.e. plan, action, results and reflection (Fig.8), they can be detailed and split into six method execution steps [6, 30]:

1. Identifying the problem(s).
2. Analyzing the problem(s) and determining some relevant casual factors.
3. Formulating tentative ideas about the crucial factors.
4. Gathering and interpreting data to sharpen these ideas and to develop action hypotheses.
5. Formulating action(s).
6. Evaluating the results of the action(s).

These AR method steps were adapted to the study of the thesis and their implementation is elaborated next.

3.3. APPLICATION OF RESEARCH METHOD AND IMPLEMENTATION

In this section previously discussed and selected research method is detailed for implementation. The process following methodological Action Research steps is clarified explaining how the project was carried all the way to the evaluation of the results.

3.3.1. Problems identification

Having reviewed previous works in PAS development, it was recognized that this research also deals with the same topics, i.e. robustness, flexibility and assessment meaningfulness. To make the solution impactful, problems related to producibility assessment had to be detailed and understood. This aided not only as a research guiding tool but allowed to get back to the issues stated to evaluate project success.

Relevant problems were identified collaborating by the work supervision at GKN:

- Current state of producibility assessment system is not known.
- Some obtained data is incorrect and systematic problems are yet to be solved.
- Although a framework is established, data post-processing needs further development.
- It is not clear what type of producibility aspects are relevant in the production.

- It is not completely known how or in what form producibility assessment metrics can be translated into indicators and introduced to multi-disciplinary design studies.
- More producibility assessment indicators are to be obtained and it is not known what implication they pose on the system.
- It is not clear how producibility indicators could be used to assess weld process plans and their preliminary time and costs.

3.3.2. Analysis of problems and relevant factors

Previously gathered project based problems were analyzed to determine relevant work execution factors.

The issues seemed to involve extensive work within the system testing it and working with data. This is because it was initially recognized that systematic errors had to be found and worked out to even make the study feasible. Clearly, ability to handle the system and knowledge about its way of execution was imperative to study success. Consequently, latter requirement yielded some factors to be hardly controllable, i.e. if the error found is not completely amendable to the best of user's capabilities.

The next focus area to allow project execution was data post-processing. For a completely realized system, a robust automated post-processing module was required. Here, many things had to be considered because post-processing would be integrated in the weld producibility assessment system. Automation of this module was highly preferable even for the limited case of this study as several cycles of data extraction had to be performed. This could be very time consuming if each data post-processing attempt was to be done manually. Therefore, post-processing structure, data input and readability for automated analysis were considered.

The problems seemed to be linked. For example, more producibility indicators needed to be identified but their implementation may have posed changes to the preceding parts of the system like data extraction or post-processing. Therefore, it was important to tackle the tasks concurrently and receive feedback continuously. Production input was used to concentrate on relevance and visualization of the indicators. It was important to establish clear mutual understanding between production and product development to really address the key metrics and translate them into meaningful indicators.

Based on identified problems, it became clear that the study with the main goal to evaluate performance and impact of the producibility assessment system is multi-objective. The key factors of the study are initial study setup, system's modifiability, data input, post-processing structure, indicators and their relevance.

3.3.3. Tentative ideas for execution

Once the problems were gathered and analyzed, it was possible to state ideas for project execution. The focal points of the study implementation are revealed below.

Current state analysis and setup

To perform current state analysis, a close practical familiarization with the weld producibility assessment system was required. It was first observed how the system performs on the simplified design cases like the ones it had been developed and tested on in the previous works. Then obtained metrics, i.e. length, material ID, curvature, reachability distance and angle were carefully evaluated for the welds of the case study.

Case study models were TRS CAD assembly DCs used to evaluate several different group welds. Obtained metrics were evaluated and encountered problems preventing execution were identified. Necessary modifications to the system were made to verify that resulting metrics are correct.

The outcome of the study setup was to identify any points of concern in later studies and possibly improve system's performance. This was realized by adapting the system to handle TRS models. As a result, application of the system could be expanded and its robustness increased.

Post-processing development

Post-processing is an extension of weld producibility assessment system which takes output data from the system and uses it as its input. The data is then modified to translate it into meaningful producibility indicators. It was certain that this module may have required additional input as indicators are usually based on production definitions, which have to be obtained as well. It was not intended to develop a fully functioning system so the way that post-processing is linked to other data sources may not follow systematic design practices used in the previous works.

Nevertheless, post-processing was fed with data several times during this study so process automation was preferred to speed up iterations and minimize manual data handling. Here, the success of post-processing development was mostly dependent on the software selection and capability to work with it.

Well developed post-processing module should allow metrics to be gathered relatively quickly. This would speed up data preparation for results visualization and integration with overall multi-disciplinary design data, which is later used to investigate parameter relations.

Production input

The project was evaluated based on the feedback from production and development specialists regarding demonstrated results of the system. Therefore, it was useful to rely on the same people to steer the project into the right direction.

Production input was required several times during post-processing development stage. This is because potential indicators were formulated first and then proposed and discussed with the production. The feedback was used to exclude or modify indicators gathering additional information. The communication was carried during project status updates to collect feedback.

This step had an effect both on system's setup to do modifications for additional data retrieval, and post-processing module to adjust data handling.

Preliminary project execution plan

Above execution ideas were summarized and presented in a preliminary project realization plan (Fig.9). It can be seen that some aspects of action research methodology were already taking shape since production input may be regarded as reflective part of the project requiring several research iteration cycles.

To sum up, some familiarization in current system's state evaluation was obtained to move on to the case study setup where all imperative systematic amendments were made to proceed with the study. Then, post-processing module development started, intermediate results were collected and refined with production input. Lastly, results were presented and evaluated to determine the impact of the study. Execution steps and final data evaluation are described next.

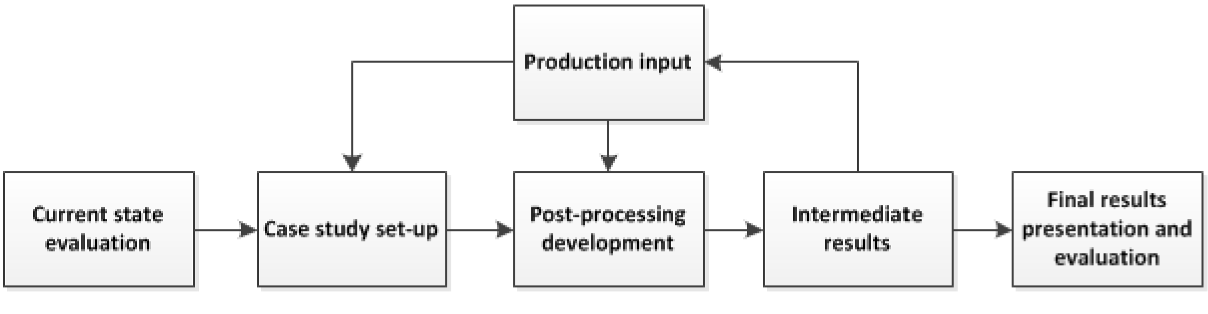


Figure 9: Preliminary project execution flow

3.3.4. Gathering and interpreting data to establish first action plan

It was first necessary to start working with the weld producibility assessment system to gain practical familiarization and evaluate its current state. That is why the title of this section implies preparation for the study leading up to the actions taken to achieve the research objective.

Design cases studied

The main focus in this research step is already mentioned TRS (Fig.10) component of a jet engine. Case study models from the previous EWB analysis were provided. They follow pre-defined DoE setup for 29 DCs with varying model parameters. Once the assessment took place, these variations had to be reflected by the weld producibility metrics.

TRS is a welded assembly of different structural parts. Each available DC consists of:

- MNT – 3 mounting sections
- MRT – 2 mounting transition sections
- REG – remaining number or regular sections

Sections can also be interchangeably referred to as struts, vanes and sectors. MRT indicates how and where TRS is mounted to the other engine components. These sections are therefore sturdier than the others. MRT is a transition section between MNT and REG. Consequently, faces of MRT are thinner than MNT but thicker than REG.

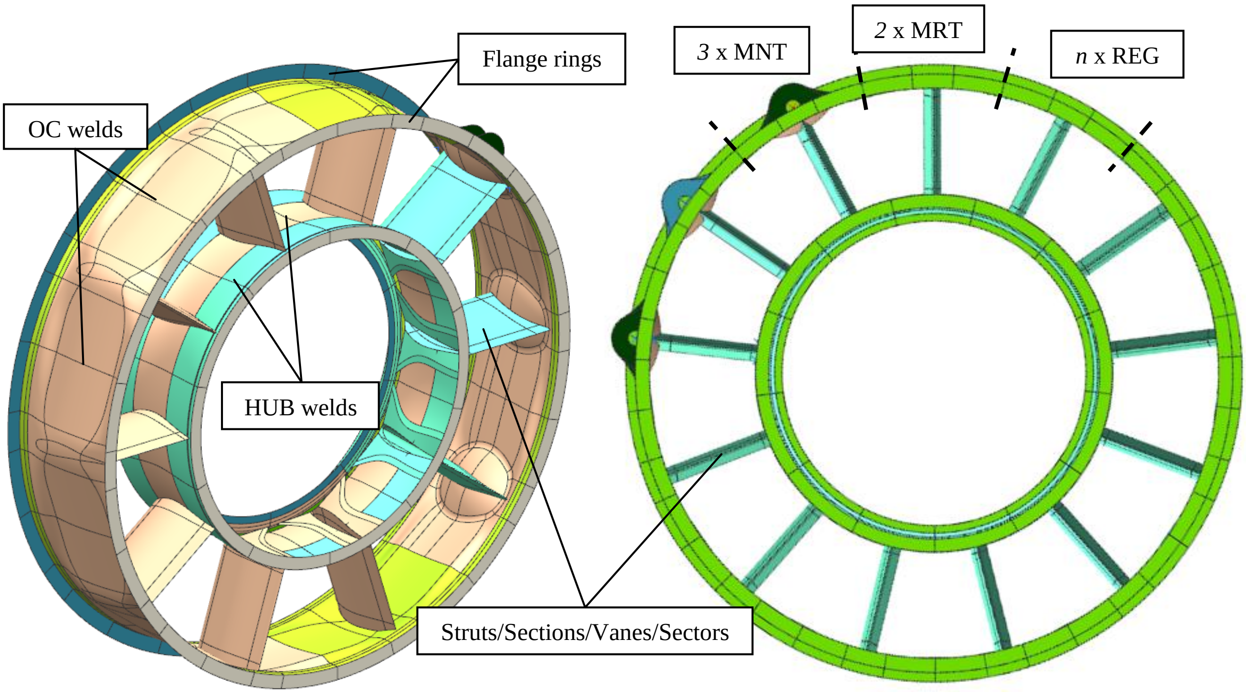


Figure 10: Turbine Rear Structure (TRS) single DC

While MNT, MRT section number is always the same for the DCs, REG section number is varied. Another variation parameter related to struts is their lean angle. In the case study there are multiple TRS models with different combinations of section numbers varying from 10 to 16 and lean angle increasing from 0 to 40 degrees (Fig.11).

Assessment study was prepared with the help of project supervision at the company selecting weld edges of interest, i.e. Outer Case (OC) edges separating the sections, HUB welds enclosed in the air flow cavity and flange rings supporting cylindrical structure from both sides.

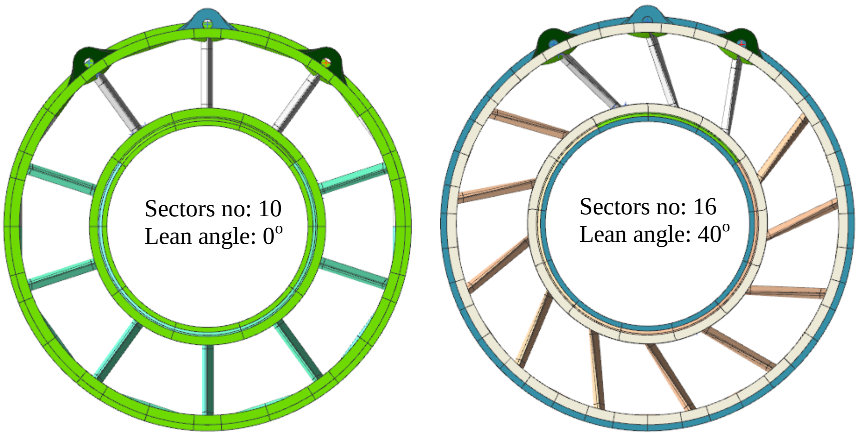


Figure 11: Structural variation across DCs (DC7 – left, DC18)

However, not everything is reflected by the DoE and CAD models for various DCs. In order to maintain stiffness for the DCs with 13 or fewer struts additional welds are introduced. In fact, between each section an additional plate is welded in to stiffen the structure. Consequently, it was recognized that different production rules may come into place based on study setup and these rules too have to be accounted for in the weld producibility assessment data.

Validation and errors traceability

There are two main sources of errors in weld producibility assessment, i.e. model and/or the system itself. Therefore, data validation for the weld producibility assessment system was performed in two ways:

- Checked manually in the NX application – reveals system errors.
- Looking for inconsistencies throughout all data – reveals model errors.

Manual checking in the NX application was done employing built-in measurement tools, e.g. edge length, curvature analysis etc. If compared data agrees, it could be concluded that the system assesses CAD model correctly. Otherwise errors may be found in analysis setup or within execution scripts of the system.

Manual data validation is highly supported by knowledge gathered in the previous part where design case study models were discussed. Since it was known how the structure is varied, consistencies for some of the different weld groups could be assumed. For example, OC welds have the same length, therefore, it was sufficient to only check one metric value per DC and look for changes in equivalent weld groups. If inconsistencies were found, then they could indicate a model related error.

Such validation approach addressed previous development project of the system where the importance of correctly setup CAD models is emphasized.

Amendment of the system

Perhaps the most important part of the case study was not just to evaluate the system but to gain knowledge on how it works. Running into systematic errors and attempting to amend them increased understanding about the system and how it is executed by scripts programmed in VBA, KF and python. It was recognized that modifications to the PAS are most certainly needed to make the study feasible. Consequently, knowledge and ability to work within it was essential for successful system's extension and data post-processing. Therefore, to speed up the process all imperative amendments were performed with the help of department support.

3.3.5. Formulating actions

Action cycle 1: Data post-processing

The most important task after successful systematic setup was the post-processing of the obtained results. At this point enough knowledge was available based on previously gathered information to handle data and establish meaningful indicators.

To maintain systematic integrity, post-processing had to be an extension of the weld producibility assessment analysis module. For mere demonstration of the system, it was only enough to apply simple data handling tools in excel. Since TRS baseline model always includes the same main weld groups, templates for their evaluations were prepared. The system had to be able to operate on two output levels, i.e. separate and overall weld evaluation of the DCs.

Additional inputs for the system were considered too because geometric CAD model data alone cannot fully define producibility assessment. It was discussed previously that EWB is interconnected where several disciplines depend on one another. If producibility assessment gets integrated as an equivalent module, then it too may have to consider inputs from other disciplines. All additional data such as relevant rules not reflected in the CAD data were regarded as inputs as well (Fig.12). The last part of established data post-processing was process plans where preliminary time and costs are intended to be defined for different welding methods. Investigation of the process plans is further explained in the 3rd action cycle.

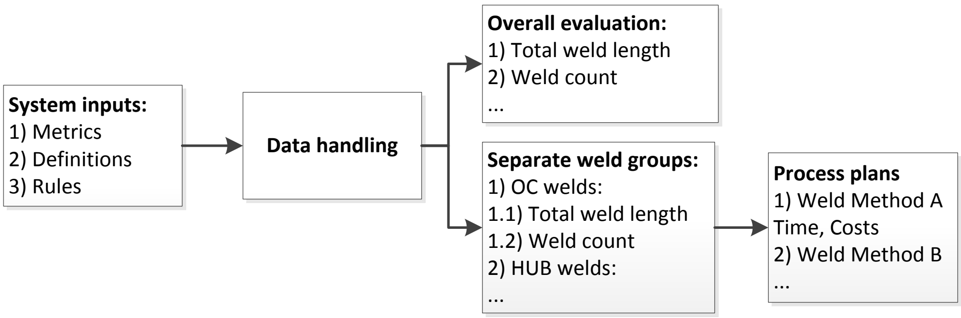


Figure 12: Data post-processing

Post-processing implementation is a cyclic process where system's development and testing requires several iterations. Such system is also prone to continuous changes due to varying range of manufacturing inputs and their values. Subsequently, a semi-automatic data post-processing module solution was approached admitting that a full automation would be a wasteful and tedious task before the impact of the system is even demonstrated and evaluated.

Action cycle 2: Investigating process plans

The next implementation step required in the post-processing was process plan analysis to determine manufacturing resourcefulness. Here, resourcefulness implies some sort of unified assessment criteria considering that definitive manufacturing time and costs are not attainable within the scope of this research. Process plans module is a part of the assessment definition within the weld producibility assessment system and includes different weld methods (Table 1). Only incomplete framework was available without sufficient manufacturing consideration to establish measurement rules. Therefore, process plans were investigated in attempt to:

- Expand process plans analyzing TRS manufacturing.
- Find and demonstrate preliminary time, costs or other unified measure based on available metrics for this study.

Considering cost modeling limitations of Pabolu V. 2016 [6] discussed in section 2.2.5 where he tries to evaluate all fixed and variable costs to express them for weld length, a different approach was taken. Instead of approximating production costs in terms of fixed and variable inputs, it was tried to find out what additional manufacturing resourcefulness comes from design changes. The intention was to relate product design to its manufacturing implications through available metrics and indicators. Therefore production platform documentation for a sample 10 sectors TRS model was used with foreseen production times estimated. The data was discussed with a process engineer during meetings and production floor visits.

Table 1: Process plan template for different weld methods

	Methods	**Laser Beam Weld 1**	**Laser Beam Weld 2**	**Tungsten Inert Gas Weld**	**Plasma Weld**	**Electron Beam Weld**
Indicators	Process plans	Tackweld	Tackweld	Tackweld	Tackweld	Tackweld
1		Machining	Machining	Machining	Machining	Machining
2		Inspection	Inspection	Inspection	Inspection	Inspection
…		…	…	…	…	…
n	**Time**	…	…	…	…	…
	Costs	…	…	…	…	…

Once the list of process plans was expanded, each operation was considered with respect to its manufacturing impact and involved producibility metrics, i.e. length, thickness, curvature, material ID, reachability angle, reachability distance. Such analysis allowed to capture more process items to be added and possibly rules for their assessment.

Action cycle 3: Metrics and indicators visualization

It was not sure that CAD model assessment metrics would lead to an increase of captured indicators. However, it was sufficient that these metrics and indicators could be used to rank DCs within their categories. Afterwards, extreme cases could be depicted depending on their max/min values, e.g. long weld length DCs were less preferable then shorter weld length DCs based on that single evaluation category.

Once data meaningfulness was realized, it was possible to visualize and interpret it. This could be achieved using different tools. Most conventional and known to the majority of employees is MS Excel where tabular data can be quickly graphed on chosen chart types. The company also uses powerful optimization tool software - modeFRONTIER for multi-objective and multi-disciplinary optimization. For the case study this software was utilized to plot response surfaces of gathered geometry data to be assessed because several interpolation and extrapolation options are available within it.

Action cycle 4: Response demonstration of producibility assessment indicators

After data post-processing and visualization was possible, demonstration of producibility assessment indicators could be prepared. All design cases were summarized and their data fed to the overall EWB multi-disciplinary analysis summary table. Here, results demonstration of potential system in action is called a demonstrator.

Following EWB structure, producibility assessment was introduced in a form of a table as an additional discipline with its indicators (Table 2). Selected indicators were used to reflect both overall and separate evaluations from the data post-processing. This allows analysis to take place on overall and separate producibility assessment level.

Table 2: General EWB results table outline

DCs	**Sections**	**Structural**	**Aerodynamic**	**Thermal**	**⋮**	**Producibility**		
						Indicator 1	Indicator 2	…
1	16					…	…	…
2	16					…	…	…
…	…					…	…	…
29	16					…	…	…
Min						…	…	…
Max						…	…	…

To determine how different indicators interact with each other, a correlation matrix was created. Correlation matrix is a table which header rows and column consist of all investigated inputs and outputs and their correlation is evaluated by the cell values in the table. Only the most relevant data from other disciplines was taken to observe its response. Correlating and other parameters of interest were visualized and discussed.

3.3.6. Evaluation of action results

It would have been a too extensive research to figure out how proposed working system affected design during a full development life cycle and gather quantitative data like reduced number of re-design loops or generated savings. However, a well developed demonstrator of the system's performance could be used as a reflection of the actual system in action. Therefore, this evaluation was focused on company specialists involved in development and manufacturing to determine what is their view on the results presented. Consequently, the impact of this study was largely evaluated in qualitative terms during continuous discussions.

Finally, to verify overall thesis success, identified problems laid out in the beginning of the methodology implementation were discussed as well.

4. FINDINGS AND ANALYSIS

This chapter concisely presents findings and analysis of the research whereas its evaluation and discussion is presented separately in the following chapter. Here covered topics include assessment setup, producibility metrics and indicators, developed data post-processing analysis, investigation of the process plans and final results demonstration.

4.1. ASSESSMENT SETUP

During the setup of the system for TRS producibility assessment, available CAD model metrics had to be verified. This revealed several systematic obstacles and confirmed initially stated requirements for the system's performance.

It was found that each CAD model contains edges of two types, i.e.

- Single edges – one edge identifies separation between two faces to be welded, e.g. vanes (Fig.13, *blue*)
- Double edges – two identical edges shared by two faces which are associated to them respectively, e.g. OC edges (Fig.13, *red*). In the figure one group of MNT edges belongs to the left section and the other to the right.

It became clear that assembly models usually have such edge types. Single edges are simply added on the face to identify potential weld. Double edges are not explicit and come from the way the model is built, e.g. separate OC sections used as CAD building blocks. The system is not able to distinguish between the types and gives two times higher values for length data when working with double edges. This was not fully resolved systematically and had to be taken into account during post-processing.

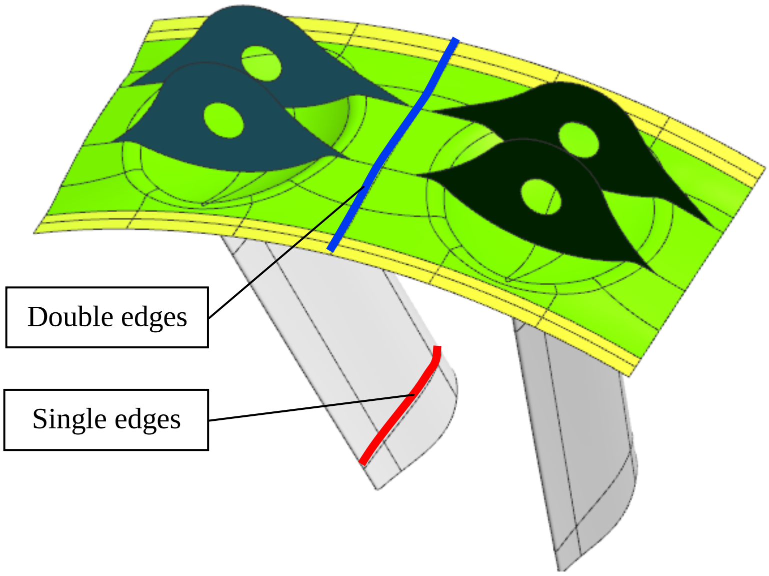


Figure 13: Edge weld type examples (*red*-single edge, *blue*-double edges)

A single OC weld (Fig.13, *blue*) in the CAD model is represented by several edges along that weld having distinct names. All these edges were grouped under a single weld group name to signify that the two OC sections are welded together in one stroke. Consequently, the whole model is essentially defined by groups of welds needed to assemble it. The option of grouping them was not responding and had to be amended systematically to allow the study.

The main errors determined for CAD geometry data included curvature, reachability angle, and reachability distance. Curvature was improved by amending problems related to double edges and evaluation precision. Reachability data was found to have fundamental problems limiting its application therefore a new indicator was proposed. Verification summary is shown in the Table 3.

Used method of verification also revealed several CAD model related problems. The most essential for the study is related to incorrectly set feature names due to which not all edges could be assessed. Since the features are named automatically, the feature naming script was adjusted. Also, for the majority of design cases HUB weld discontinuities were detected. As a result, their weld lengths had to be collected manually.

Table 3: CAD metrics verification

Metrics	**Verification 1**	**Change**	**Verification 2**	**Change**	**Verification 3**
Length	NOK	Fixed CAD feature naming script	NOK	No – adjusted in post-processing	OK
Curvature	NOK		NOK	Script change	OK
Thickness	NOK		OK		OK
Reachability distance	NOK		NOK	New indicator implemented	OK - partially
Reachability angle	NOK		NOK	New indicator implemented	OK - partially
Material ID	NOK		OK		OK

4.2. ANALYSED METRICS AND INDICATORS

CAD geometry metrics were verified therefore it was possible to start establishing producibility indicators. After discussions with project supervision and production specialists, the following list of indicators was created.

4.2.1. Length

Length predicts the amount of welding needed. This metric is capable to enable time and costs estimations for welding process alone if the amount of filler material deposited is known. However, weld length alone is more relevant if the design includes long continuous welds but it is always considered in combination with the number of welds involved.

Length metric can be used not only to define the total welding amount but also to track model geometry changes and reflect DoE setup. Other disciplines like aerodynamic calculations imply geometric changes on the CAD model. Single section length of the OC weld is observed to decrease linearly with an increasing number of sections (Fig.14)

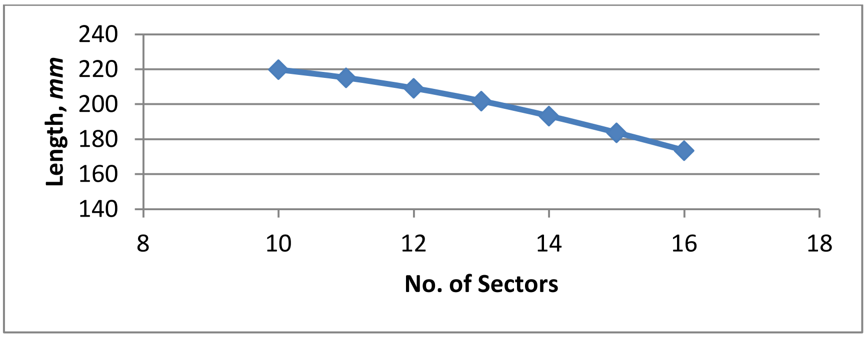


Figure 14: Single OC weld length vs no. of Sectors

4.2.2. Start/stop count

Start/stop count is simply obtained from the number of group welds per model where one group always has a start and end point. It was determined that this indicator may have the highest significance in process execution.

Each welding start point begins with a material damage as it creates a weld hole in the metal. The same happens to the end point of the weld. To avoid this additional weld extension sheet plates are added to offset weld start and end points so that required weld would not be damaged. Afterwards, weld salvage operation is required for which plate extensions need to be removed. This is how OC welds are produced and causes additional operational time for each weld.

Flange welds, however, cannot include sheet plate weld extensions as the weld is circular. Here, the starting point of the weld is treated by the same continuous weld going over it and only the end point needs to be fixed manually.

Both OC and flange type welds are illustrated in Figure 15.

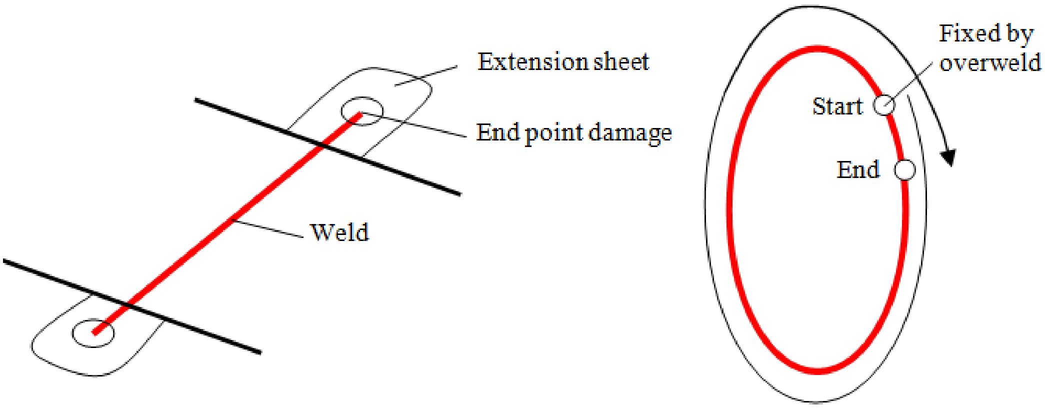


Figure 15: OC (left) and Flange (right) welding

4.2.3. Curvature

Curvature has the potential to assess the difficulty of edges welded. It was found to be most relevant for the generally higher curvature value features like struts (Fig.16). Here, the difficulty is related to automated welding motion setup and quality execution. High curvature edges lead to increased weld head acceleration rates due to the change in welding direction. Although, the metric is not directly used in manufacturing but its impact is recognized.

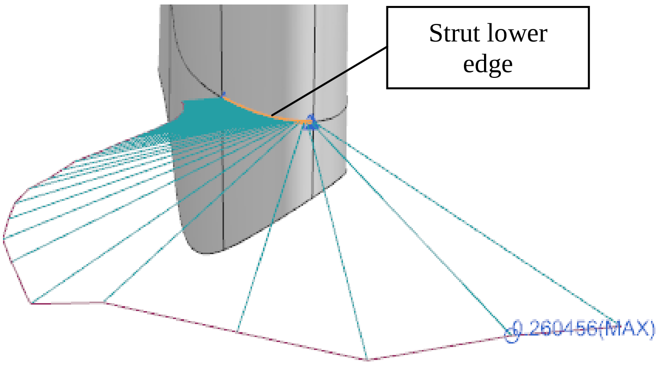


Figure 16: Single edge strut maximum curvature

Feature curvature in struts geometry is related to air flow and many structural design alternatives can be considered to maintain aerodynamic performance. Later presented correlation matrix will show that curvature is not the only indicator influencing aerodynamic performance. Therefore producibility can be optimized for favorable curvature values changing other design inputs.

It was noted that the relevance of curvature could be diminished if the component involving difficult weld is cast as a whole piece instead of welded together. For the TRS such alternative would solve related issues but there may be other problems due to different manufacturing methods employed.

4.2.4. Thickness variance

There are many variables related to thickness variation such as machining operations to level welded surfaces and weld susceptibility to distortion. Discussions about this issue concluded that thicknesses uniformity is a general desirable for any favorable weld producibility. Therefore, variance was proposed as the key indicator to evaluate weld uniformity. This single indicator allows general weld quality and difficulty prediction. The variance is also supported with absolute thickness data which can be used to calculate milling operation to establish smooth transition between welded faces.

For thickness variance values above 0, maximum and minimum thicknesses of welded features are of interest. These values determine how parts to be welded should be milled for required transition and if milling is even feasible for such thicknesses (Fig.17).

Thickness variance works by describing thickness uniformity along a single weld group. The indicator is compiled knowing all the thicknesses associated with one weld group (Fig.18). A mathematical variance is calculated for those thicknesses signifying how much thicknesses of the weld deviate from the mean value.

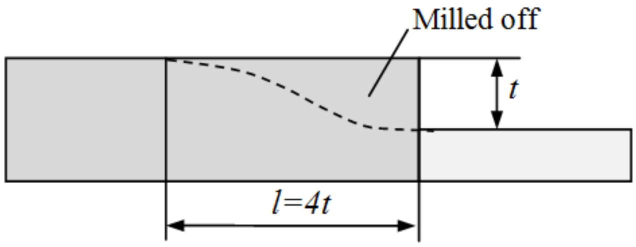
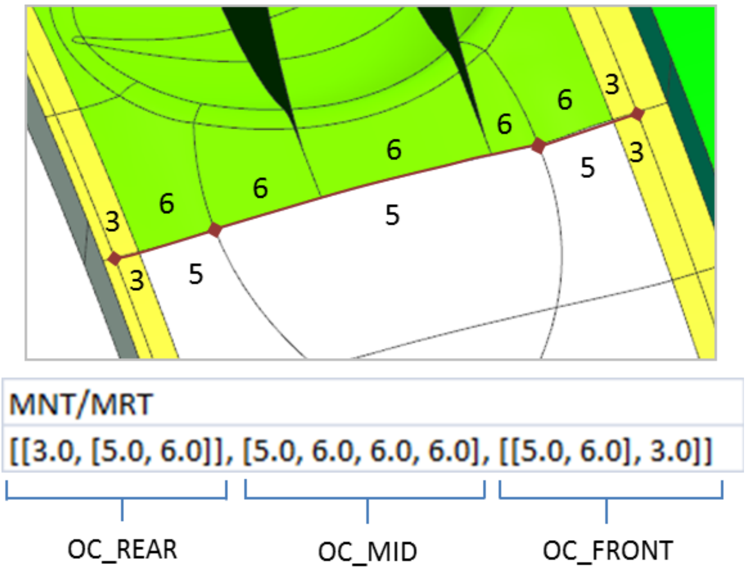


Figure 17: Thickness transition between welded faces



MNT/MRT
[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]

Figure 18: Single weld group and associated thicknesses

To extract thickness variance, a specific output string had to be implemented in the system. This data output example can be found in Figure 18. Each OC weld group is usually divided into named categories, i.e. rear, mid and front. According to these naming conventions, thickness values can easily be read in the data string. However, to obtain single variance indicator value, this string is handled in the post-processing.

Thickness variance for the most severe weld group was graphed across the whole range of DCs (Fig.19). If thickness variance definitions are proven to be practical and employed by the production, a threshold value could be assigned to determine cases of increased severity or even unfeasibility to manufacture.

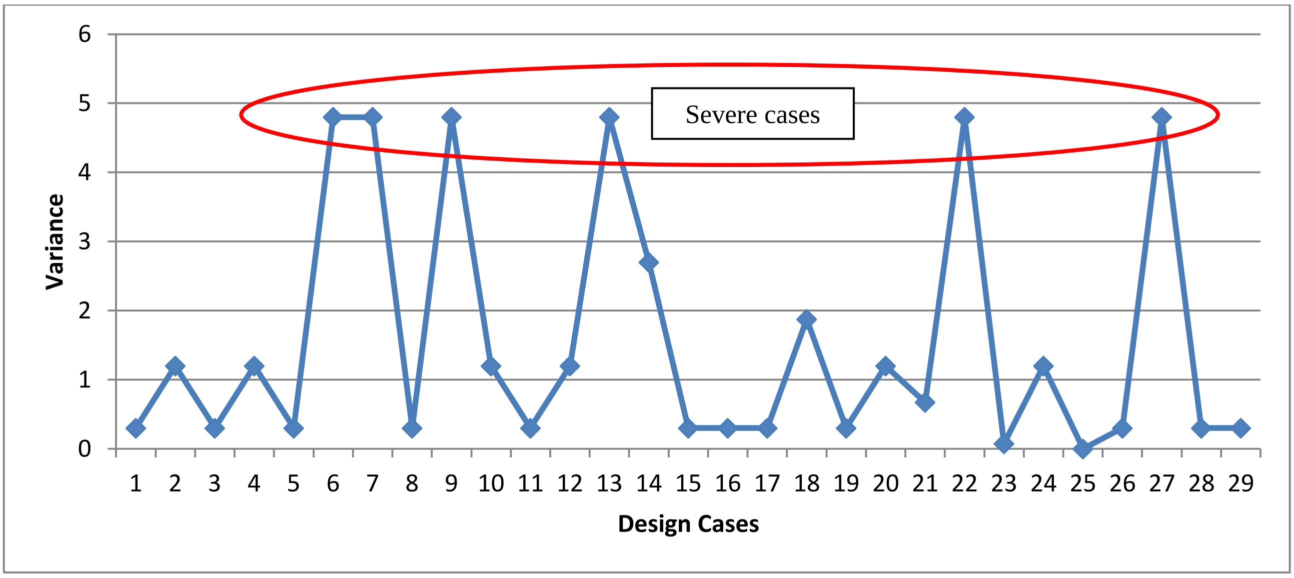


Figure 19: Sever thickness variance (weld - REG/REG)

Finally, the same thickness value string was used to find minimum and maximum thicknesses for each weld. In addition to already mentioned thickness relevance, these values are also required to determine feasible weld methods based on specified weld penetration depths.

4.2.5. Minimum accessibility

It was found that reachability metrics are not valid for enclosed weld assessment when a weld resides in a cavity constrained from all directions (Fig.20). That is because while estimating reachability, a normal direction to the weld is checked first and then the angle of that normal is changed until the first intersection with a constraining surface is detected. When a weld is constrained from above, the system finds intersection normal to the weld and the found reachability angle output value is 0. Consequently, any other constraining surface points are not even considered.

The issue could be resolved if minimum feasible reachability distance and angle values were known. Since these definitions depend on the production and would require constant updates in the system’s scripts, a minimum accessibility indicator was proposed instead.

Minimum accessibility looks for constraints in all directions surrounding the weld. Relatively small angle values are omitted to prevent 0 reachability distance for intersections at the weld itself. This minimum accessibility indicator also indicates an associated reachability angle value. Consequently, the point of nearest collision can be identified in a polar coordinate system where weld point is the point of origin.

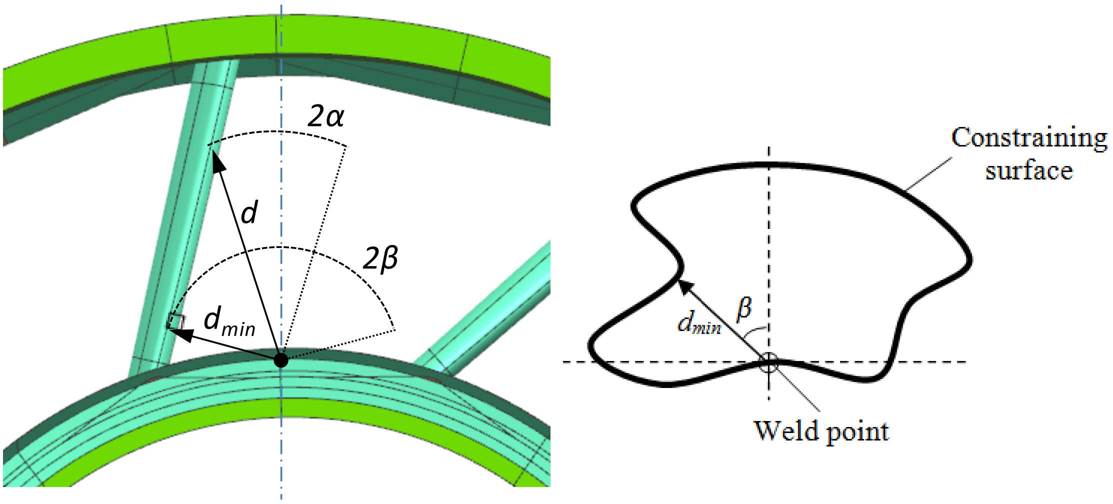


Figure 20: Enclosed weld representation

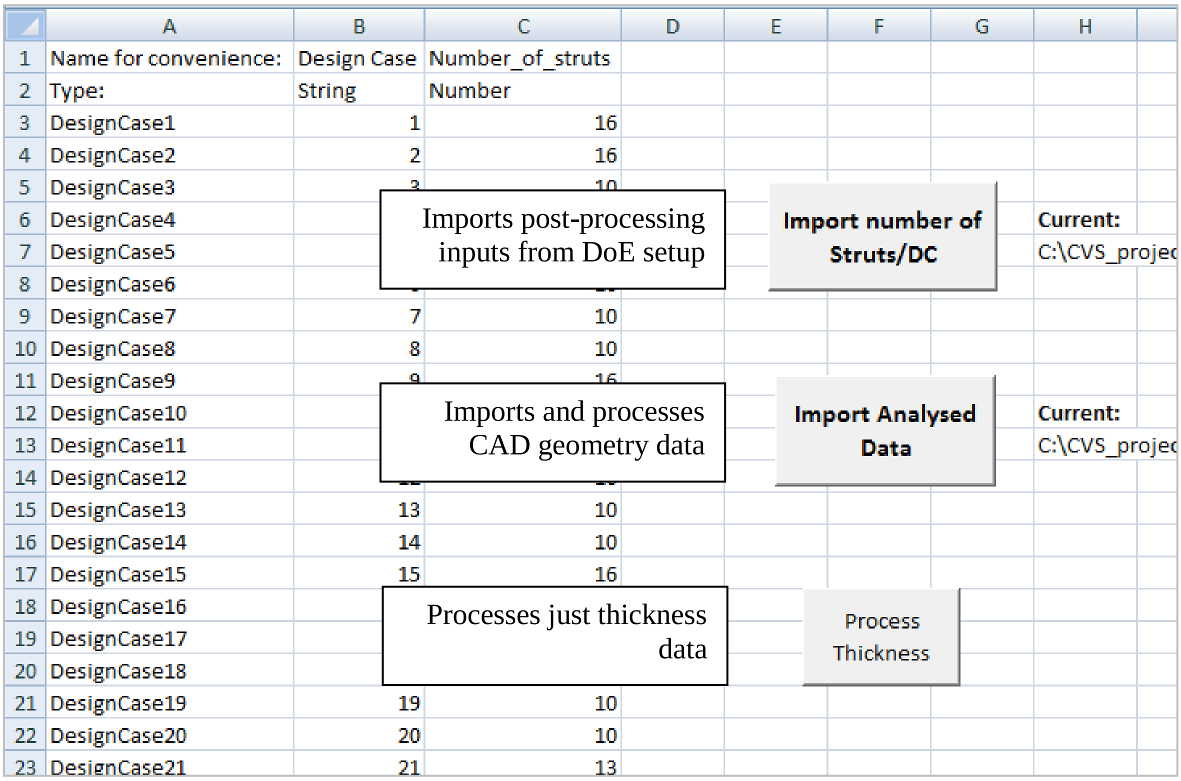
4.2.6. Material ID

Material identification is a specific number associated with faces in the group weld. For this study, it could not be used as a metric allowing comparative DCs assessment because given DoE does not explore material variation. Nevertheless, it was found that material may have significant influence on manufacturing operations involved. For example, time extensive heat treatment operation is only used with super-alloy materials common in jet engines which may be omitted if design material alternatives were found.

4.3. DATA POST-PROCESSING

Data post-processing was implemented in excel utilizing VB functionality (Fig.21). This allowed implementing a semi-automatic solution with a basic user interface.

Two inputs are introduced in the examined cases that are resulting files from the CAD geometry analysis and DoE setup. In the post-processing a link with DoE file allows to automatically pull section numbers for each DC. For example if OC weld length for one section is known and the total number of sections or struts is imported from DoE, then their multiplication is an overall length of OC welds in the model. Latter is just one example on how post-processing inputs could be used.



	A	B	C	H
1	Name for convenience:	Design Case	Number_of_struts	
2	Type:	String	Number	
3	DesignCase1	1	16	
4	DesignCase2	2	16	
5	DesignCase3	3	10	
6	DesignCase4			Current:
7	DesignCase5			C:\CVS_projec
8	DesignCase6			
9	DesignCase7	7	10	
10	DesignCase8	8	10	
11	DesignCase9	9	16	
12	DesignCase10			Current:
13	DesignCase11			C:\CVS_projec
14	DesignCase12			
15	DesignCase13	13	10	
16	DesignCase14	14	10	
17	DesignCase15	15	16	
18	DesignCase16			
19	DesignCase17			
20	DesignCase18			
21	DesignCase19	19	10	
22	DesignCase20	20	10	
23	DesignCase21	21	13	

Imports post-processing inputs from DoE setup

Imports and processes CAD geometry data

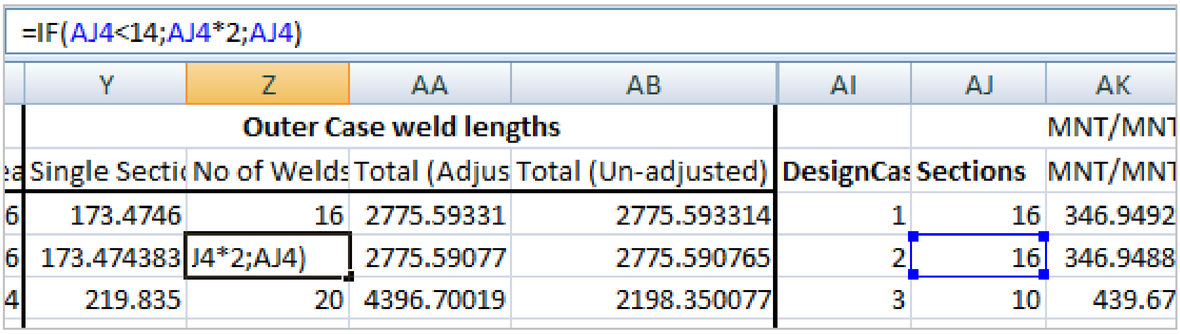
Processes just thickness data

Figure 21: Semi-automated post-processing interface

Appendix A-1 represents post-processing data for one of the weld groups, i.e. mounting section (MNT) welded with mounting transition section (MRT). The table shows how imported result file data is organized in post-processing excel sheet before actual data-processing takes place.

Since the data for all analyzed weld groups is available in the described form, it is easy to manipulate it in excel and create separate weld assessment templates. Appendices A-2, A-3 show relevant separate weld group evaluations. Separate evaluations are already processed data tables taking into account all necessary inputs from the analyzed CAD geometry data, DoE for different section numbers and added production rules.

The production rules are additional inputs which are not reflected in the DoE or CAD model itself. For instance, it was already mentioned in method implementation that if the number of sections for TRS is too small, the sections have to be extended to maintain overall model size. Such design of fewer sectors is not as stiff and in order to compensate for the stiffness loss, additional plate is welded in between each sector. The stiffness is maintained but weld length increases. Therefore if the production rule states that for all DCs with 13 or fewer sections an additional plate is welded between each section, then this rule can be described utilizing excel functionality. Here an ‘IF statement’ is used to include rule definition and adjust total weld length of OC welds (Fig.22).



=IF(AJ4<14;AJ4*2;AJ4)

	Y	Z	AA	AB	AI	AJ	AK
	Outer Case weld lengths						MNT/MNT
ea	Single Secti	No of Welds	Total (Adjus	Total (Un-adjusted)	DesignCas	Sections	MNT/MNT
6	173.4746	16	2775.59331	2775.593314	1	16	346.9492
6	173.474383	J4*2;AJ4)	2775.59077	2775.590765	2	16	346.9488
4	219.835	20	4396.70019	2198.350077	3	10	439.67

Figure 22: Production rules assessment (OC example)

Overall assessment table with process plan analysis inputs is shown in Appendix A-4. Here, unlike in separate evaluations of weld groups, product design is considered as a whole. Only extreme values in each indicator category are registered for every DC. This assessment table is highly customizable and can be adjusted to show to which weld groups the values correspond. For instance, next to the thickness variance entry there may be a cell automatically identifying the weld group of highest severity.

4.4. PROCESS PLANS

Time and costs of mere welding procedure were found to be insignificant in comparison to the number of operations required to manufacture them. This was concluded realizing that welding time and costs of deposited filler material are completely overwhelmed by the resources it takes to prepare and carry each operation. After discussions with process engineers, production platform documentation review and observing manufacturing process in action, it was decided to pursue design driven manufacturing time based on only the two most impactful indicators, i.e. number of welds and their length.

Weld method selection

Weld method selection is determined by application feasibility and preference. Feasibility mostly depends on the plate thickness alone as different methods have different material penetration depths. TIG and laser beam methods are the two most preferential methods and have the minimum feasible penetration to handle TRS. Although other methods have higher applicability due to wider material penetration ranges they are less preferred for TRS manufacturing. This is related to welding costs, quality, setup complexity and production capacity. For the specific TRS case study, it was found that TIG and Laser beam welding methods are enough to produce all the welds.

TIG weld method produces a wider seam than laser beam which allows it to cover slight geometrical variation. This is one aspect of weld method prioritization but quantifying its benefit is complicated because identically designed parts are not always so in reality.

Process plan operations

Fabrication can be described by a set of process plan items which are influenced by several parameters. Relatively detailed list of operations was taken from the production platform documentation available at the company for a sample 10 sector TRS manufacturing. Used data summarizes main operations that belong to the weld assembly where sectors are already available and the TRS needs to be welded together. It does not reflect processes taking place after weld assembly where the structure is further detailed and inspected. Only variable weld assembly process times are shown which were assumed to be dependent on available design metrics and indicators. Here heat treatment and other operation times are not included as they are considered to be standard and fixed for different TRS structures (Table 4).

Table 4: Weld assembly for TRS

Main operations	**Operation description[1]**	**Time[2], *t***	**Indicators, *n***	**Weighting coeff.[3], *k***	**Hourly indicator rates, (*t*k)/n***
Sectors (MNT/REG)	Total fabrication	t_0	-	-	hours/sector
Weld Assy. for 10 sector TEC					
Tack welding	Positioning and tack welding the parts prior to actual welding	t_1	No. of parts	0.7	hours/part
			Weld length	0.2	hours/meter
Welding	Setup for welding, included time is generalized for all weld methods and TRS welds	t_2	No. of parts	0.3	hours/part
			Weld length	0.15	hours/meter
Machining	Flanges prep, welds salvage repair, alignment, deburring, cleaning etc.	t_3	No. of welds	0.8	hours/weld
Weld class finish	High class welds deburring to increase weld life	-	Class welds length	-	hours/meter
Inspection	Final X-ray, final inspection	t_4	Weld length	0.8	hours/meter
Heat treatment	Stress relief due to welding for superalloyed materials	-	-	-	-
Other	FPI complete part, CMM	-	-	-	-

[1] Operation description is reduced only to the influenced operation

[2] Production platform documentation of 10 sector TRS product design is not disclosed and used values are scaled

[3] Weighting coefficients assigned subjectively to define indicator influence

The reasoning for particular indicators comes from operation descriptions. Here it was attempted to capture only the most influential indicators affecting process times. Weighting coefficients or multipliers were subjectively assigned to determine their impact. Remaining coefficient portion that is not covered by any of the indicators in an operation is assumed to be inherent constant operation execution part.

TRS manufacturing process begins with sub-parts manufacturing. Producibility of each sector design depends on strut welds curvature, thicknesses and accessibility. Just as for the main TRS assembly, sectors also go through a number of operations. They are tack welded, milled to create a smooth transition between welded parts and thoroughly inspected. Sub-parts may be purchased or manufactured in-house. Here, sub-parts manufacturing is not detailed and only general time for single sector manufacturing is taken from the documentation.

When required sectors are produced the TRS weld assembly takes place. All edge welds are always tack welded first. This operation is needed to reduce the risk of distortion caused by transverse shrinkage. Distortion related defects can be caused by relatively long welds across thin parts. However, more variables determine distortion risk for which special simulations are performed. Tack welding operation may be skipped if distortion assessment was included into multi-disciplinary studies.

Welding operation was found to be a timely process, although welding alone is automated. Apparently, this operation is almost completely design independent because most of the time is consumed in preparation for the manufacturing.

Machining for TRS weld assembly was used to describe multiple actions taking place. It includes the whole sequence of flanges preparation and welds salvage due to start and end point damages already explained in section 4.2.2. Flange salvage repairs are assigned to fixed time while other repairs completely depend on the number of axial welds performed.

One significant operation assessment related to machining was pointed out by the production. When a weld is made, its cross-section profile is not even. High enough curvature values in the profile affect weld life and need to be evened out. Such finished weld treatment is not always required and depends on its weld class. The weld class is usually assigned based on required performance of that product area which is determined by fatigue and other analyses. It is noted in the design guidelines that high-class welds should be avoided. Anyhow, deburring process time for such welds depends on weld length.

Inspection is certain for all welds. Different quality check methods can be applied and are highly dependent on product design. To establish preliminary assessment, production platform data was used in a simplified manner where the time of inspection is assumed to be mostly dependent on weld length.

Heat treatment was found to be completely dependent on the material. If nickel super-alloy is used, final heat treatment must be performed to relieve the stresses induced during welding. For TRS, heat treatment always applies and its operational time is regarded as fixed.

For other operations, time dependency on other metrics was ignored. This part is a compilation of different activities i.e. cleaning, measuring etc.

Design driven weld assembly time

Hourly rates of derived indicators were summarized to predict design driven assembly time. This time is based on highly subjective weighting coefficients and a single product type production platform documentation. Therefore, it cannot be concluded that the total manufacturing time of any assessed design equals to the design driven manufacturing variable and fixed times added. Design driven weld assembly time was estimated based on variable times t_1,t_2,t_3,t_4 and the total weld assembly manufacturing time was estimated taking into account the time to produce the sectors t_0.

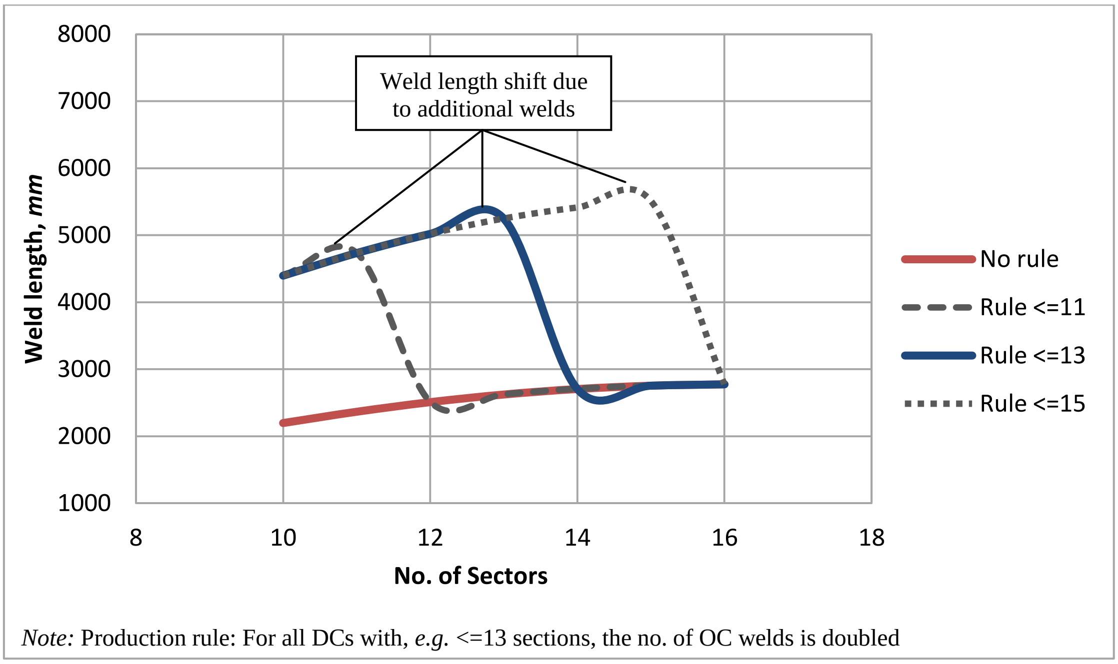
4.5. RESULTS DEMONSTRATION

CAD model metrics were reviewed and used as indicators considering their relevance to the process plans. Available data was used to complete its post-processing output in the form of separate weld group evaluations and overall assessment. In this section, final demonstration of the results was prepared adding assessment data to multi-disciplinary studies’ database to create correlation matrix to visualize cases of interest.

Multi-disciplinary studies were complemented with producibility assessment data and correlation between different parameters was investigated. Correlation matrix can be observed in Appendix A-5 where structural mass was assessed taken from the other studies. Here, the number of sectors and their lean angle of vanes are analysis inputs and all the other indicators resulting from post-processing are analysis outputs.

Compiled matrix indicated expected relations, e.g. between the number of sectors and total weld length. However, the correlation is not as strong as one would expect due to the production rule to maintain design stiffness by additional welds. The rule causes non-linear weld length response which does not necessarily increase with an increasing number of sections. The rule where the number of OC welds is doubled for 13 or fewer sections is visualized in the Figure 23. Here it is also shown how different additional weld rules would affect the total OC weld length.

Weld length and the number of parts relation can be used to reason trade-off decisions in design selection. According to presented data, the shortest weld length following the 13 sections production rule corresponds to the 16 sections solution. Here, reduction in production time can be compared with an alternative case to weight its benefit against the cost drives of additional production of sections.



Note: Production rule: For all DCs with, *e.g.* <=13 sections, the no. of OC welds is doubled

Figure 23: OC case weld rules visualization

Interestingly, correlation matrix points out that maximum curvature for different DCs is mostly dependent on inputs, i.e. number of sections and the lean angle of vanes (Fig.24). It could be argued that lean angle and the number of sections affect TRS airflow so geometry of the struts has to take that into account.

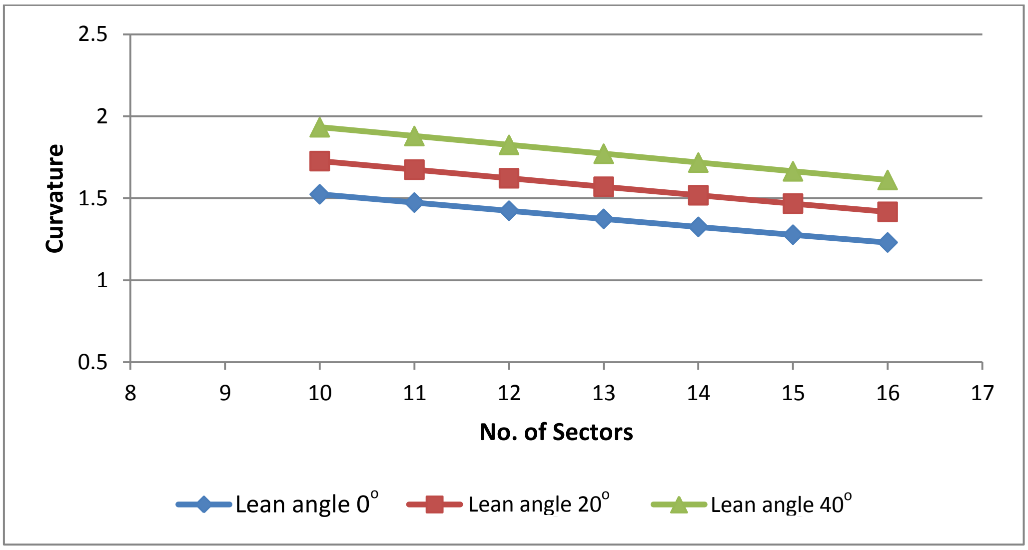


Figure 24: Struts curvature response to the no. of sections

Similarly, proposed accessibility indicator for HUB welds is correlated with the number of vanes and their lean angle (Fig.25). It was recognized that higher numbers of sections reduce accessibility of the HUB welds for all lean angle groups because it creates a more compacted TRS model. Meanwhile, increasing lean angles indicate slight reduction in accessibility.

It was determined that the reduction of lean angle is both favorable for accessibility and curvature improvement. Minimum or no lean angle solution seems to be rational at least from producibility aspect.

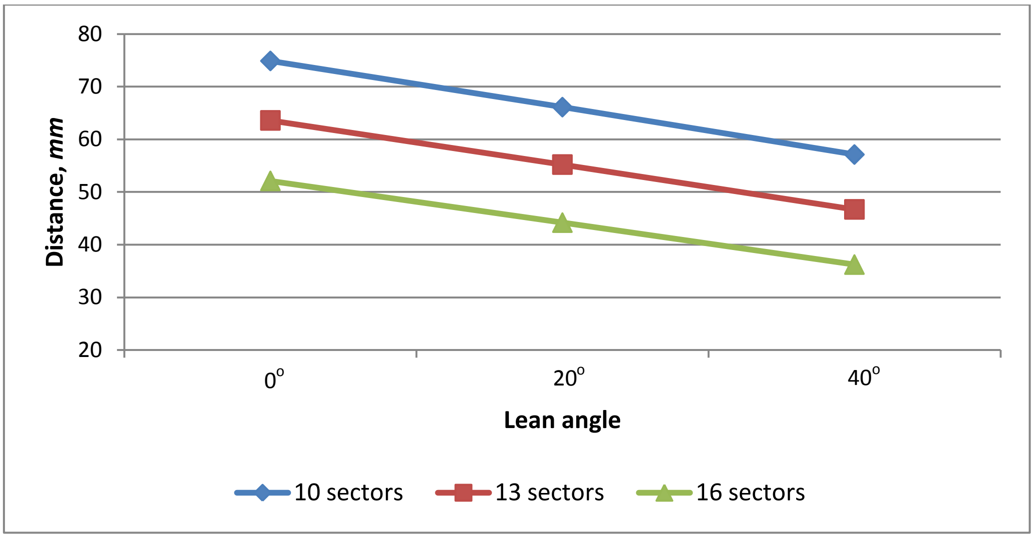
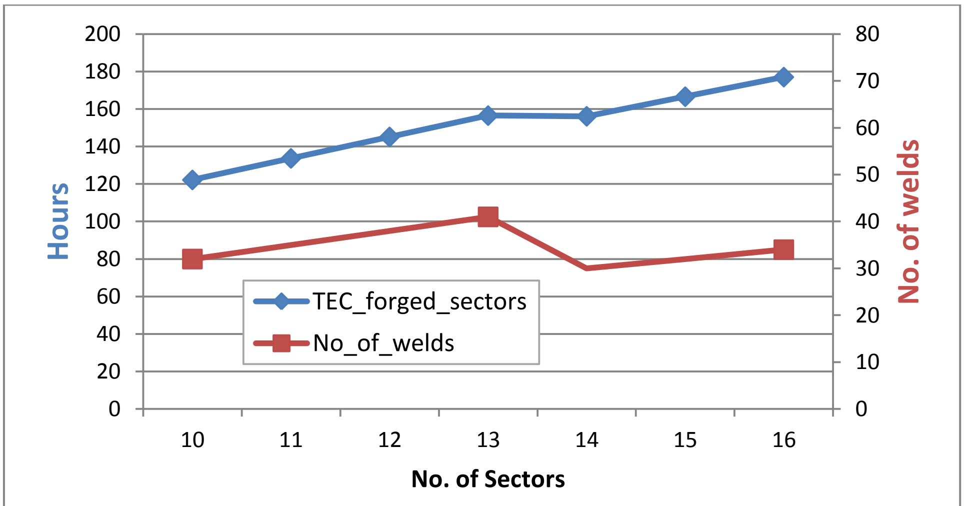


Figure 25: HUB welds accessibility response to the no. of sections

It is already known that preliminary added manufacturing time is mostly based on the number of welds and their length. Due to application of the production rule, no strong correlation was found between the number of sectors and design driven manufacturing time. However, it can be recognized that total manufacturing time is affected by the production rule to increase the stiffness by additional plates. Here, manufacturing time curve for increasing number of sectors is not completely linear in response to the increased number or welds (Fig.26).

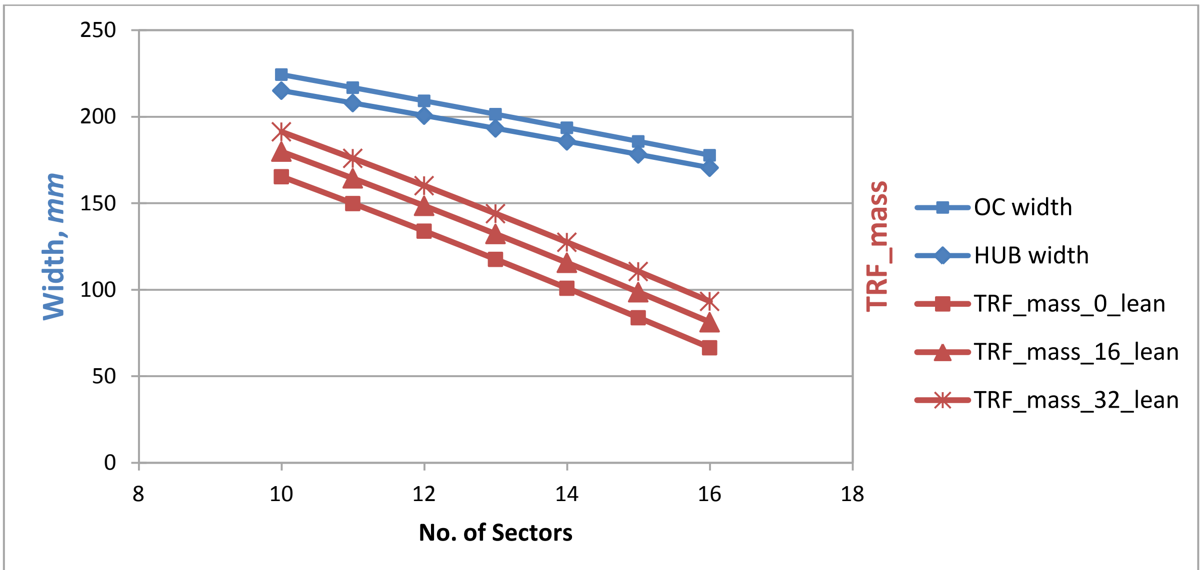


Note: Reflected rule where for all DCs with <=13 sections, the no. of OC welds is doubled

Figure 26: Overall weld assembly time and the number of welds

Weld method coverage was calculated as percentage of total design length which can be welded with prioritized welding method. It was assessed in the correlation matrix as well. Thickness variance indicator was determined to be able to identify which specific weld must be addressed to increase weld method applicability. Here it was found that REG and HUB weld thicknesses have the highest influence on weld method coverage according to the established DoE.

Analyzed response surfaces revealed that structural mass decreases with the increasing number of sectors. Since TRS diameter is maintained, such unintuitive change in mass with additional structural components is explained by reduction in structural width. Here OC and HUB single weld lengths were plotted together with mass response (Fig.27). It was also observed that structural mass curves shift up with an increase in lean angle of the struts. The difference is relatively small and accounts for additional material corresponding to the higher lean angles.

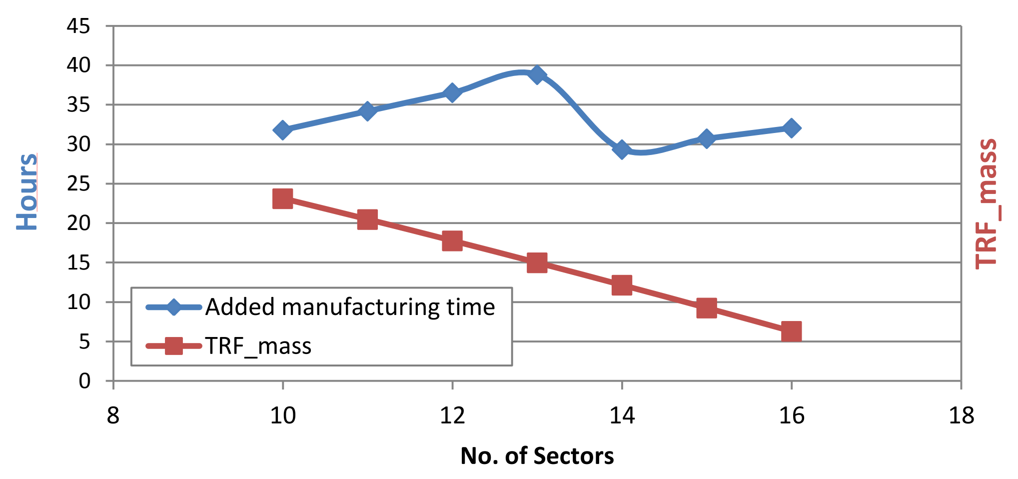


Note: Mass data omitted due to confidentiality concerns

Figure 27: TRS mass and width reduction

According to already visualized data, it was shown that 0 degree lean angle is a mutually favorable option for mass, curvature and accessibility. Objective design performance always strives for maximum reduction in mass. Here, design driven weld assembly time was visualized on the same graph as mass to show what implications different number of sectors could have on the production and product performance (Fig.28). One should note that here the assembly time does not reflect manufacturing of separate sectors to emphasize the effect on TRS weld assembly time alone.

Assuming that 10 TRS design is the benchmark solution, it was compared with 13 and 16 sector designs and their indicator trade-offs were registered in the Table 5. It was revealed that 13 sector solutions increase manufacturing time the most due to additional plates to stiffen the structure. However, 16 sector solutions increase assembly time by mere 0.79% and reduce product mass by 7.79%.



Note: mass data omitted due to confidentiality concerns

Figure 28: TRS mass and additional manufacturing time

Table 5: 0^{o} lean angle design solution trade-offs (10 sector TRS as baseline)

Sectors	**Added design driven manuf. time**		**Curvature**		**Accessibility**		**TRF mass**
10	31.80	-	1.527	-	75.8	-	-
13	38.82	22.08%	1.422	-6.91%	60.5	-20.16%	-3.76%
16	32.05	0.79%	1.302	-14.73%	49.4	-34.77%	-7.79%

Note: Highlighted cells with *green*-positive and *red*-negative trade-offs in comparison to 10 TRS design

5. DISCUSSION

This section seeks to evaluate and discuss thesis success. Here, used implementation method was critically reviewed as a whole and for each action cycle. Then, all findings were discussed and weighted against internal problems identified by the company which were presented in the beginning of method implementation.

5.1. DISCUSSION OF METHOD

Used Action Research method is based on iterative study approach where all implementation cycles are linked and refined concurrently. The method was found to be most effective considering the knowledge scarcity about the research topic and difficulty to predict its implementation steps. Focusing on problems' identification and analysis first, it allowed to develop solution orientated actions and provided a fundamental reference point for research success evaluation. Implementation advantages through cyclic actions were very noticeable as different study approach had been considered initially and changed based on its fulfillment. This is because a larger extent of problems' complexity and solution capability was learned through actionable efforts.

Although, the method is focused on action by definition, a lot of time and efforts were consumed in data gathering and interpretation stage. This of course is mostly related to inherent complexity of the problems and limited expertise in systematic handling. However, with internal support it was possible to at least partially overcome the most imperative bottlenecks. Initial steep learning curve resulted in higher capability to work on the issues independently. It was recognized that data post-processing could be implemented in data analysis module using python script but decision to go with more familiar VB in excel environment lead to its own benefits. Here, enough knowledge was obtained to implement a semi-automated data post-processing tool and refine data evaluation templates.

Initially, it was clear that the main focus of implementation is data post-processing. This action cycle is where all other actions meet. As different metrics were investigated, post-processing module was being developed. Then during continuous reflections all action cycles had to be refined so that the data for the resulting system demonstrator would be readily available. Adapted cyclic project execution improved the study through several focused reflections from the production. Once implementation framework was established it was possible to complement it with additional data and process plans.

It was difficult to predict the scope of the research following AR methodology. While the efforts are focused on identified problems, the solution can become very extensive and even superficial if aimed to address all the problems. Unfortunately, this can only be revealed later on into the study. Here, process plans were found to be very under developed and too broad to achieve desired impact demonstration. Subsequently, only a theoretical proposal with hypothetical impact could be reflected by process plans. Since all action cycles are interdependent, this had a carry-over effect limiting data post-processing fulfillment.

Another shortcoming is related to verification of the metrics. Reachability metrics could not be confirmed and proposed solution was limited to data visualization having no impact on process plans if not further investigated. It is therefore evident that high dependency in actions in for a very limited research implementation can increase the risk preventing study success.

Finally, correlation matrix was found to be a straightforward approach to get the ‘big picture’ for all metrics used. It showed that producibility integration into multi-disciplinary studies is no more complicated than having the right data. The difficulty lies in accessing the most meaningful data.

5.2. DISCUSSION OF FINDINGS

The performed case study revealed that producibility assessment system is capable of handling different CAD models if they follow required setup for feature names. Robustness of the system can still be criticized as different edge types are not recognized and therefore initially presented results must be adjusted. Nevertheless, systematic modifications are relatively easy implementable if sufficient programming expertise is available.

Although geometry metrics were eventually verified, their translation into meaningful indicators is limited. Arguably, at least two new indicators resulted from this study, i.e. minimum accessibility, and thickness variance.

Accessibility was only useful as an analysis parameter to measure geometry change response. It cannot be directly used to define reachability for different weld methods. Reachability calculations were found to be very time intensive and not applicable to all weld cases. Here, new ways should be implemented in KF script to extract the data.

Thickness variance inputs are meaningful as more uniform thickness parts are easier to weld with sufficient quality. However, the production effect of severe thickness variations is not readily known. Thickness data can be used for weld method selection as method related material penetration depth is specified.

The post-processing was found to be flexible for intermediate data preparation but its main part is templates for different welds. Here, data analysis standardization is hardly avoidable because different metrics are relevant to different welding groups. Fortunately, established analysis tables can easily be reused, especially if similar type structural component studies are carried.

The least available knowledge underlies in producibility metrics relation to manufacturing processes. After discussions with the company process engineers and seeing the manufacturing process in action, it was realized that gathering process plan definitions is not straightforward. This is because not all presented metrics and indicators are employed in manufacturing and measuring their effect would require separate focused analyses.

Discussions also revealed that the biggest portion of manufacturing is design independent operations with improvable uptime. However, the key design aspects defining manufacturing resourcefulness are length, the number of welds and parts. This was not difficult to realize seeing that each interface includes the same list of operations. Nevertheless, it is hard to predict their separate impact on manufacturing process. For example, design cases of the same number of parts may have different mounting operations. Therefore, input from production experts and manufacturing capability definitions are not separable from early product development stages.

It was possible to demonstrate rough estimates of design driven manufacturing time. However, the approach involved subjectively assigned weld length and part number weighting coefficients. Having applied them to the sample TRS production platform process list, evaluation for different designs was obtained. Unfortunately, those estimates did not distinguish between different weld methods and reflected no other available metrics, e.g. thickness, curvature etc.

It was shown that 16 sector TRS with 0 degree lean angle of vanes is the most optimum alternative for producibility with the highest reduction in mass. Unfortunately, even if established design driven manufacturing time was an accurate assessment of manufacturing resourcefulness, it alone is not enough to argue design trade-offs. Here it only reflects weld assembly process and does not include production of separate sectors. All advantages related to increased number or sectors have to be weighted against their manufacturing or purchasing costs.

5.3. DISCUSSION OF RESEARCH QUESTIONS

This section restates and discusses research questions raised in the section 2.1.6. The discussion is based on the overall research findings and gained insight collaborating with company support as in the preceding implementation steps.

How can already extractable CAD model data be used for weld producibility assessment in a meaningful way?

It is not difficult to predict the objective of each assessment category. For example, a better design for producibility is the one with smaller curvatures, higher accessibility, shorter weld length etc. It must be visible that any considered assessment category is relevant for the production. In fact, it was shown that rather than trying to relate available data to process plans, it should first be investigated what is most relevant to the manufacturing process. Here, it was found that the number of welds is one of the most influential indicators and not explicitly defined in the system.

Once it is known that the data is relevant, producibility indicators can be formed which true impact on the producibility can be determined through specified production definitions.

Therefore, any extracted CAD model weld data needs to be post-processed which translates the data into meaningful indicators for producibility assessment.

What are the most relevant producibility indicators of TRS to predict manufacturing time and do they maintain robustness in the context of other components?

If the same manufacturing process, i.e. welding is applied for other components besides TRS, the same producibility indicators are relevant. For TRS assembly, the most important indicators to predict manufacturing time are length, the number of welds and parts. Although pure welding time is insignificant, length is relevant to other time intensive operations, e.g. inspection. Each weld includes the same number of operations and welded parts have to be mounted in place. The latter mentioned indicators are of course relevant in manufacturing time prediction but they do not communicate design complexity. For the same number of parts or length manufacturing time may differ vastly for different components where another indicator may happen to be decisive, e.g. weld reachability.

Consequently, manufacturing of each component must be analyzed to identify and assess its most relevant indicators. Otherwise, all aspects of product design and manufacturing must be detailed to the point where manufacturing time assessment would be possible for any component.

How can producibility indicators be summarized for a preliminary but relevant single evaluation value?

The only preliminary but relevant assessment using available data was possible for added design driven manufacturing time since most impactful indicators were identified and related to actual production platform documentation of TRS.

To arrive to a single producibility assessment measure, all process operations must be expressed in the same units of measure, e.g. hours. Then, if the knowledge about the effect of each indicator on every specific operation is known, their impact can be estimated in terms of that measure. The impact value of each indicator is a sub-part of all carried operations. If the baseline design is the same, parametric changes in product design will contribute to the defined total producibility evaluation.

6. CONCLUSIONS AND RECOMENDATIONS

This is the final chapter which concludes the research by addressing initially stated thesis objectives in the introduction. Recommendations are provided based on research evaluation and discussion with considerations for future work.

1. Performed case study on producibility assessment system revealed that the system was not robust enough to handle assembly models. It was also found that analysis success mostly depends on correctly established systematic setup criteria stated in the Jacobson M., 2016 [4] thesis.

   The system required huge efforts in error identification some of which were not completely resolved. Continuous department support allowed overcoming most imperative bottlenecks and current PAS is capable of handling assembly models with a few data post-processing implications, i.e. weld length adjustment.

2. New producibility indicator was conceptualized from thickness data strings, i.e. thickness variance. However, it was left aside as a supportive information for production. More extensive manufacturing assessment must be made to confirm thickness variance as a meaningful tool.

   Reachability data was replaced due to assessment issues of enclosed cavity welds. Here accessibility indicator was established to show the minimum distance to the nearest collision point.

   Process plans investigation concluded that the most relevant attainable indicators are length, the number of welds and parts, which were used to establish preliminary design driven assembly time assessment. Other metrics like thickness and reachability are also very much relevant but were not used for production assessment due to project limitations.

3. A semi-automated data post-processing module was implemented in excel using VB programming. It allowed addressing remaining CAD geometry data issues and successfully modifying the data to obtain producibility indicators. The data in evaluation templates was shown to be applicable for multi-disciplinary studies.

4. The performed demonstration of the system for the case study showed that producibility metrics can be correlated and explained with multi-disciplinary data. Created correlation matrix immediately indicated parameter relations which were successfully visualized as response surfaces. It was demonstrated that TRS mass reduction solution involves higher number of sectors which drives manufacturing time. Here, it is important to demonstrate the effect in terms of costs as a decision could be made to purchase sub-parts to minimize manufacturing time.

Objective study success was determined through discussions with manufacturing and design specialists. Results concluded that a big step was taken towards successful producibility integration into multi-disciplinary studies. Showed data was found to be rational but its meaningfulness was arguable due to insufficient manufacturing assessment.

It is evident that a continuation of the project should focus on further development of the system which would accommodate discussed indicators. Essentially, it was revealed that producibility assessment indicators can be used in multi-disciplinary environment. Since this thesis involved a production screening type of approach to determine most relevant design aspects, more focused work needs to be carried to address them individually.

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APPENDICES

A-1. Post-processing: Single weld group data (MNT/MRT – reachability excluded)

A-2. Post-processing: Separate weld groups assessment 1

A-3. Post-processing: Separate weld groups assessment 2

A-4. Post-processing: Overall design assessment

A-5. Results demonstrator: Correlation matrix

A-1. Post-processing: Single weld group data (MNT/MRT – reachability excluded)

		Length		**Curvature**		**Material ID**		**Thickness**
DesignCases	Sections	MNT/MRT		MNT/MRT		MNT/MRT		MNT/MRT
1	16	346.949178		0.07673		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
2	16	346.948815		0.069447		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
3	10	439.670011		0.085671		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
4	16	346.949178		0.07673		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
5	10	439.663768		0.085697		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
6	16	346.947995		0.054777		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
7	10	439.670294		0.085674		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
8	10	439.670294		0.085674		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
9	16	346.949178		0.07673		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
10	10	439.670011		0.085671		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
11	13	403.654246		0.051137		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
12	16	346.948815		0.069447		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
13	10	439.670011		0.085671		[1002.0, 1001.0]		[[6.0, [4.0, 5.0]], [4.0, 5.0, 5.0, 5.0], [[4.0, 5.0], 6.0]]
14	10	439.670011		0.085671		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
15	16	346.948815		0.069447		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
16	16	346.949178		0.07673		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
17	16	346.949178		0.07673		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
18	16	346.949178		0.07673		[1002.0, 1001.0]		[[4.5, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 4.5]]
19	10	439.670294		0.085674		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
20	10	439.670294		0.085674		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
21	13	403.656511		0.051137		[1002.0, 1001.0]		[[4.5, [4.0, 5.0]], [4.0, 5.0, 5.0, 5.0], [[4.0, 5.0], 4.5]]
22	10	439.670294		0.085674		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
23	10	439.670294		0.085674		[1002.0, 1001.0]		[[4.5, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 4.5]]
24	13	403.657121		0.051137		[1002.0, 1001.0]		[[6.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 6.0]]
25	16	346.948815		0.069447		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
26	10	439.670011		0.085671		[1002.0, 1001.0]		[[3.0, [5.0, 6.0]], [5.0, 6.0, 6.0, 6.0], [[5.0, 6.0], 3.0]]
27	16	346.948815		0.069447		[1002.0, 1001.0]		[[6.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 6.0]]
28	10	439.670011		0.085671		[1002.0, 1001.0]		[[3.0, [3.0, 4.0]], [3.0, 4.0, 4.0, 4.0], [[3.0, 4.0], 3.0]]
29	16	346.948815		0.069447		[1002.0, 1001.0]		[[3.0, [4.0, 5.0]], [4.0, 5.0, 5.0, 5.0], [[4.0, 5.0], 3.0]]

A-2. Post-processing: Separate weld groups assessment 1

	OC weld lengths			**HUB weld lengths**		**Flange weld lengths**			
DCs	Single sec. weld	Weld no.	Total (Adjusted)	Single sec. weld	Total	Single sec. front	Total Front	Single sec. rear	Total Rear
1	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
2	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46
3	219.835	20	4396.700187	210.1977695	2101.977695	306.66	3066.56	298.45	2984.54
4	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
5	219.831883	20	4396.637694	209.9165255	2099.165255	306.66	3066.56	298.45	2984.54
6	173.47398	16	2775.584135	165.7256105	2651.609768	191.66	3066.56	187.03	2992.46
7	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
8	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
9	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
10	219.835	20	4396.700187	210.2027695	2102.027695	306.66	3066.56	298.45	2984.54
11	201.827121	26	5247.505238	193.818225	2519.636925	235.89	3066.56	229.58	2984.52
12	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46
13	219.835	20	4396.700187	210.2027695	2102.027695	306.66	3066.56	298.45	2984.54
14	219.835	20	4396.700187	210.2027695	2102.027695	306.66	3066.56	298.45	2984.54
15	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46
16	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
17	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
18	173.4746	16	2775.593314	165.963151	2655.410416	191.66	3066.56	187.03	2992.46
19	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
20	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
21	201.828244	26	5247.534873	193.8936305	2520.617197	235.89	3066.56	229.58	2984.52
22	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
23	219.835133	20	4396.703136	209.840155	2098.40155	306.66	3066.56	298.45	2984.54
24	201.828547	26	5247.542843	194.1708835	2524.221486	235.89	3066.56	229.58	2984.52
25	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46
26	219.835	20	4396.700187	210.2027695	2102.027695	306.66	3066.56	298.45	2984.54
27	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46
28	219.835	20	4396.700187	210.2027695	2102.027695	306.66	3066.56	298.45	2984.54
29	173.474383	16	2775.590765	165.657698	2650.523168	191.66	3066.56	187.03	2992.46

A-3. Post-processing: Separate weld groups assessment 2

	OC thickness variance				HUB accessibility			Minimum thickness (all weld groups)					
DCs	MNT/MNT	MNT/MRT	MRT/REG	REG/REG	Accessibility	Vane lean angle	Vanes	MNT/MNT	MNT/MRT	MRT/REG	REG/REG	FF	RF
1	2.142857	1.433333	1.982143	0.3	38.732661	40	16	3	3	2	2	3	3
2	0.952381	1.211111	1.553571	1.2	49.481326	0	16	4	3	3	4	6	6
3	2.142857	1.433333	1.982143	0.3	53.326321	40	10	3	3	2	2	3	3
4	0	0.233333	0.696429	1.2	38.732661	40	16	6	5	4	4	6	6
5	2.142857	1.433333	0.696429	0.3	69.388442	20	10	3	3	3	3	3	3
6	0.952381	1.211111	2.839286	4.8	42.543091	20	16	4	3	2	2	6	6
7	0	0.233333	3.267857	4.8	75.852695	0	10	6	5	2	2	6	6
8	0.238095	0.277778	0.267857	0.3	75.852695	0	10	3	3	3	3	3	3
9	0	0.233333	3.267857	4.8	38.732661	40	16	6	5	2	2	6	6
10	0.952381	1.211111	1.553571	1.2	53.326321	40	10	4	3	3	4	6	6
11	0.238095	0.277778	0.267857	0.3	60.562207	0	13	3	3	2	2	3	3
12	0	0.233333	0.696429	1.2	49.481326	0	16	6	5	4	4	6	6
13	0.238095	0.544444	2.785714	4.8	53.326321	40	10	5	4	2	2	6	6
14	0.952381	1.211111	2.7	2.7	53.326321	40	10	4	3	3	3	6	6
15	2.142857	1.433333	1.982143	0.3	49.481326	0	16	3	3	2	2	3	3
16	0.238095	0.277778	0.267857	0.3	38.732661	40	16	3	3	3	3	3	3
17	0.238095	0.277778	0.267857	0.3	38.732661	40	16	3	3	3	3	3	3
18	0.059524	0.344444	1.071429	1.875	38.732661	40	16	4	3	2	2	4.5	4.5
19	0.238095	0.277778	0.267857	0.3	75.852695	0	10	3	3	2	2	3	3
20	0.952381	1.211111	1.553571	1.2	75.852695	0	10	4	3	3	4	6	6
21	0.059524	0.211111	0.428571	0.675	55.215358	20	13	4.5	4	3	3	4.5	4.5
22	0	0.233333	3.267857	4.8	75.852695	0	10	6	5	2	2	6	6
23	0.535714	0.433333	0.214286	0.075	75.852695	0	10	4.5	4.5	4	4	4.5	4.5
24	0	0.233333	0.696429	1.2	50.161348	40	13	6	5	4	4	6	6
25	2.142857	1.433333	1.071429	0	49.481326	0	16	3	3	3	3	3	3
26	2.142857	1.433333	0.696429	0.3	53.326321	40	10	3	3	3	3	3	3
27	0.952381	1.211111	2.839286	4.8	49.481326	0	16	4	3	2	2	6	6
28	0.238095	0.277778	0.267857	0.3	53.326321	40	10	3	3	2	2	3	3
29	0.952381	0.677778	0.3	0.3	49.481326	0	16	3	3	3	3	3	3

A-4. Post-processing: Overall design assessment

Overall assessment									Weld method application	
DC	Sectors	Length, mm	Starts & stops count	Max thickness variance	Weld	Max curvature	Weld accessibility, mm	Weld assy time	TIG weld	Laser weld
1	16	11490.02064	66	2.142857143	MNT/MNT	1.59254	38.732661	32.05	68%	32%
2	16	11485.13094	66	1.553571429	MRT/REG	1.302759	49.481326	32.05	0%	100%
3	10	12549.77882	62	2.142857143	MNT/MNT	1.92754	53.326321	31.80	89%	11%
4	16	11490.02064	66	1.2	REG/REG	1.59254	38.732661	32.05	0%	100%
5	10	12546.90386	62	2.142857143	MNT/MNT	1.50846	69.388442	31.80	48%	52%
6	16	11486.2112	66	4.8	REG/REG	1.41732	42.543091	32.05	0%	100%
7	10	12546.20563	62	4.8	REG/REG	1.527792	75.852695	31.80	0%	100%
8	10	12546.20563	62	0.3	REG/REG	1.527792	75.852695	31.80	48%	52%
9	16	11490.02064	66	4.8	REG/REG	1.59254	38.732661	32.05	0%	100%
10	10	12549.82882	62	1.553571429	MRT/REG	1.92754	53.326321	31.80	0%	100%
11	13	13818.21665	80	0.3	REG/REG	1.422227	60.562207	38.82	94%	6%
12	16	11485.13094	66	1.2	REG/REG	1.302759	49.481326	32.05	0%	100%
13	10	12549.82882	62	4.8	REG/REG	1.92754	53.326321	31.80	0%	100%
14	10	12549.82882	62	2.7	MRT/REG	2.100415	53.326321	31.80	0%	100%
15	16	11485.13094	66	2.142857143	MNT/MNT	1.302759	49.481326	32.05	68%	32%
16	16	11490.02064	66	0.3	REG/REG	1.59254	38.732661	32.05	53%	47%
17	16	11490.02064	66	0.3	REG/REG	1.59254	38.732661	32.05	76%	24%
18	16	11490.02064	66	1.875	REG/REG	1.59254	38.732661	32.05	0%	100%
19	10	12546.20563	62	0.3	REG/REG	1.527792	75.852695	31.80	76%	24%
20	10	12546.20563	62	1.553571429	MRT/REG	1.527792	75.852695	31.80	0%	100%
21	13	13819.22655	80	0.675	REG/REG	1.569439	55.215358	38.82	18%	82%
22	10	12546.20563	62	4.8	REG/REG	1.527792	75.852695	31.80	0%	100%
23	10	12546.20563	62	0.535714286	MNT/MNT	1.527792	75.852695	31.80	17%	83%
24	13	13822.83881	80	1.2	REG/REG	1.812094	50.161348	38.82	0%	100%
25	16	11485.13094	66	2.142857143	MNT/MNT	1.302757	49.481326	32.05	91%	9%
26	10	12549.82882	62	2.142857143	MNT/MNT	1.92754	53.326321	31.80	65%	35%
27	16	11485.13094	66	4.8	REG/REG	1.302757	49.481326	32.05	0%	100%
28	10	12549.82882	62	0.3	REG/REG	2.100415	53.326321	31.80	93%	7%
29	16	11485.13094	66	0.952380952	MNT/MNT	1.302759	49.481326	32.05	76%	24%

A-5. Results demonstrator: Correlation matrix

	Number_of_vanes	*Vane_lean_angle*	*TH1_*	*TH2_*	*TH3_*	*TH4_*	*TH5_*	*TH6_*	*TRF_mass*	*Length_total*
Number_of_vanes	1									
Vane_lean_angle	0	1								
TH1_	0	0	1							
TH2_	0	0	0	1						
TH3_	0	0	0	0	1					
TH4_	0	0	0	0	0	1				
TH5_	0	0	0	0	0	0	1			
TH6_	0	0	0	0	0	0	0	1		
TRF_mass	-0.282	0.076	0.423	0.132	0.745	0.078	0.033	0.368	1	
Length_total	-0.675	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.231	1
StartStop_count	0.362	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.051	0.443
Curvature_max	-0.587	0.753	-0.076	0.036	-0.049	-0.022	0.036	0.090	0.186	0.408
TH_MNT_MNT	0.000	0.000	0.285	-0.428	0.000	0.000	0.000	0.000	0.020	-0.208
TH_MNT_MRT	0.000	0.000	0.082	-0.123	0.000	0.000	0.000	0.000	-0.033	-0.239
TH_MRT_REG	-0.023	0.023	0.163	0.592	-0.566	0.023	-0.029	0.029	-0.266	-0.197
TH_REG_REG	0.000	0.000	0.000	0.727	-0.485	0.000	0.000	0.000	-0.246	-0.118
TH_HUB	0.042	0.000	-0.042	0.573	-0.042	0.573	-0.042	0.000	0.018	-0.203
Accessibility_HUB	-0.771	-0.594	0.036	0.000	0.036	0.036	0.000	0.000	0.220	0.534
Weld_Assy_Time	-0.586	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.210	0.993
OC_width	-0.997	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.285	0.726
HUB_width	-0.996	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.287	0.737

	StartStop_ count	*Curv_ max*	*TH_MNT_MNT*	*TH_MNT_MRT*	*TH_MRT_REG*	*TH_REG_REG*	*TH_HUB*	*Access_ HUB*	*Weld_Assy_Time*	*OC_width*	*HUB_width*
TRF_mass											
Length_total											
StartStop_count	1										
Curvature_max	-0.201	1									
TH_MNT_MNT	-0.262	-0.027	1								
TH_MNT_MRT	-0.302	0.001	0.924	1							
TH_MRT_REG	-0.277	0.053	0.083	0.274	1						
TH_REG_REG	-0.148	0.006	-0.333	-0.115	0.854	1					
TH_HUB	-0.205	-0.095	-0.182	0.012	0.461	0.480	1				
Accessibility_HUB	-0.261	-0.040	-0.079	-0.100	-0.029	-0.003	0.043	1			
Weld_Assy_Time	0.543	0.355	-0.228	-0.262	-0.219	-0.129	-0.216	0.468	1		
OC_width	-0.295	0.586	-0.020	-0.023	0.003	-0.011	-0.059	0.771	0.643	1	
HUB_width	-0.279	0.592	-0.025	-0.028	-0.002	-0.014	-0.063	0.765	0.655	1.000	1