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Development of a conceptual framework to assess producibility for fabricated aerospace components

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Abstract

The aerospace industry is undergoing an intense competitive pressure due to new market demands and regulations. In the next 20 years the number of aircraft in service is expected to double. At the same time, there is a rapid development of new technologies to fulfil tougher requirements, typically with regards to lower emissions and fuel consumption, where *lightweight* is a key issue. Along with this, some aircraft-engine manufactures have adopted a fabrication approach to build their large structural components. Within fabrication, smaller parts are welded together into the final shape. This manufacturing approach has significantly broadened the number of possible variants of a defined product and production concept. In addition, fabrication has brought to the forefront important problems such as geometrical variation and weld quality. Tailoring the product design to fulfil customer requirements and moreover, tailoring the fabrication process to suit the product design, becomes really complex. Therefore, a systematic approach is required to assess the *producibility* of the different design solutions in order to secure the final product quality throughout the fabrication process. In this paper, a conceptual framework, by means of a model, is presented. This model serves to identify, in a structural way, the parameters and features that are contributors to variation in the process quality output. Furthermore, the model helps to describe the parameters within the manufacturing process that build up the quality into the product, and ultimately, what are the product characteristics that deliver the final quality to the customer. Thus, the model provides a base for a systematic approach that will support the creation of product variants from a *producibility* perspective.

Keywords: Quality assurance; Model; Assembly; Weld quality

1. Introduction

One of the current global challenges of the aerospace industry is to reduce CO2 emissions (see Clean Sky and LEMCOTEC European research programs). From a design perspective, lightweight is the key requirement to meet this challenge. Along with this, some engine suppliers have adopted fabrication as the preferable manufacturing solution for their large structural engine components. In the fabricated product, smaller parts are welded together into the final shape. The goal is to gain significant reductions in the weight of the aircraft-engine component, up to 20% [1].

Replacing large castings and forgings with fabrication has had several effects in product and production development. The new approach has broadened design freedom, due to the possibility of configuring several materials and geometries, which allows an optimization regarding the weight of the final product. This has increased the number of possible design variants for the same product definition. In addition, a fabricated solution is believed to bring advantages to the in-house production, due to the increased possibility of reusing technologies, materials and manufacturing processes to meet a broader product portfolio [2].

However, with fabrication, the manufacturing process becomes more complex. The number of assembly steps multiply, with the added difficulty of incorporating the use of novel technologies, such as welding [3]. Additionally, the heat generated during welding induces stress and deformation [4, 5]. All in all, fabrication increases sources of variation in terms of geometrical variation and weld defects, thus deteriorating the quality outcome of the manufacturing process and consequently the performance quality of the

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product [1,6,7]. Using the fabrication approach, designing and building high quality products become more sensitive in terms of unwanted product variation, and associated risks such as time and cost [3,8,9].

At the same time, current market trends reveal that development of new engines is increasing. Studies have forecast an increment of double of the number of aircrafts in use for the next twenty years [10,11]. For the engine suppliers, introducing new fabricated design variants requires a platform strategy in order to improve the efficiency of their development programs and stay competitive in this market. Platforms enable the creation of variants on a defined product and production concept by reusing knowledge and technologies [2,12,13].

Consequently, a systematic approach is required in order to develop an increased number of high quality product variants, at the same time variation is minimized and lead times are shortened. This approach should support the fabrication process and secure final product quality in such a way as to facilitate re-use of manufacturing knowledge within the platform-base.

1.1. Scope of the paper

The aim of this paper is to present a conceptual framework, by means of a model that can describe how variation is generated during the production sequence and how this affects the product performance. The purpose of such a model is to decompose customer quality requirements into separate requirements for each operation, and at the same time, to identify the factors within the manufacturing process that are contributors to variation in each operation. The model provides a framework to support the creation of high quality variants within a platform. It enables the formulation of predictive models for the quality of the fabrication process. With such a framework at hand, *producibility* analysis of the proposed design solutions can be performed.

This paper, first presents a background to the problem, where needs are explained in more detail, followed by a review of theories that try to cover those needs. As a result of this review, a framework by means of a model is proposed that can represent how quality is built up in the product through manufacturing. In the discussion section, the completeness of such a model and how adequate it is for a case under study at the engine supplier is argued. The paper concludes with a summary and contributions.

Nomenclature

SIPOC	Supplier Input Process Output Customer
TTS	Theory of Technical Systems
TP	Transformation Process
HuS	Humans (operator)
TS	Technical System (operator)
KC	Key Characteristic
Op	Operation
CNC	Computer Numerical Control
TACK	Tack welding

2. Variation problems in a fabricated product

Variation is a latent problem among most manufacturing industries [14-17], and an even more critical issue for aerospace manufactures [18]. Aircraft-engine components must be precision engineered due to the high technical and safety demands they have to fulfil to be able to operate. This translates into tough requirements with small margins to absorb the variation generated during production [6,19].

Fabrication, as the preferred manufacturing solution for some aircraft-engine suppliers, is characterized to be an assembly process. Small, supplied parts are fed into a repeated set of operations (pre-welding operations and welding) that sequentially add building blocks to the product through the different assembly levels until the final assembly is reached. Problems arising from this manufacturing disposition are: 1) Geometrical variation stacks up through the different system levels [6,15,16]. 2) The heat generated during welding induces deformation and stress, influencing the geometrical variation at assembly level [4], and also causing weld defects that do not fulfil product life requirements which is other expression of unwanted variation.

These different forms of variation cause low repeatability levels in production. In addition, the low production volumes and long lead times that characterize the aerospace industry translate to few learning cycles, which does not help to increase the maturity of such novel technologies. Moreover, the manufacturing process is highly tailored to each design variant, the level of automation is rather low and true craftsmanship is required to find the correct process parameters and set up to make the components fit specifications. Overall, the effects of the technology applied to certain design variants are not predictable today. Manufacturing capabilities are neither fully known nor adapted to predictable serial production. Therefore, simulations are hard to perform due to the lack of predictive data, which makes inspection and rework a common way today to assure and control quality. This hasty short-term solution does not support the platform strategy adopted to deal with the new era of serial production the aerospace industry is facing.

Consequently, as aerospace products become increasingly complex, with high functional and technological content and many variants, an overall increased knowledge intensity has resulted, which necessitates a more explicit approach towards knowledge and variation management in product development. This implies the need to define applicable criteria for analysing products and processes from the aspect of efficient manufacturing [3].

Understanding which information is needed regarding variation of parts and processes to support analysis and simulation during design will facilitate comparison between design concepts regarding *producibility*. Also, any design change or decision to control quality at an early stage of product development would be associated with a lower cost in comparison to the cost of product rework, consequence of controlling quality during full production [17].

Therefore, there is a need for a systematic approach to manage complexity by sectioning the problem. Further, there is a necessity to understand quality requirements operation-wise, in order to track the root cause of variation problems. Identifying the important characteristics that assure the final functionality of the product, and understanding how these product characteristics are delivered during the manufacturing process, is the key to control and measure what is needed to deliver at each operation step. With applicable capability data, it is possible to model and estimate the impact of the current design into the production system. Thus it is possible to evaluate the final quality of the different design variants early on in design.

3. Literature Review

3.1 Modeling of manufacturing process

When the objective is to make quality improvements to the manufacturing process, a prerequisite for any improvement opportunity would be to first understand the context in which the operations are set. There are several tools available for this purpose, usually found in Operations Management books and Total Quality Management methodology [20-22]. For example, input and output diagrams and flow charts serve as a base for the manufacturing process analysis, since they enable process mapping, thus giving a useful overview of the process context. In essence, they are helpful when setting process boundaries and they establish the different kind of elements processed from operation to operation. Such elements can differ, for example, physical elements, design properties, information etc. However, in the end, these diagrams are only tools for identifying basic elements of the process, such as process inputs, steps, and process outputs [23]. A tool from Six sigma methodology, SIPOC (Supplier/ Input/ Process/ Output/ Customer), goes beyond these basic tools, since it incorporates output elements related to customer needs in the analysis, and establishes a relation with the critical-to-quality requirements for those outputs [22]. However, these diagrams do not suffice to represent the natural phenomena of variability, since they do not identify the factors within the process that control variation.

All manufacturing processes exhibit variation and the output responses of such process are influenced by a number of factors. A common representation for this is the P-diagram, from Robust Design Methodology [9,24]. Considering, in this case, the system or black box as a process, instead of a product, the P-diagram, Fig.1. illustrates the transformation of input M into response Y (defined as quality characteristic by Phadke [24]) and how this transformation is not ideal, due to the influence of noise and control factors. Noise factors are characterized as sources of variation difficult or expensive to control. In contrast, control factors are controllable, parameters that can be specified freely by the designer.

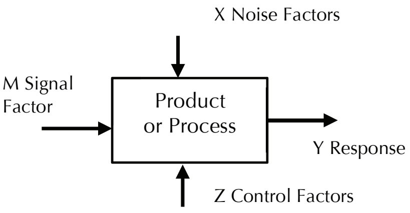

Fig. 1. P-diagram, as defined by Phadke [24].

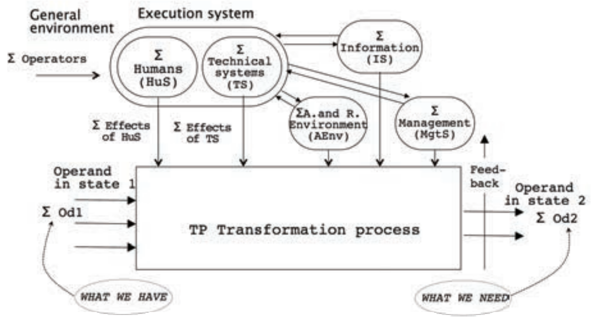

Fig. 2. Model and example of a Transformation Process [25].

Continuing along this line, the model within the *Theory of Technical Systems (TTS)* that Hubka and Eder [25] created to represent the product as a technical system and the transformation accomplished by such system can also be used to represent a manufacturing operation.

Stating from the perspective that the transformation system is the manufacturing system, the model shown in Fig.2 can represent an operation by exemplifying the actual physical transformation process that occurs. Where an operand, the workpiece in this case, is transformed from the existing input state 1 to a desirable output state 2. There are a number of “operators” or influencing factors that will affect this Transformation Process (TP) and will have an influence on the output response, thus manifesting variation. Examples of those factors are the execution system consisting of humans (HuS) and Technical System (TS), in this case the real workshop operators and the manufacturing technology used in the operation, respectively. Depending on the level of automation, human and technical system interaction would be stronger.

Nevertheless, neither the product being manufactured nor the product design are considered as being an “operator” or influencing factor within this model.

While the P-diagram is simpler, the TTS model records more complexity by enabling more details. Both are useful as conceptual models, although they lack information regarding potential control factors, and control factors related to design characteristics and properties. Therefore, they do not enable a complete systematic identification of the factors that are sources of variation.

3.2 Variation propagation modeling

To deal with unwanted variation during the manufacturing process, and its impact in product performance, previous research has shown the significance of describing how product quality is delivered and the potential of controlling quality output after production early on in the design stage.

Mørup [26] described, for instance, how quality is synthesized through product design properties and how these quality carriers are realized through the manufacturing process. By proposing a model for Design for Quality, he also developed adequate concepts and terminology to help describe the interdependencies concerning variability and quality between product development and manufacturing. Thus, establishing a difference between quality parameters

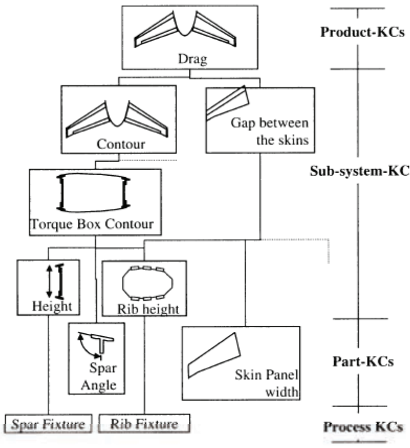

Fig. 3. KC Flowdown by Thornton [8].

depending on the nature of their stakeholder, either an external customer (big *Q*) or internal customer (little *q*). However, the control factors relating to the variability within the manufacturing process are only mentioned briefly.

Thornton [8] and Chakhunashvili et al. [27] have developed methods to systematically identify and assess variation-related risks throughout product development. Thornton [8], [28] presented a Key Characteristics (KC) flowdown to explore how sub-system, part and process KCs relate to one another and how they deteriorate product KCs upon variation, see Fig. 3. Furthermore, Chakhunashvili et al. [27] looked for noise factors that have effects on key product characteristics, making use of an Ishikawa diagram.

Although the KC flowdown is a good approach to break down product requirements when the product can be decomposed into several system levels, it does not identify and classify the different control factors that have an effect at each assembly level.

The Ishikawa diagram proposed by Chakhunashvili et al. [27] examines the most technical aspects in-depth, tracking the technical causes within a manufacturing technology to deliver certain product characteristic. However it omits other relevant sources of variation that are important to assembly products. Instead, these sources are covered in the diagram proposed by Söderberg [29], see Fig. 4, who advocates that final geometry variation on a product characteristic is affected by three different sources, the manufacturing variation (at part level), the assembly variation, and also the robustness of the design. Accordingly, design aspects are considered as a contributor to output variation.

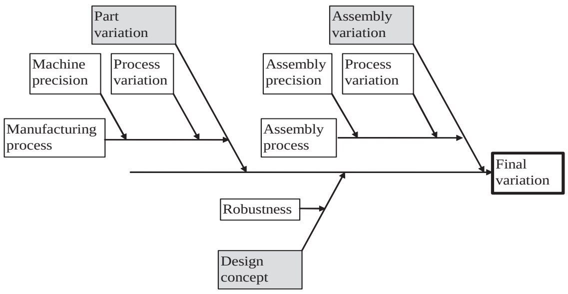

Fig.4. Contributors to final geometrical variation by Söderberg [29].

4. Proposed model to enable *producibility* assessments

The aircraft manufacturing industry is characterized by a business-to-business situation. The long chain of customer-supplier relations determines the final quality specification of a jet engine component. Therefore, customer requirements on structural engine components are ultimately grouped into performance measures, categorized by main product functions in which stakeholders are aerodynamics, thermal, strength, life and weight, and interface interactions. For a selected design these requirements are realized through a production process where each activity transforms certain product characteristics that make up final quality.

The model presented in this paper describes what is stated above. That is, how the manufacturing solution for certain design transforms the key product characteristics, operation by operation, until delivering the final product quality required by the customer.

In principle, the model in Fig. 5(a) represents the transformation process undergone by the product in one operation. The product characteristics being transformed, and that compromise the final quality, are named as operands (*Q*). These are the inputs or outputs to each box that symbolize one operation. The representation has been based on the Theory of Technical Systems [25], where the Technical System is considered as the manufacturing operation itself.

In Fig. 5(b) a horizontal KC flowdown [28] can be distinguished by adding all the assembly levels of the fabrication process, each of which is in fact connected to a set of operations, i.e. to a sequence of "boxes". This means that the functional requirements on the product, fulfilled at the final assembly, have been broken down into separate requirements for each operation following pull thinking. These requirements are the outputs of each Transformation Process (TP), the "what we need" seen in Fig. 2, the operands (*Q*). And they are the product characteristics whose variation has a significant impact on product function requirements. In fact, this is a formal definition for KC given by Thornton [28].

At the same time, the key product characteristic output

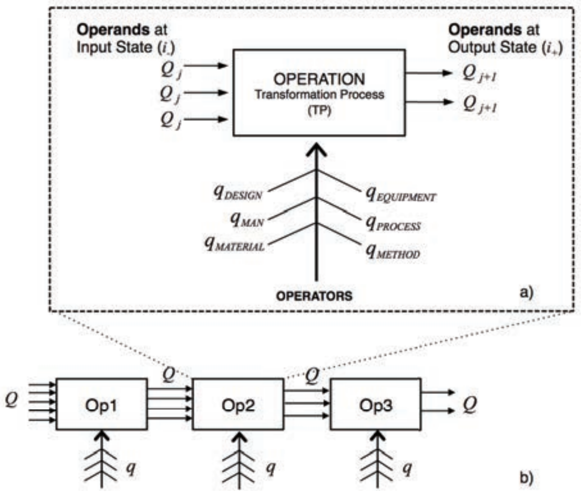

Fig. 5. Proposed model for *producibility* assessment. (a) Model of an operation. (b) Model of the fabrication process

(operand) is influenced during the transformation by the TS (machine tools, fixtures, robots) and other factors. To cover this aspect an Ishikawa diagram based on Söderberg [29] has been added to each operation as a representation of the "operators" (q) in TTS theory.

An important thing to observe is the type of factors, "operators" (q), that are affecting the Transformation Process (TP) and causing output variation stepwise, thus influencing the operand in the output stage (Q_{j+1}), see Fig.5(a). Besides operation parameters and machine, or human factors, there are also design parameters (q_{DESIGN}), which are not undergoing a transformation themselves, but are influencing other product characteristics critical to assuring the assembly process. Therefore, these can be considered critical design parameters to ensure correct quality during manufacturing; i.e. the implementation of Design For Manufacturing method [3].

With the objective of giving consistency to model terminology, definitions and concepts developed by Mørup [26], the big Q and little q, have been selected and adapted. Thus, "Q" defines those product characteristics that are transformed and that deliver the final quality to the customer, the operands; and "q" defines those parameters that from a manufacturability point of view have an impact in the quality of the manufacturing process, the "operators".

4.1 Example

In order to gather data to illustrate and test the idea of the model in Fig. 5, four products of the same kind, Turbine Exhaust Cases (TEC), see Fig. 6, and their respective manufacturing operations, were studied. A generic bill of process has been created to describe the fabrication process, thus supporting platform thinking.

Fig. 7. describes how the TEC system would be modeled using the framework from Fig. 5.

The assembly process is mainly composed of a number of welding operations. Previous to each welding, preparation steps consist of machining and tack welding. This set of operations is repeated for all assembly levels of the component. Additional operations are interspersed, such as cleaning or inspections; however, these operations have not been included for the development of this model, as they are not considered to be important contributors to geometrical variation and weld quality.

In this illustrative application of the model, an example of a possible Q would be weld geometry, which will affect the crack propagation factor and thus the life of the product; one of the customer requirements. The Q, weld geometry, is the output result of the main welding operation. Therefore this represents the final requirement for each assembly level. The requirement can be decomposed into different requirements from previous operations. For instance, during the tack welding operation, good alignment conditions for the parts to be welded need to be guaranteed. Prior to that, during machining, the flatness of the surfaces to be welded need to be assured in order to deliver good weld alignment conditions while tacking, which eventually would result in good weld geometry after the main welding. The little q represents those parameters at each operation that control the required output. For example, looking at the main welding operation, process parameters, such as gun speed or heat input ($q_{process}$), will have an effect on the weld geometry (Q).

Fig. 6. Turbine Exhaust Case (TEC) system.

5. Discussion

The model presented in this paper is a holistic and integrative representation of how performance quality is built up through the transformation of the product at the different manufacturing process steps. Holistic because it exemplifies the whole manufacturing process step by step, which enables traceability through the process. Integrative because it incorporates a quality analysis operation-wise by taking into consideration the quality parameters of manufacturing that build up quality in the product (q) and also, the characteristics that deliver the quality to the customer (Q).

The type of manufacturing process that characterizes the components in this study, a fabrication approach defined by different assembly levels, requires such a holistic and integrative approach. The reason being that requirements at each operation need to be defined from a pull thinking process, driven by the main requirement, which is the functionality of the product. From this, a breakdown can reveal the requirements of each of the operations upstream, as seen in the example.

Only looking at the quality realized through manufacturing, thus optimizing operation performance and variation, is not enough to enable a robust product realization process where features critical to the products and their relation to manufacturing system need to be understood. At the same time, switching focus towards only optimizing the functionality of the product, and not including a depth analysis of the possible factors that during manufacturing have an effect on the product key characteristics, cancels out the *producibility* aspects.

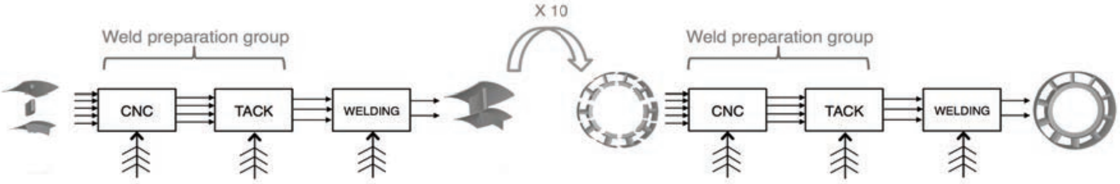

Fig. 7. Model applied to TEC system.

A combination of the TTS model [25] that focuses on representing the physical transformation carried out during an operation with an Ishikawa diagram [29], which covers the identification of the manufacturing parameters as well as critical design parameters (robustness), which are contributors to variation, works as a complete representation of the transformation that occurs during an operation.

In addition, this operation model is integrated to approaches [28] that focus on decomposing customer requirements into product characteristics requirements at each system level, the resulting framework turns out to be an adequate representation for the problem per se.

The combinations of these models and tools argue for the completeness of the framework result of this study, and which make it suitable for the purpose presented in this paper. That is to say, a model able to represent the key product characteristics that will eventually deliver quality to the customer and the parameters or factors which, during the manufacturing of the product, have an impact on the output variation of the key product characteristics.

6. Summary & Conclusions

The conceptual framework by means of a model presented in this paper, see Fig. 5, will work as a base for a systematic approach to manage the complexity that characterizes the problem here described. This framework enables a systematic identification of the important product characteristics that need to be delivered at each operation (Q). At the same time, an identification of the parameters (q) that cause variation to these characteristics can be made.

What defines *producibility*, meaning what characteristics of the product deliver quality to the customer and what parameters control that quality in a deterministic way during production, is covered by this framework. Identifying what to inspect and measure during production is the first step towards developing predicting models. What to measure and how to measure will lead to applicable data that can be used to study correlations between the manufacturing factors and the process output; thus supporting future design analysis when performing simulations.

Therefore, in this model, a framework is set to support the generation of future product variants, based on the reuse of manufacturing knowledge and data acquired from previous design and manufacturing interactions. The model will enable the assessment of fabrication process quality output early in the design, thus working as a base for *producibility* analyses.

7. Future work

Future work will focus on validating the model in one or several case studies and making the necessary improvements. Simulations will be linked to the model in order to predict the output values at the different manufacturing steps. A database will also be linked to the model for the reuse of the manufacturing data, which in its turns would serve as input to the simulations.

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