# MITIGATING RISK OF PRODUCIBILITY FAILURES IN PLATFORM CONCEPT DEVELOPMENT

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## Abstract

*Late detection of producibility problems once a product is in production implies several risks. In aerospace applications, high manufacturing variation rates on a product can imply design modifications with subsequent increase of lead time and detriment of product performance, decreasing customer satisfaction. In the context of platform development, in which a wide range of customer needs are met by designing a variety of product variants, these risks can multiply to an unmanageable sum. To mitigate the risk of late modifications of a variety of designs, producibility aspects needs to become an imperative part of the early platform development stages. This paper presents a two-stage producibility assessment method employed to systematically narrow down a set of product-manufacturing variants based on information generated using various types of rule-based and simulation-based models. The assessments are used to mitigate the risk of producibility failures, classified in this study as operational failures and quality failures. The two-stage producibility assessment method is demonstrated in an aerospace case wherein a variety of aero engine sub-systems and welding resources are modeled and assessed. The results show that the risk of producibility failures can be mitigated by means of rapid and precise assessments during platform concept development. By mitigating these risks early on, the negative effects on manufacturing variation and lead time may be reduced.*

## 1 Introduction

While air travel is growing at pace, airline and aircraft companies collaborate to find a fleet of aircraft sizes that can serve the demand. The development of this variety of aircraft sizes is not a straightforward process. There is typically a complex organization of suppliers and sub-suppliers. Customer needs propagate and transform within this extensive value chain. Early stages of the design process are therefore characterized by changing requirements and high levels of uncertainty.

Developing aircraft sub-systems is multifaceted; for example, aircraft sub-systems should deliver optimized aerodynamics, long functional life and induce minimal weight while at the same time prove to be producible at anticipated time, cost, and quality. The sequential approach "product performance first and producibility second" is based on the notion that a final design determines the choice of the manufacturing process [1]. In fact, products and production systems are typically modeled separately until a product design is finalized and the product performance is optimized. If, at this late stage, the performance-optimized design proves to be non-producible, time-consuming and costly design modifications are required which in some cases might cause a detriment of product performance.

To support increased robustness and flexibility of the early design decisions and mitigate the risk of the late time-consuming and costly modifications of fixed designs, producibility aspects needs to become an imperative part of the design process; from concept to final design [2]. This paper presents an approach to assess a design space of a variety of product-manufacturing variants while evaluating the producibility of the variants systematically. The aim is to mitigate the risks of producibility failures during early design phases, in platform concept development. A two-stage producibility assessment approach is proposed to systematically narrow down the design space formed by a number of product-manufacturing variants when information becomes available using various types of simulation models. To demonstrate the approach, a variety of aero engine sub-systems that will be welded are modeled and assessed in parallel.

## 2 Literature Review

In this section, research on platform concept development and risk assessment methods in relation to producibility is discussed.

### 2.1 Platform Concept Development

Platforms are often used as a way to reduce manufacturing cost by providing manufacturing with high volumes per parts which are shared among a variety of product variants [3]. However, this product platform approach lacks support for early-stage manufacturing involvement [4] which is imperative to avoid over-optimizing on product performance before assessing producibility.

A way forward in research to better support early-stage platform modeling is by employing reuse of intangible design elements among a set of variants [5] and to increase manufacturing involvement by co-platforming [6, 7]. However, co-platforming approaches lack inclusion of methods supporting systematic assessment of producibility of many variants simultaneously. Recent research results indicates that by employing the comprehensive design approach of set-based concurrent engineering the modeling of both products and manufacturing systems may be supported during platform concept development using a function modeling technique [8].

### 2.2 Set-Based Concurrent Engineering

Set-Based Concurrent Engineering (SBCE) advocates systematic design space exploration of products, contrary to the selection of an early winning solution based on assumptions [9, 10]. Alternative design solutions are kept open as possible candidates until enough knowledge has been gained to prove the feasibility of each solution. To ensure robustness in design decisions, facts need to be collected. Thus, SBCE is based on three main principles: the mapping of a design space, elimination of unfeasible designs based on intersecting design spaces from different domains, as well as the establishing of feasibility before committing to a solution [10]. These principles entail a funneling process to reduce the number of unfeasible designs as constrains are involved. The focus is on keeping the design space open to build knowledge in a systematic way.

To evaluate the feasibility of design variants there are significant achievements in automated analysis within Mechanical Engineering and Computational Fluid Dynamics (CFD) for design space exploration. However, producibility assessments in early stages are not equipped with the same tools and approaches.

### 2.3 Producibility and DFM

The assessment of producibility and the evaluation of manufacturing aspects during design phases began to be supported with the introduction of Design for Manufacturing (DFM) methods [11-14]. Despite of the existence of qualitative guidelines that describe the basic capabilities of a number of different processes [13, 14], most of research effort in the last decade has been focused on developing quantitative analysis tools for DFM, for example [15]. These tools assist designers in choosing the most technically and economically suitable manufacturing process to build an already selected detail product design. The choice is made by comparing design parameters with manufacturing process capability information in terms of material, shape, size, tolerances, production cost and time [1]. The latest research incorporate machine learning theories to automatized these approaches [16]. However, in the concept development phases, sufficient data about the product design and process capability are rarely available, especially when considering a variety of products and manufacturing systems. Consequently, the risks of system failures caused by producibility problems can be detected late.

## 2.4 Risk Assessment Approaches in Product and Production Development

To mitigate the potential risk of system failure, the use of Failure Mode and Effect Analysis (FMEA) is common practice within product and production development. A failure is defined as "the loss of an intended function of a device under stated conditions" [17] (p. 488).

With the use of tools such as design-FMEA, potential failure modes during the indented product use can be identified and assessed for different design solutions [18].

In the manufacturing field, process-FMEA among other methods are used to identify and assess the risk of failures during the manufacturing process for a number of manufacturing solutions [18]. Kim and Gershwin [19] presented a method to analyze long manufacturing lines considering two type of failures, operational and quality failures. These failures only reflect failure of manufacturing machines or tooling. Thus, most approaches consider risks on product design solutions separately from manufacturing and vice versa. In fact, Teng and Ho [18] states that producibility is rarely considered in FMEA. Therefore, the impact that the interplay of product design and manufacturing system has on the quality achieved is not contemplate.

# 3 A Two-Stage Systematic Producibility Assessment Approach for Variety

In this section, an approach to mitigate producibility failures during platform development is presented. The work is a clear continuation of a number of publications [20-25] conducted at Chalmers University of Technology in Sweden in close collaboration with the aerospace industry.

The approach proposed concerns the modeling, configuration and assessment of product-manufacturing variants based on platform modeling. The approach focuses on producibility assessments and consist of two consecutive stages: *Rapid* producibility assessments and *Precise* producibility assessments. The aim is to generate a large number of possible product-manufacturing variants and systematically assess their producibility simultaneously, adopting set-based principles. To ensure validity of product-manufacturing screening decisions, the assessments are based on producibility failure modes. By producibility failure modes, the authors refer to failures that occurs during the manufacturing process and that are caused by the product design in combination to the selected manufacturing solution. Two general classes of producibility failures are identified: Operational failures and Quality failures. These two classes have a clear purpose each.

*Producibility Operational Failure* refers to the potential failure modes that inhibit the manufacturing operation from being executed. The producibility measure related to operational failure is binary: *OK* contra *NOTOK*; for example, if a product design is blocking the accessibility of the weld gun to the weld split line, the weld cannot be executed and thus the operational failure will occur or have a high risk of occurring.

*Producibility Quality Failure* refers to producibility failures in manufacturing that will cause the product to inferior quality levels. Quality refers to the technical requirements derived from the customer needs, i.e. if the output variation of the manufacturing operation is within tolerance limits [26]. Thus, manufacturing variation is a producibility measure related to the quality failure. For example, a design of a complex product geometry can cause higher distortion during welding and thus geometrical variation exceeding tolerances.

The two-stage systematic producibility assessment for variety approach entails a systematic funneling analysis, evaluation and subsequent elimination of inferior variants generated using a platform based on the work of Landahl et al. [20]. In Fig. 1, the process is shown. An integrated platform approach is applied to model variety, from which a number of product and manufacturing solutions are generated. The different variants generated by the platform are combinations of product design solutions, manufacturing design solutions and manufacturing operations. A product design solution can be a type of solution, including multiple design parameters, or a single design

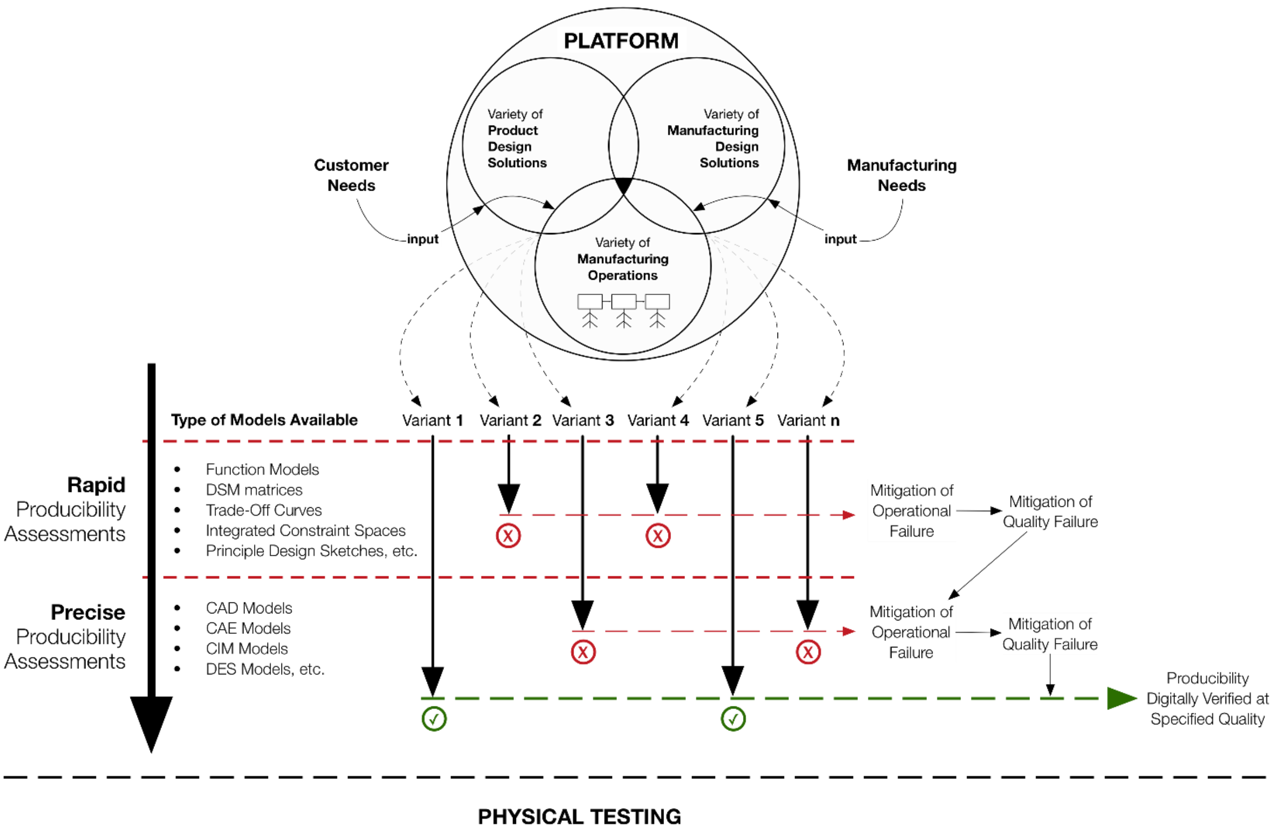


**Fig. 1. Two stage systematic producibility assessment for variety: Rapid and Precise.**

parameter. A manufacturing design solution can be a type of equipment, a sub-part of a manufacturing machine, a tool or a process parameter. Lastly, the manufacturing operations represent the physical interaction between the product and manufacturing design solutions. During each manufacturing operation the product design and thus the design parameters are physically realized by the manufacturing solution. Therefore, a manufacturing operation model (see Fig. 2.) that represent the different producibility drivers including design parameters, is connected to the integrated platform, based on the work presented in [22].

The producibility model represents manufacturing operations as transformation systems in which the product, with all design parameters, is transformed from an input state to an output state. The factors controlling the quality of this transformation, i.e. the producibility drivers, are represented in an Ishikawa diagram. On the left side, all factors related to the product system are categorized into material ($q_{MATERIAL}$) and design parameters ($q_{DESIGN}$). On the right side, all factors related to the manufacturing systems are categorized into equipment, process and method ($q_{EQUIPMENT}$, $q_{PROCESS}$, $q_{METHOD}$).

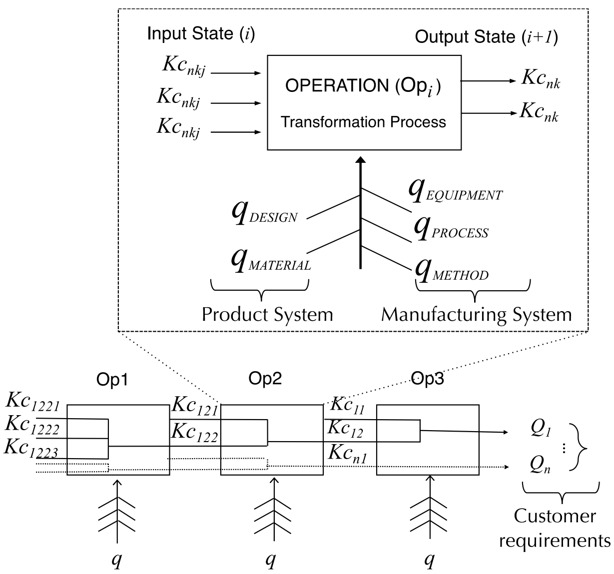


**Fig. 2. Producibility model representing the manufacturing operations [24]**

From this model, design parameters are mapped to the two types of producibility failure modes embedded within the approach (operational and quality failures), as conducted in [25]. This mapping is core to serve the systematic elimination of the product-manufacturing variants. Once design parameters have been mapped to potential producibility failure modes, two types of assessments (rapid and precise) are conducted based on the level of detail of the existing product and manufacturing models.

### 3.1 Rapid Producibility Assessment

To serve screening of product-manufacturing variants during stages when models are uncertain and only data of previously developed products exist, rapid producibility assessments are devised. During these stages, preliminary models such as function models, Design Structure Matrices, Trade-Off Curves, Integrated Constraint Spaces, Principle Design Sketches, etc. may exist. These models are used to serve as the basis for the rapid producibility assessments. Within this rapid assessments, variants are first eliminated based on the feasibility to be produced or not produced, i.e. mitigating producibility operational failures. Variants that prove to be incapable of being produced within the function and performance of the manufacturing resources are eliminated. Thus, the variants that give a negative answer to the question, – *can we produce "this"?* – are eliminated at this stage.

The remaining variants are then assessed to mitigate producibility quality failures. Thus, the underlying question at this stage is – *at what quality level can we produce "this"?*. The variants that prove to cause the product to inferior quality levels will be eliminated.

By using low fidelity models, the objective of the rapid producibility assessment is to eliminate the variants that are not feasible. However, when information is gathered and detailed models are created as the design process progresses, a more precise screening needs to be carried out.

### 3.2 Precise Producibility Assessment

To serve screening of product-manufacturing variants during stages when models are more certain and detailed models are created, precise producibility assessments are devised. During these stages, Computer Aided Design (CAD) models, Computer Aided Engineering (CAE) models, Computer Integrated Manufacturing (CIM) models and Discrete Event Simulation (DES) models, etc. may exist. These models are used to serve as the basis for the precise producibility assessments which are conducted to evaluate in more detail the variants remaining from the rapid assessment.

Following the same logic as for rapid producibility assessments, producibility operational failures are mitigated first and thereafter producibility quality failures.

The output is a set of product-manufacturing variants of which: *producibility* has been *digitally verified at specified quality* (see Fig. 1).

## 4 Case Study – Aerospace Sub-System

To demonstrate the approach, a case from an aerospace company is presented. The case company, GKN Aerospace Sweden AB, is a component supplier that designs and manufactures components and sub-systems for commercial jet engines among other products.

The studied product, Turbine Rear Structure (TRS), is located at the rear of the engine and is illustrated in Fig. 3. The TRS is developed and

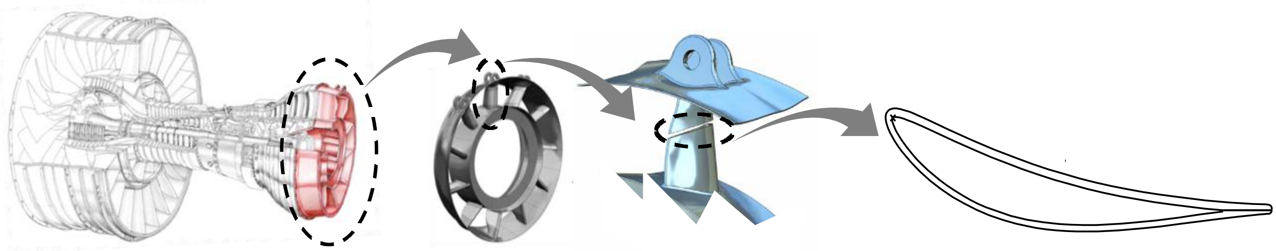

**Fig. 3. Jet engine system, Turbine Rear Structure (TRS), mid section, location of the weld and cross section of the weld**

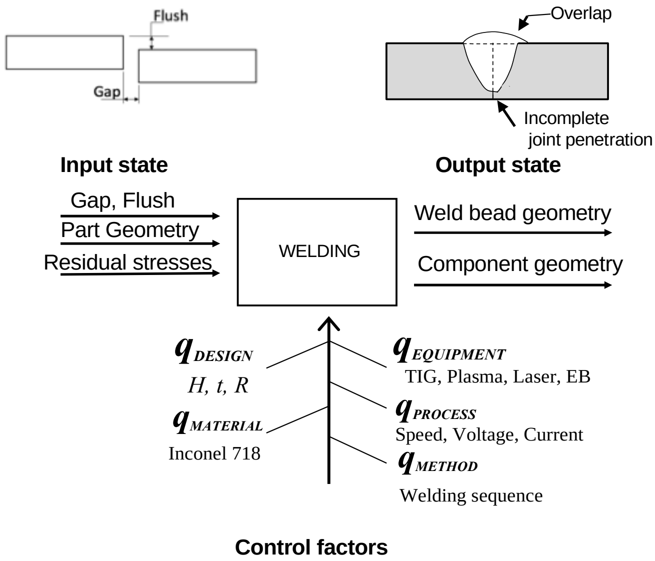


**Fig. 4. Producibility model applied to the welding case**

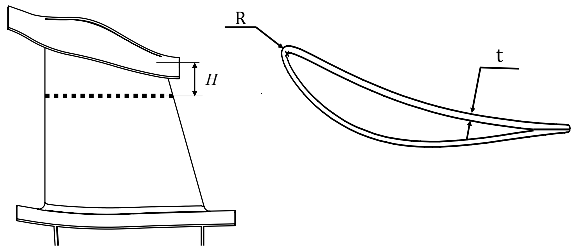


**Fig. 5. Design parameters**

produced to meet the needs of aircrafts with different configurations and performance. Each TRS is manufactured at a yearly volume of a few hundred units.

GKN has a clear welding fabrication strategy. Even though fabrication increases the manufacturing complexity and the increase focus on producibility aspects (such as geometrical variation and weld quality), fabrication enables reduction of engine weight and fuel consumption. To reduce weight, the material thickness can be reduced and to increase the aero engine fuel efficiency the temperature in the combustion chamber can be increased. Therefore, new requirements are introduced, which has made the material thickness bandwidth decrease from 4-8 mm to 1-4 mm. Operating temperatures have increased from 500°C to 700°C. Because of the new temperature requirements, the thermal loads of the TRS will increase. In simple terms, this can be solved by leaning the mid-section of the TRS, shown in Fig. 3. Because of the fabrication strategy of welding, the TRS is divided in segments that will be welded into a hub, shown in Fig. 3. Four different welding methods commonly employed in the aerospace industry are: Tungsten Inert Gas (TIG), Plasma Arc, Laser Arc and Electron Beam (EB) welding. In this case study, vane geometry and the position of a specific weld are studied (see Fig. 3) in the context of the new temperature requirement posed. By applying the "two-stage systematic producibility assessment process" the design space can be systematically explored and inferior product variants can be eliminated to mitigate the risk of producibility failures.

## 4.1 Applying the Two-Stage Systematic Producibility Assessments

To identify key design parameters that affect producibility of the TRS concerning welding, the producibility model (see Fig. 2) has been applied to the particular case of welding (see Fig. 4).

In a previous study [25], the authors have presented guidelines to link design parameters with producibility failure modes during welding in aerospace applications. From discussion with experts at the company and the use of these guidelines, three key design parameters have been derived from identified producibility failure modes in the given scenario. The design parameters are represented in Fig. 5. The design parameter *H* refers to the location of the weld split line, which connects to the design of form division. *R* refers to the radius of the leading edge of the section and *t* refers to the thickness of the material. Thus, these two design parameters connect to part geometry design. Five different values of the design parameters thickness (*t*) and radius (*R*), i.e., a large number of variants within the design space, are considered for precise producibility assessments.

The classification of failure modes and the link to design parameters are shown in Table 1. In this table, the models available to support producibility assessments are also prescribed for each of the two stages of the producibility assessment approach, rapid and precise. In the coming sections, examples of producibility operational and quality failure mitigations are shown for each rapid and precise assessment.

**Table 1. Guidelines to derive design parameters from identified failure modes adapted and developed from [25]**

| | Failure Modes | Design Parameter ($q_{DESIGN}$) | Virtual Assessment Model |
|---|---|---|---|
| *Rapid Screening* | **Producibility Operational Failures** | | |
| | Limited accessibility to weld | H | Principles design sketches |
| | Limited accessibility to inspect | R | Principles design sketches |
| | **Producibility Quality Failures** | | |
| | Incomplete joint penetration | t | Handbook data and limit curves |
| | Overlap root side | R | Principles design sketches |
| *Precise Screening* | **Producibility Operational Failures** | | |
| | Limited robot rotation | R | Path planning simulation model |
| | **Producibility Quality Failures** | | |
| | Overlap top side | t, R | Welding simulation model |

The producibility failures highlighted in grey in Table 1 are left outside of this case study.

## 4.2 Rapid Producibility Assessments

In this sub-section, the rapid producibility assessments are conducted. Producibility operational failures are mitigated by means of a principle design sketch and producibility quality failures are mitigated by means of handbook data and limit curves, which represent the bandwidths of the technology.

### *4.2.1 Mitigating Producibility Operational Failures – Principle Design Sketch*

From the guidelines presented in Table 1, production engineers can derive that there is a risk of "limited accesability to weld" due to the

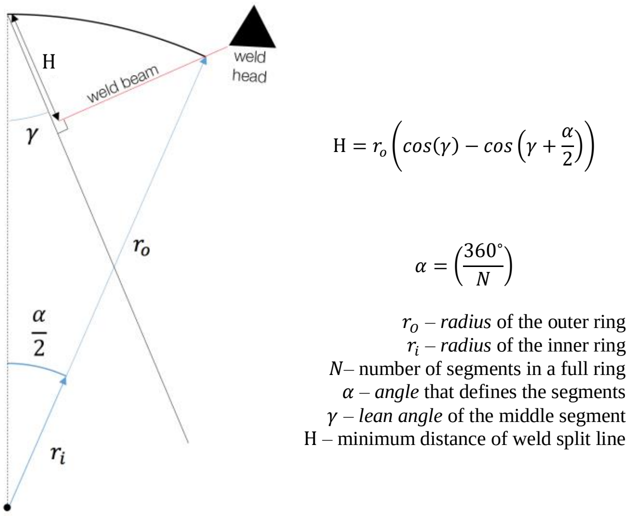


**Fig. 6. Principle design sketch showing the interplay of a TRS segment and a weld beam.**

location of the weld split line (H). Based on ideal conditions of welding, such as maintaining a perpendicular weld beam to the weld split line, principle design sketches can be created. In Fig.6, the interplay of a TRS segment and a weld beam is shown. Principally, the minimum distance of the weld split line (*H*) partly depends on the parameters: TRS outer radius, mid-section angle, and the number of segments in a full TRS ring. Based on this principle design sketch, rapid producibility assessments are conducted. The ideal conditions of welding will constrain the bandwidth of the mid-section angle and thus the minimum distance of the weld split line (*H*). In this way, inferior variants can be eliminated, mitigating the operational failure accessibility.

The remaining variants are then assessed based on the potential producibility quality failures.

### *4.2.2 Mitigating Producibility Quality Failures – Handbook Data and Limit Curves*

The quality failure "incomplete joint penetration" is related to the thickness, as derived from Table 1. Incomplete joint penetration occurs when the intended weld depth has not been reached, thus showing a visible gap on the root side of the weld (see Fig.4.). Because of the demanding reliability and safety requirements of aero engine components, partial penetration is regarded as unaccepted quality, which is why complete joint penetration is required.

Principally, the thickness ($t$), the material and welding technology will determine whether complete joint penetration can be achieved.

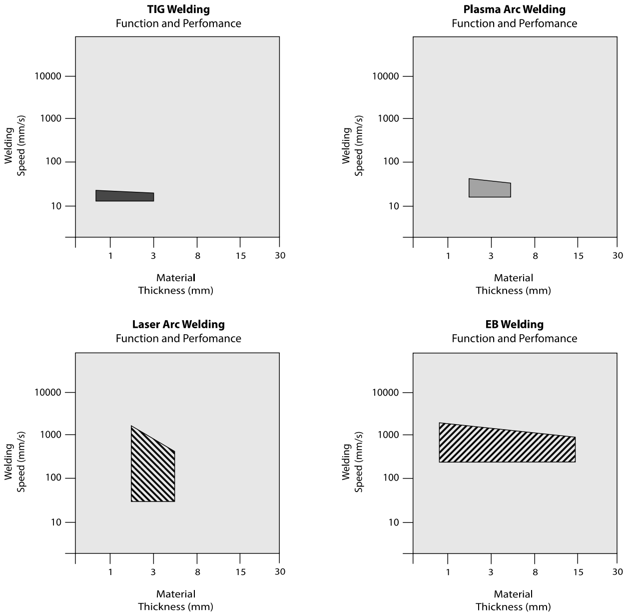


**Fig. 7. Limit curves**

Handbooks [27, 28] include information and data about feasible thickness ranges for different materials in relation to the capability of different welding technologies. To gather knowledge about the real function and performance of the welding machines, physical experiments on flat plates with uniform thicknesses are performed at the company.

In Fig. 7. four limit curves are shown based on a certain Inconel material, thicknesses and welding speed for the four available welding technologies. Concerning the new material thickness bandwidth 1-4mm, TIG and EB welding are fully capable while Plasma and Laser are partially capable.

## 4.3 Precise Producibility Assessment

At this stage, the level of details in the CAD models and the different welding technologies allows us to mitigate producibility operational and quality failures by means of simulation verification.

### *4.3.1 Mitigating Producibility Operational Failures – Path Planning Simulation*

The function and performance of the welding equipment and tooling can be tested for the risk of producibility operational failure “limited robot rotation and movement”. This operational failure can be mitigated by means of path planning simulations, shown in Fig. 8. There are several design parameters linked to the operational failure “limited robot rotation and movement”. However, in this example the radius, introduced as *R* in Fig. 5, will affect whether the robot can move smoothly or not. Based on the path planning simulations, inferior variants can be eliminated.

By eliminating variants, producibility operational failure can be further mitigated. The remaining variants are then assessed based on the potential producibility quality failures.

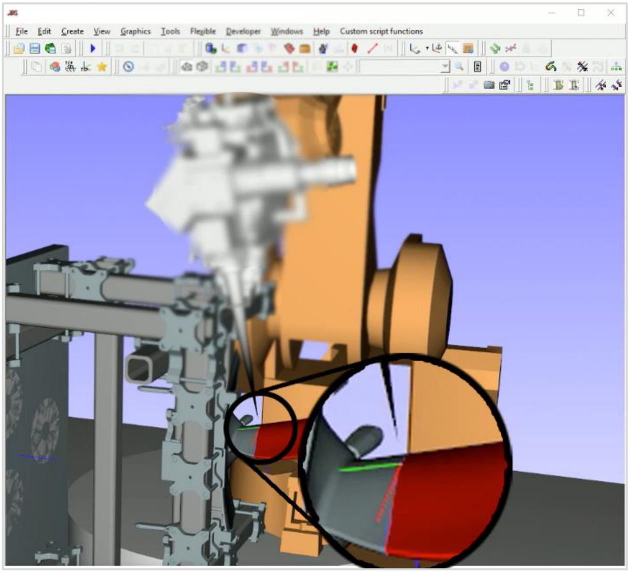


**Fig. 8. The path planning software IPS.**

### *4.3.2 Mitigating Producibility Quality Failures – Welding Simulation*

The curvature of the weld geometry (*R*) can lead to a risk of the producibility quality failure “overlap top side” (see Fig.4.), as indicated in Table 1. “Overlap top side” typically occur in narrow curved and thin geometries. The relative rotation between the product and the robot causes a drop of the melted material (weld pool) in the curved area of the product due to the gravity effect. This phenomenon results in an overlap of the weld bead on the top side and incomplete joint penetration on the root side of the joint.

A method to evaluate the severity of this producibility quality failure using welding simulations is presented by the authors in [25]. MSC software has been employed for welding simulation on this assessment to evaluate the effect of radius (*R*) and thickness (*t*) into the failure mode “overlap” (see Fig. 9). The results

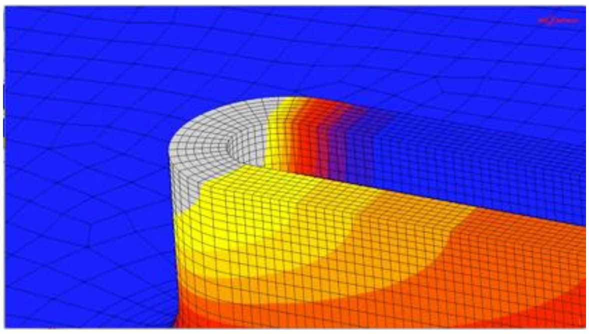

**Fig. 9 MSC software**

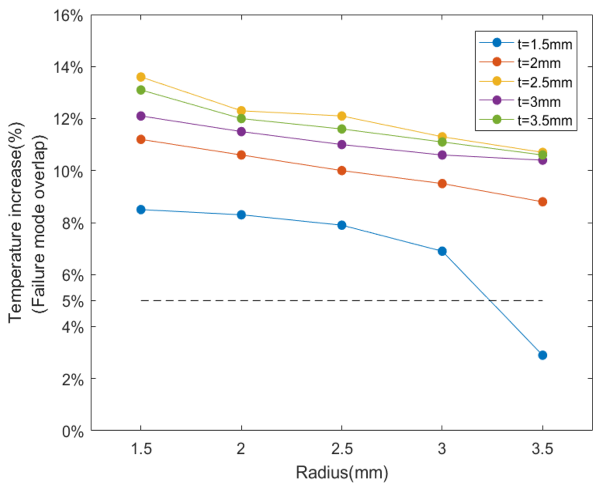


**Fig. 10 Welding simulation results: effect of radius (R) and thickness (t) into failure mode overlap**

of the welding simulations considering TIG as the welding technology are presented in the graph plotted in Fig. 10. The graph shows the following trend: for narrow radii and thin thicknesses, the probability of overlap decreases. The constraint determined is at 5% eliminating the variants above (see Fig.10.). The results show that the promising product-manufacturing variant has a thicknesses of 1.5 mm, radius of 3.5 mm and is fabricated through TIG welding.

## 5 Discussion and Conclusions

Commonly, design engineers are focused on mitigating the risk of failures during product use, while production engineers focus on the risk of failures of production machines and tooling during production use. Approaches that concern the potential failures of products designs during the manufacturing processes are rare. The lack of mitigating producibility failures may be a symptom of the separation of design and manufacturing models during the early design stages of product development.

In this paper, producibility failures are defined and classified, and a two-stage systematic producibility assessment approach is devised to mitigate the risk of producibility failures during platform concept development.

Producibility failures are classified into operational and quality failures. *Producibility Operational Failure* refers to failures caused by the product design that inhibit the manufacturing operation from being physically executed. *Producibility Quality Failure* refers to failures rooted in product design that will create manufacturing variation causing the product to inferior quality levels.

The two-stage systematic producibility assessment approach, proposed in this paper, supports the assessment of a variety of product-manufacturing variants and the elimination of inferior variants following two sequential stages: (1) Rapid producibility assessments are conducted when low fidelity models of the design are available. (2) Precise producibility assessments are conducted once the design process has progressed, information has been gathered and there are more detailed design models. In each of these stages product-manufacturing variants are eliminated in relation to first producibility operational failures and thereafter producibility quality failures.

The approach builds on set-based concurrent engineering principles and is demonstrated on a case that entails the fabrication of aero engines sub-systems through welding. Key design parameters linked to producibility failures and four welding technologies are embedded into a product-manufacturing design space. The product-manufacturing variants generated through the use of the platform are consecutively eliminated based on the systematic of the rapid and the precise producibility assessments devised. The approach presented in this paper can support the absorption of uncertainty during the early design stages because of the systematic risk mitigation of producibility failures during platform concept development. If we can mitigate producibility failures in early stages of product development, we can reduce lead time and avoid redesign while being in production.

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