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**Abstract.** Including production considerations in the early design stages of aircraft structures is challenging. Production information is mostly known by experts and rarely formally documented such that it can be effectively used during the design process. Producibility is mostly considered after completing the design, resulting in increased cost and development time due to the late discovery of production issues. This paper presents a new model, called the Manufacturing Information Model (MIM), which supports the automatic inclusion of production considerations into the design process. The MIM provides a single source of truth and a generic structure to capture and organize production-related information in a product system. Furthermore, it provides compatibility analyses to automatically warn for or exclude infeasible designs. Analysis tools use the information stored within the MIM to calculate the mass, costs, and production rate of the product. To show the functionalities of the MIM, it has been applied to the conceptual design of a wing box at a Tier 1 company. This use case shows how the MIM supports trade-off decisions, as it allows for the identification of trends and the ranking of different manufacturing concepts. Overall, the MIM provides a structured and formal approach to include production information in the conceptual design, improving the decision-making process.

## 1. Introduction

Considerations that dictate the producibility of a design are among the most important criteria that drive the selection of a concept over others. This is because a design cannot be successful if it is not possible to be manufactured within the constraints and capabilities of the stakeholders. These production considerations can be defined as "*factors from the perspective of production that have an influence on the system design*" [1]. For example, they include information about joints in the product, as different joining methods (such as fasteners or welding) have different requirements for minimum edge distances and corner radius, which in turn result in different flange widths for parts such as ribs (Figure 1).

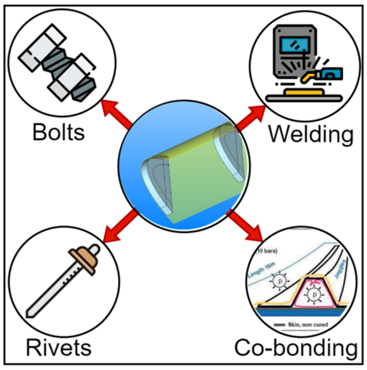



**Figure 1:** Production consideration: joint method influences flange width.

Designs that do not include production considerations carry a high risk. This risk can be associated with either design changes at later stages of development to include the missing production considerations (such as accounting for correct fastener arrangement and assembly clearances), or with a reduced fidelity of the system model and thus of the analyses that depend on it (such as cost and mass) [2]. Design changes are directly associated with higher costs and delays, which reduce a product's viability. Additionally, analyses on a system with a lower-than-required fidelity make the calculated performance indicators of interest less reliable in trade-off decisions.

Though desirable, the simultaneous design of a product and its production system can be quite challenging, especially during early design stages when little is known about the product. Furthermore, managing the different, and often conflicting requirements between product design and manufacturing can be quite difficult. Production knowledge is generally known by manufacturing experts and not necessarily well documented such that it can be integrated into the product design process. Therefore, manufacturing experts and designers are brought together at different stages of product development to enable them to share their knowledge and resolve potential design conflicts. This results in an informal, time-consuming and error-prone process. Often, no effective means are in place to leverage the experts' knowledge in a systematic or automated approach during the design process.

Various attempts at overcoming the challenges of this manual approach can be found in literature, but they have their own limitations, which prevent their widespread adoption. These studies can be grouped based on their shortcomings as follows [1]:

(i) Accounting for production considerations only as manufacturing cost [3–5].

(ii) Specific solutions tailored for certain designs, manufacturing methods, materials, etc. [6–9].

(iii) The methodology depends on the use of software tools (such as Product Lifecycle Management (PLM) or manufacturability analysis) not suited for automation/conceptual design [9–11].

(iv) Aspects of manufacturing ([3, 4, 8]) and assembly ([12–16]) are not considered together.

This paper presents a new model, called the Manufacturing Information Model (MIM), which focuses on formalizing and documenting manufacturing and assembly knowledge while overcoming the challenges stated above. This new model-based approach enables the inclusion of production considerations in the conceptual design stage in a systematic and automatic way. The application of the methodology is shown through an industrial use case at GKN Fokker Aerostructures, focusing on the conceptual design of a wing box.

## 2. The Manufacturing Information Model

The MIM provides a single source of truth and a generic structure to capture and organize production-related information. It is a software package that can integrate with Knowledge Based Engineering (KBE) applications such as the GKN Fokker moveable modeler called MDM (Multidisciplinary Modelers) [17] to account for production considerations in product design. The MIM has been implemented using ParaPy[1], a Python-based KBE platform. Figure 2 shows

[1] `https://parapy.nl/` (accessed 19 September 2023)

the overall structure of the MIM (left), along with some key points (right) highlighting the main features that help overcome some of the shortcomings of the state of the art.

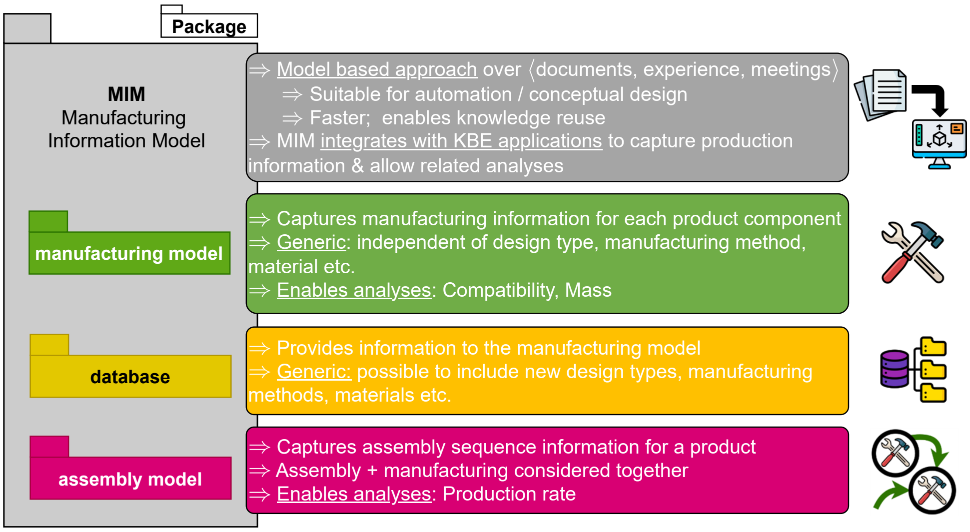



**Figure 2:** Overview of the Manufacturing Information Model (MIM).

As shown in Figure 2, the MIM consists of three modules: the manufacturing model, database and assembly model, which together are able to capture information about how a product (and its constituent parts) will be produced. It allows for the formalization of information that is usually stored in documents or only known by engineers through experience. This enables its effective reuse, for example, to perform automatic checks for compatibility between different production and design decisions to ensure feasible designs. The next sections will discuss each of the modules of MIM in more detail.

### *2.1. Manufacturing Model*

The main role of the manufacturing model is to store manufacturing information for each component in the product design, in a standard manner. For each manufactured primitive, a manufacturing model is defined as shown in Figure 3 (bottom left). A manufactured primitive is defined as "*a constituent of a product, identified based on what object is manufactured*" [1], and hence can represent parts, joints, or even integrated parts (Figure 3, top left).

The manufacturing model stores all information on how a primitive can be manufactured in five information categories: design specifications, method, material, equipment set, and site. The design specification category contains specific design characteristics that are relevant from the perspective of producing the manufactured primitive. For example, this could include the bounding box dimensions of the part, which is relevant in case the part has to go into an autoclave, or the length of the welded joint, which can be used to calculate the welding time. This information category is design-specific (to the primitive).

The other four information categories are design-independent and are hence referred to as the "manufacturing information categories" in Figure 3. Based on the selections made for each category, the information related to these categories is taken from the database (see subsection 2.2). As soon as a selection is made for one of the four categories, the possible options for the other categories are automatically reduced based on the compatibility rules in the database. For example, if aluminum is chosen as the material, then hand-layup (for composites) is removed from the available manufacturing methods. This way, conflicting information between design and manufacturing is avoided.

An example of the final result of integrating the manufacturing model in a product tree of a KBE application can be seen in Figure 3 (right).

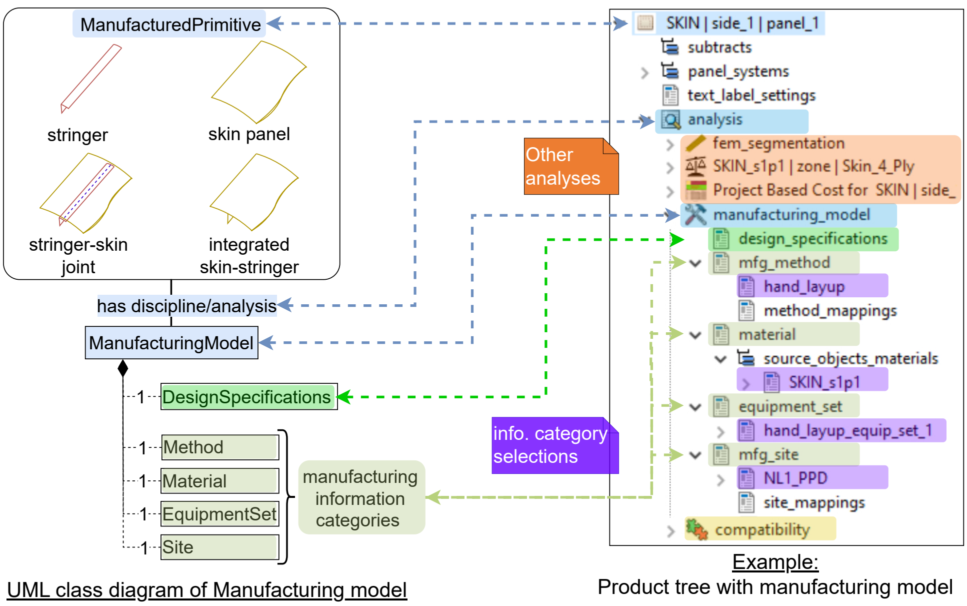



**Figure 3:** Overview of the manufacturing model. Left: structure of the manufacturing model as a UML class diagram. Right: an example product tree showing the integration of the manufacturing model in GKN Fokker's MDM (see section 3).

### *2.2. Database*

The database module contains all design-independent characteristics of the different manufacturing methods, materials, equipment, and manufacturing sites. Besides general information on these categories, specific relations and compatibility rules between the different elements are also defined in the database. For example, suitable materials for each manufacturing method or the available equipment at each manufacturing site are listed. Also, material compatibility rules are defined, for example, carbon fiber should not be in contact with aluminum to avoid galvanic corrosion. The benefit of these compatibility analyses is that infeasible designs can automatically be detected.

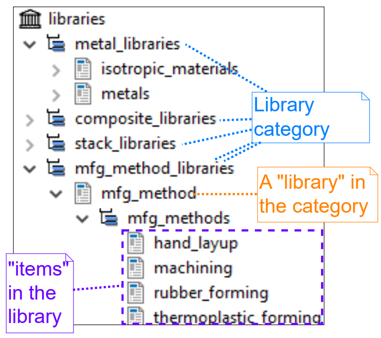



**Figure 4:** Database libraries in a product model [1].

All this data is stored in JSON files, each of which is referred to as a "library". This data is processed and made available to the manufacturing model with the `libraries` subpackage of the database. The result of its integration is shown in Figure 4.

### *2.3. Assembly Model*

The assembly process is modeled in MIM using two directed acyclic graphs (DAGs) [18], referred to as the "operation graph" and the "station graph". These are shown in Figure 5. The Python package NetworkX[2] is used to model the graphs. Operations are defined as the *"execution of manufacturing process(es) that result in the materialization of a manufactured primitive"* [1]. Therefore, steps in the overall manufacturing and assembly process of a product are captured by the operation graph. The nodes represent the operations (and their results), while the edges represent the sequence in which the operations are performed and which results are passed onto the next operations.

Operation nodes are also assigned to different "production stations", indicating a physical location where they will be executed. The station graph can thus be (automatically) derived

[2] `https://networkx.org/` (accessed 19 September 2023)

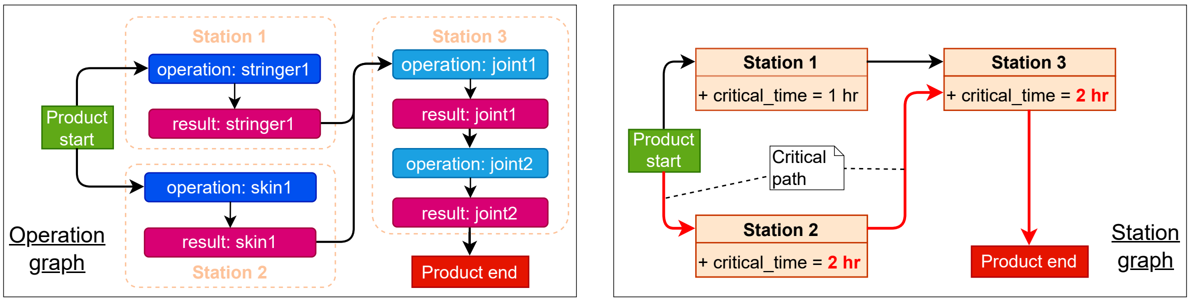
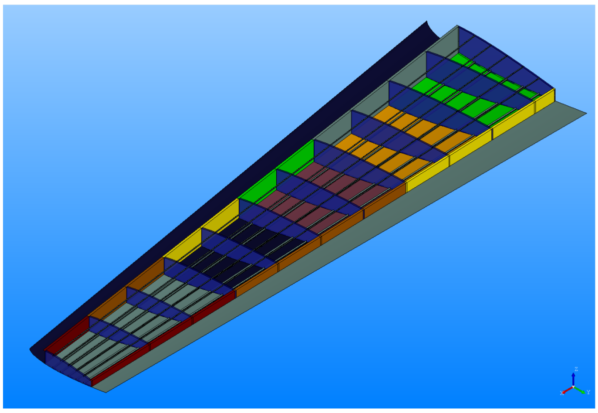



**Figure 5:** Representation of the operation and station graphs in the assembly model. Part manufacturing operations are shown in dark blue and assembly operations in light blue.

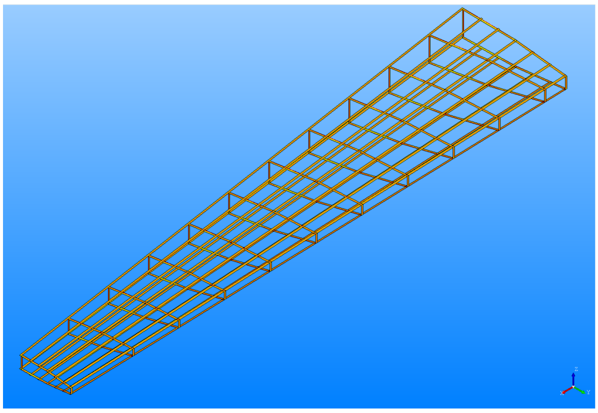
by collapsing all operations/result nodes belonging to a station. With information from the manufacturing model of each operation, the critical (minimum) time required to complete all operations at each station can be calculated. This can then be used to find the critical manufacturing path through the station graph, which is used to calculate the overall production rate.

## 3. Case study: Wing box conceptual design at a Tier-1 company

The MIM presented in the previous section has been applied to the conceptual design of a wing box at GKN Fokker Aerostructures. The goal of the study is to explore different production concepts through a Design of Experiments (DoE) while varying the material, the production process and the assembly sequence for the different parts and joints. Varying all the variables within one DoE would lead to a design space that is too large. Therefore, the DoE is split into a manufacturing and an assembly DoE, as described in subsections 3.1 and 3.2, respectively. Figure 6 shows the baseline concept used within the study. GKN Fokker's MDM [17] has been used to generate the model. An example of the MIM integration into the MDM is shown in Figure 3. Note that the number and location of the parts are fixed and do not change during the design study.



**(a)** Wing box part primitives. The wing box consists of two skin panels, ten stringers, twelve ribs, and two spars.



**(b)** Wing box joint primitives. The stringer-skin, rib-skin, spar-skin and rib-spar joints are considered during the DoE.

**Figure 6:** Baseline concept of the wing box generated using the MDM [1].

### *3.1. Manufacturing DoE*

The manufacturing DoE varies the material of the parts, the production process for the parts and joints and the type of stringers. The possible values for the variables are shown in Table 1. Note that the equipment set and site were set constant for this study. Part integration was accounted for through the blade stringers. In this case, the stringer and skin form one integrated part with its own manufacturing method. This means that the individual skin and stringer parts and the stringer-skin joint are not considered and no manufacturing/joining method is selected for them.

The combinations for the input variables resulted in 1536 design options. The validity of each design point was automatically assessed by the compatibility analyses. 240 out of the 1536 options were valid. Only for these options, the total costs (calculated using CATMAC [20]) and total mass were evaluated, reducing the computational time required for this DoE. Note that a sizing optimization needs to be performed to set the material thicknesses for all parts. However, due to time limitations, the sizing was skipped and the material thicknesses were set using reference values. Furthermore, the cost calculation only considers the recurring costs and not the non-recurring costs.

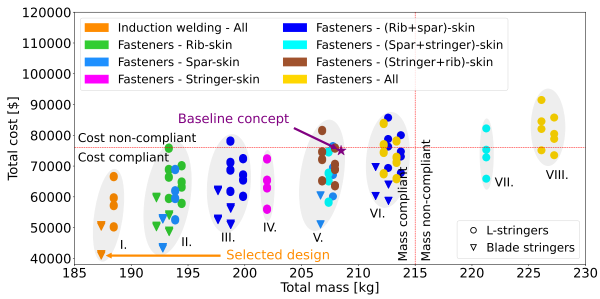
**Table 1:** Input variables for the manufacturing DoE.

| Input variables | Values |
|---|---|
| Material | CFRP<br>Aluminum 7075 |
| Part manufacturing method | Hand layup<br>Thermoplastic forming<br>Machining<br>Rubber forming<br>Tapas layup [19] |
| Joint assembly method | Fasteners<br>Induction welding |
| Stringer type | L-stringer<br>Blade stringer |

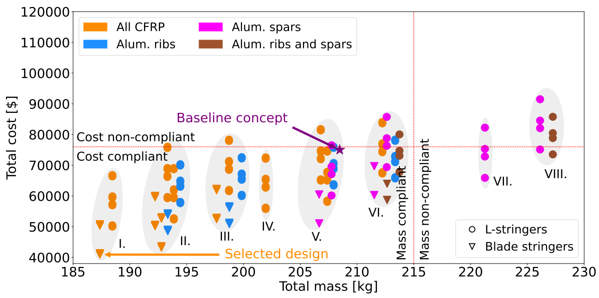
The results of the valid points in the manufacturing DoE are shown in Figure 7. All three scatter plots show the same design points however different design characteristics are highlighted, namely material, assembly and manufacturing method.

A cost requirement of max $76000 and a mass requirement of max 215 kg were added to the design and the requirement compliance of each design was evaluated.

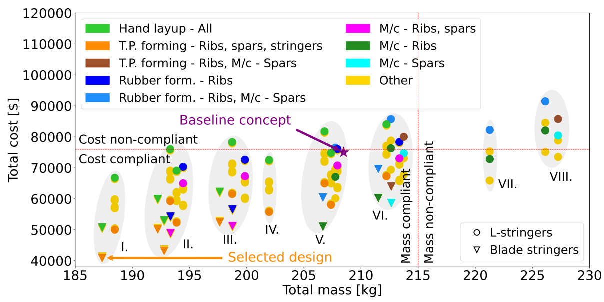
The results can be divided into 8 mass groups. As can be seen in Figure 7a, the different groups are mainly caused by the assembly method chosen for the joints. The




**(a)** Scatter plot labeled based on the selected assembly method. The default method is induction welding unless stated otherwise. E.g. "Fasteners - Rib-skin" means fasteners are used for the rib-skin joints and induction welding for the other joints.




**(b)** Scatter plot labeled based on the selected part material. The default material is CFRP unless stated otherwise. E.g. "Alum. ribs" mean the ribs are made of aluminum, while all other parts are made of CFRP.




**(c)** Scatter plot labeled based on the selected manufacturing method. The default method is hand layup unless stated otherwise. E.g. "Rubber form. - Ribs" mean the ribs are produced using rubber forming and all other parts using hand layup.

**Figure 7:** Scatter plots of the valid design points of the manufacturing DoE. The baseline design and the design selected for the assembly DoE are marked with an arrow. 8 mass groups can be identified as indicated with the gray ovals. [1]

lightest mass group consists of designs that are completely welded, while the heaviest designs have all fasteners. Furthermore, it can be concluded that for the same assembly method, blade stringers are in general cheaper than L-stringers and have a slightly lower mass.

Figure 7b shows that designs made out of composites are the lightest, while the designs made fully out of aluminum are the heaviest. Lastly, Figure 7c indicates that the cost of the designs is largely determined by the manufacturing method, hand layup being generally the most expensive method and thermoplastic forming the cheapest.

During the execution of the DoE, the MIM automatically takes the correct production data from the database and identifies infeasible points. As shown in Figure 7, the effect of different design and production choices is quantified, thereby supporting engineers in the selection of the best combination of materials and manufacturing methods.

### *3.2. Assembly DoE*

The design with the lowest mass and cost of the manufacturing DoE was selected to be used in the assembly DoE. This design has blade stringers, is completely made from composites, has induction welded joints and the parts are produced using thermoplastic forming. Within the assembly DoE, stations are defined once and kept constant while the arrangement of operations at each station (sequential or parallel) and the station sequence are varied.

The assembly sequence with the highest production rate is shown in Figure 8. This assembly sequence starts with the parallel production of all the spars, ribs and integrated skins and stringers at three different stations. As soon as the ribs and integrated skin are finished, they are joined. Next, the spars are connected to the skin and finally, the ribs are connected to the spars. The numbers between the stations indicate the production time. This assembly sequence results in a production rate of 18 shipsets per month.

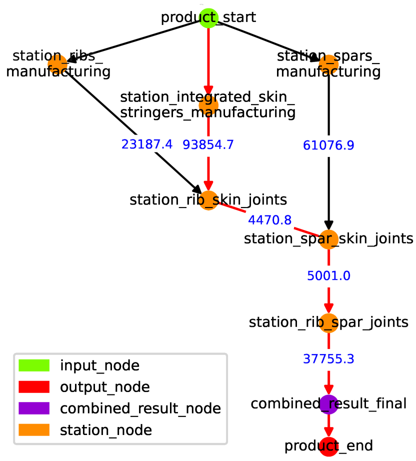



**Figure 8:** Station graph for the assembly sequence with the highest production rate.

## 4. Conclusions and outlook

Including production considerations in the conceptual design of aircraft structures is challenging as most information is known by experts, but not well documented such that it can be integrated into the product design process. To provide a more structured way for storing production information and connecting this information to the different parts in the product model, the Manufacturing Information Model was introduced.

The MIM provides a single source of truth for all production information. Furthermore, it provides a generic structure to capture and organize production-related information. Infeasible designs are automatically detected based on the compatibility analyses that are enabled by the MIM, which saves time and computational resources. Analysis tools use the information provided by the MIM to calculate the cost, mass, and production rate of the product.

The application of the MIM to the conceptual design of a wing box demonstrated its ability to identify trends and rank different manufacturing concepts and assembly sequences. Overall, the MIM supports exploring feasible design options and making trade-off decisions with regard to design and manufacturing.

So far, the MIM has only been used to evaluate fixed design points within a DoE. In the future, the MIM will be implemented into Multidisciplinary Design Analysis and Optimization (MDAO) workflows to enable the simultaneous optimization of design, manufacturing and assembly, which will result in optimal designs that are also producible.

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