INTERACTIVE AND MODEL BASED DEVELOPMENT AT THE EXAMPLE OF A STRUCTURAL AND AERODYNAMIC COMPOSITE VANE FOR A JET ENGINE

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ABSTRACT

Against the background of digitalization within mechanical engineering, this paper presents an approach to model development processes down to the models, methods and data (MMD) used, using sequences of the Engineering Design Process of a structural carbon fibre reinforced polymer guide vane for a future jet engine. Firstly, the MMD approach is explained in terms of how it can be used to describe development processes and their sub-processes at the most detailed level. Secondly, the sequences of an interactive development process, considering the design, dimensioning and manufacturing disciplines, from the specification of requirements to the implementation of physical and testable functional samples, are described in terms of the modelling approach. Thirdly, both the modelling and engineering processes are combined into a process model of the development process, considering the MMD elements used. It is shown that this approach enables to describe development processes, allowing a variety of analyses to be carried out in relation to the development process in order to understand such processes and improve them in the future.

1 INTRODUCTION

Constantly increasing requirements for the performance and efficiency of engineering products and systems, such as jet engines, can be achieved through the use of hybrid designs combining carbon fibre reinforced polymer (CFRP) and metal in combination with structural function integration. Figure 1 shows the Rolls-Royce Pearl 700 (left) with function-integrated metallic intermediate case (IMC) and a hybrid composite/metal intermediate case of future jet engine generations (centre) as well as a key structure to enable this - the functional example of a CFRP outlet guide vane (right). CFRP is used in areas of remote load transmission with direct load paths. Areas subject to complex loads are designed using metal.

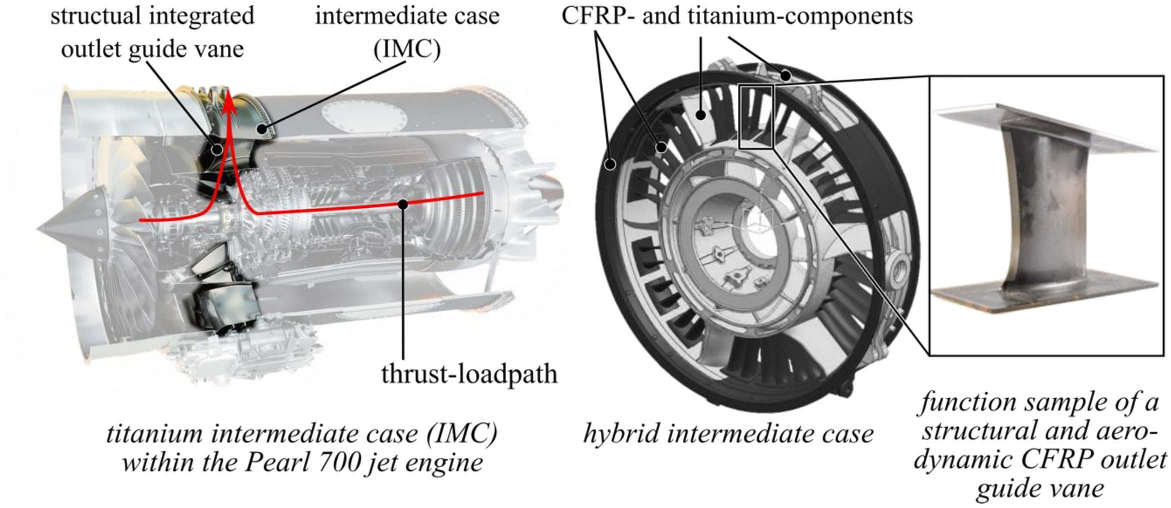

Figure 1: Rolls-Royce Pearl 700 (left) with function-integrated IMC, composite-metal IMC of future jet engine generations (centre) and function sample of a CFRP outlet guide vane (right) [8]

The multitude of adjustable parameters of composite materials in general and in combination with metallic elements in particular lead to complex Engineering Design Processes (EDP) [1] to achieve the ambitious goals of development programs for high-tech lightweight products. The individual disciplines of design, material development, manufacturing and dimensioning run in parallel and interact with each other. Such an interdisciplinary development process, from structural concept to detailing and implementation, consists of parallel and interacting sub-processes that are based on each other. The multitude of models, methods and data for the development of hybrid composite structures along the development process can lead to extraordinarily complex procedures that pose great challenges for engineers. Digitalization is an approach to reduce the risk and accelerate the EDP of high-performance lightweight structures and systems.
On the one hand, digitisation can speed up the development process. However, it often involves a greater effort to set up the development process in such a way that different development steps can be digitally linked to one another, which can lead to major challenges, especially in the case of new developments e.g. on low technology readiness levels in combination with the use of new technologies, since development processes have to be rebuilt in detail. New models, new methods and new data are used, and in some cases their compatibility must first be established. Figure 2 proposes a classification of the degree of digitisation of an EDP into four levels, where the degree of digitisation, and thus the robustness and speed of the digitised process, increases continuously from level 1 to level 4. At the same time, the effort required to set up a new development process chain increases from level 1 to level 4. The highest level is a fully digitised EDP, where all models, methods and data are linked and the process can be fully automated if required.

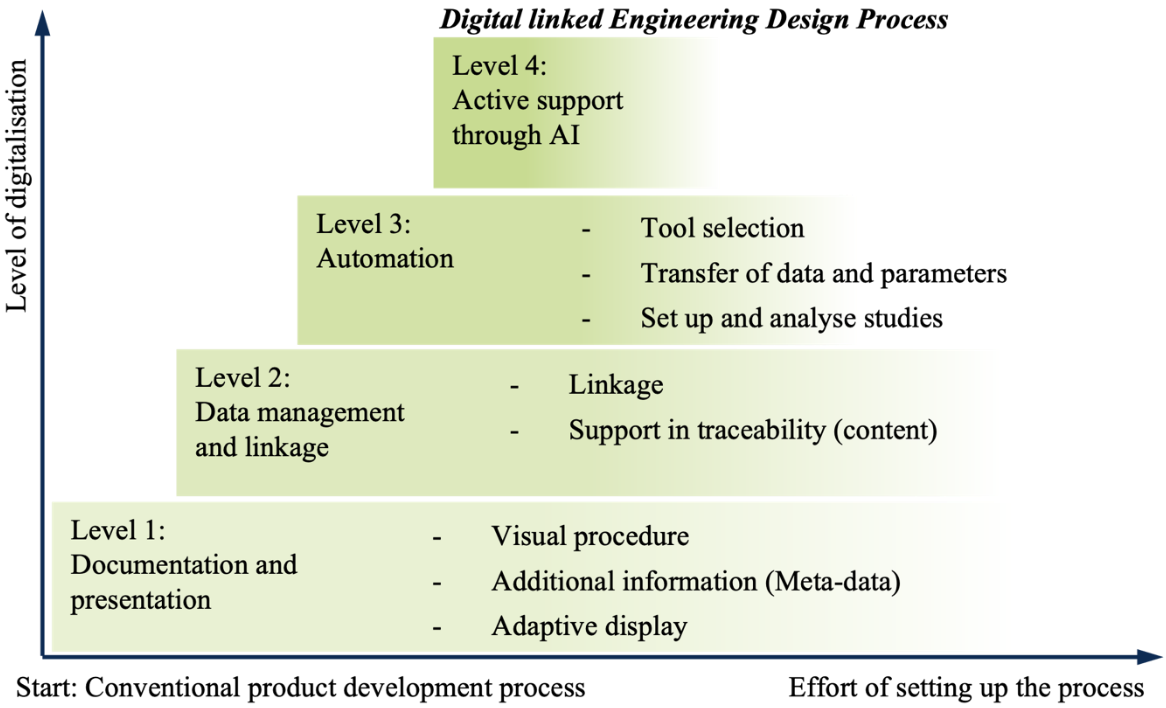

Figure 2: Level of digitalisation projected above the associated effort to build the development process chain

At level 1, the development process to be performed or that has been performed is fully documented and can be represented visually. In addition, metadata can be stored in such a model. To accommodate the involvement of various specialists and stakeholders, each offering unique perspectives on the development process, the process can be effectively represented through customized views. In level 2, the necessary data is organised in a data management system and the individual process steps are digitally linked. Interrelationships can be identified and the effects of changes on the process result become visible. Level 3 is accompanied by automation, where sub-processes can run independently.

The necessary data is entered automatically and studies can be carried out with little manual effort. In level 4, algorithms support the engineer in setting up a development chain by suggesting models and methods to be used. Product properties and required parameters can be estimated at an early stage. The subject of this paper is to investigate how the development process can be described in a formalised way to enable Level 1.
The VDI 2221 [2] describes a systematic and generic approach of the product development process (PDP). The VDI 2014 [3] extends this approach specifically for carbon fibre reinforced polymers (CFRP). HELMS [4] presents a methodology for the development of lightweight structures, which considers design, dimensioning and manufacturing and a strong interaction between the different engineering disciplines. FELDHUSEN [5] describes the EDP as different process steps, each consisting of an executive method, an associated model and a set of data (MMD, cf. Figure 3).

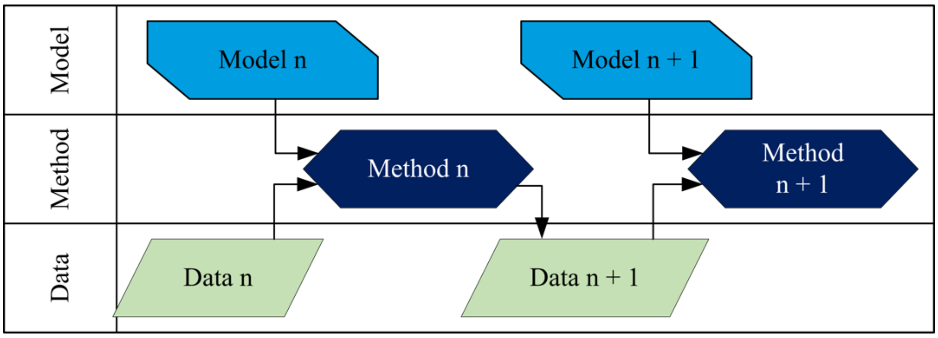

Figure 3: Interaction of model, method and data in process steps according to FELDHUSEN [5]

HAIDER et al. [6, 9] show exemplary the process modelling for the EDP of hybrid metal-composite structures. DARGEL et al. [7] and KLUGER et al. [8] show the virtual development of a CFRP structural guide vane using model and data driven approaches.
In this paper, the described methodology is applied to the specific example of the aerodynamic and load-bearing structural vane. By illustrating the complex PDP of a CFRP structural vane, a first MMD approach of the process is elaborated, which can be further detailed and used for quality assurance of the current process and for more efficient development of subsequent component generations.

2 METHOD

2.1 Process Modelling According to the MMD-Approach

Following the established systematic approaches [2, 3, 4], a CFRP guide vane for future engines is developed and the work carried out is documented in relation to the MMD approach [5].
A model representation of the PDP is used to provide an overview of the strongly interacting individual disciplinary processes. The used model has different levels that reflect the level of detail of each process step (cf. Figure 4). The highest level is based on the generally valid phases of methodological engineering according to VDI 2221, from the specification of requirements to the conception, the detailing and the implementation (level zero, L0). The basic work steps contained in the individual phases are shown in a deeper level one (L1), with individual process steps in level two and, if necessary, in further descending levels. Where possible, the methods, models and data required for the process steps are specified. At L0, the interaction between the MMD of the different phases is necessary to ensure an efficient and compatible PDP. Therefore, the deeper levels (L1, L2, …) of each individual process are, if required, examined in terms of their compatibility on the level L0.

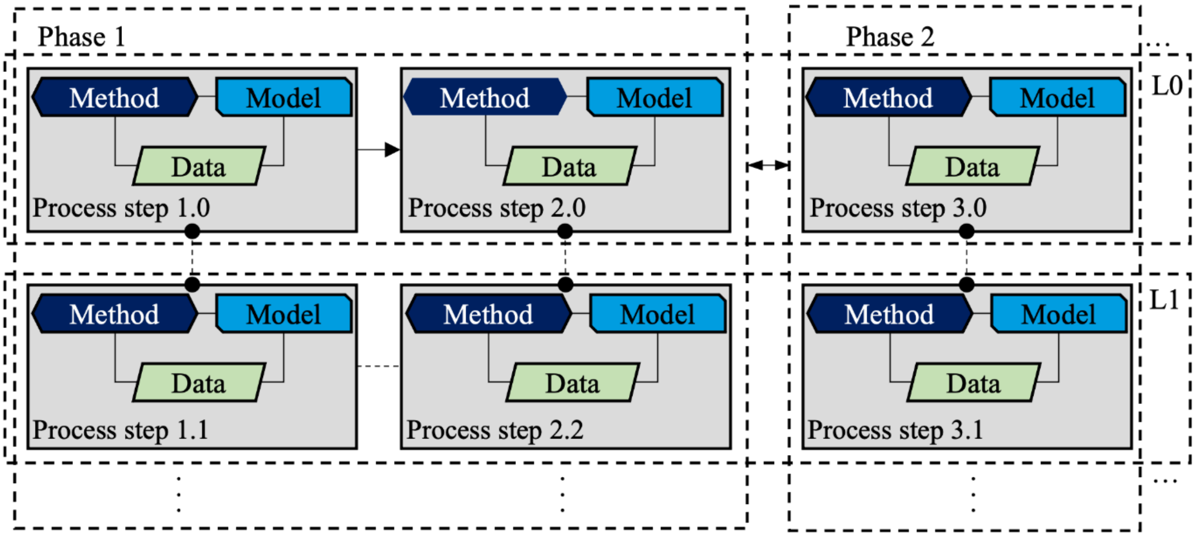

Figure 4: Process and method, model and data modelling on different levels for each phase of the PDP following the approach of [5]

By modelling the need for input data and resulting output data, the data flow is visualised. This is the basis for efficient data acquisition, storage and use. The models and methods used are clearly named and stored in parallel in a catalogue.

2.2 Engineering Design Process Sequence at the Example of Conception and Pre-dimensioning

The vane is a component of a hybrid engine structure that positions the engine and transfers the generated thrust to the airframe (see Figure 1). In previous engine architectures, separate outlet vanes performed aerodynamic functions and structural capacity was provided by integrated metal struts. The engine structure of future generations aims to unify both aerodynamic and structural functions to reduce the weight and increase the efficiency of the engine.

Based on the requirements specification and an analysis of the reference engine system, design concepts were developed and modelled (cf. Figure 5 - 1). At this early stage of the design process, analytical tools such as Classic Laminate Theory (CLT) in combination with a plate model supported the pre-dimensioning process. Numerical methods and models were used to analyse the associated stress peaks (cf. Figure 5 - 2) and principal stresses (cf. Figure 5 – 3 and detail A). Based on the requirements and weighting criteria, the concepts were evaluated and a preferred aerodynamic and structural blade variant was selected and further detailed. Recommendations for a first material model definition including the fibre architecture were developed.

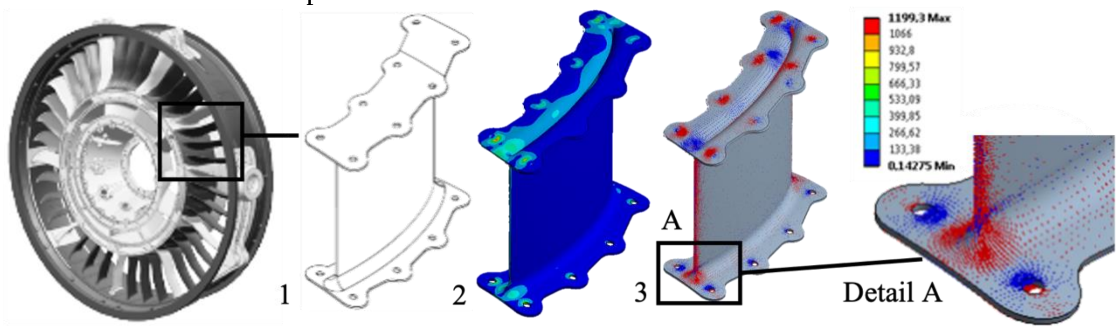

Figure 5: Concept for structural vane with double-T-shape (1), associated stress peaks (2) and main principal stresses for design of fibre architecture (3)

The development process carried out can be represented by a combination of descriptive text and figures. In this paper, FELDHUSEN‘S MMD approach is combined with the more advanced development work and its applicability is examined.

3 RESULTS

3.1 Process Modelling of the Detailed Dimensioning

As the level of detail increased, first shell models of the vane were built up and a modelling method was developed. The different modelling levels of the engine structure had to be considered in order to ensure a model transition - from component up to the engine - at different phases of the Engineering Design Process (EDP, cf. Figure 6). The vane as a part of the engine structure and engine required the consideration of the sub-system and system. The main characteristics of the design and the material model were converted into compatible data inputs for the component modelling. The load and constraint boundaries for the sub-system and system were provided. Since the thickness of the vane is a fixed parameter due to aerodynamic requirements, only the fibre angles and stacking sequence data of the vane laminate are varied initially. Here, node displacements and stress values as a data output in combination with an analysis method were used to evaluate the stiffness and strength of the vane structure virtually.

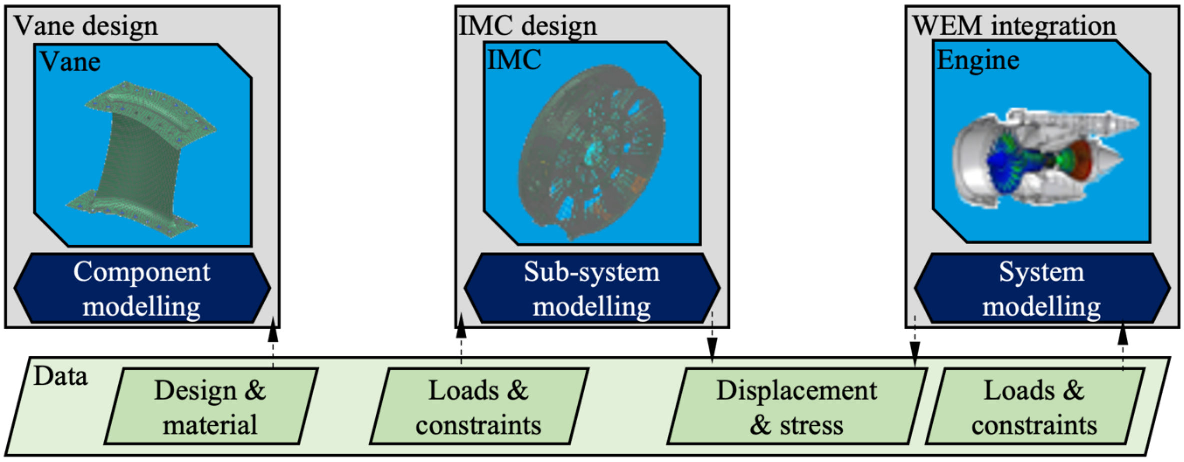

Figure 6: Modelling scales of the structural vane with different associated models, methods, input and output data

The presented models so far were based on the established technology of patched single layers. In interaction with the manufacturing process development, a stress-adapted material structure was determined. The process of the dimensioning of the structural vane is shown in Figure 7.

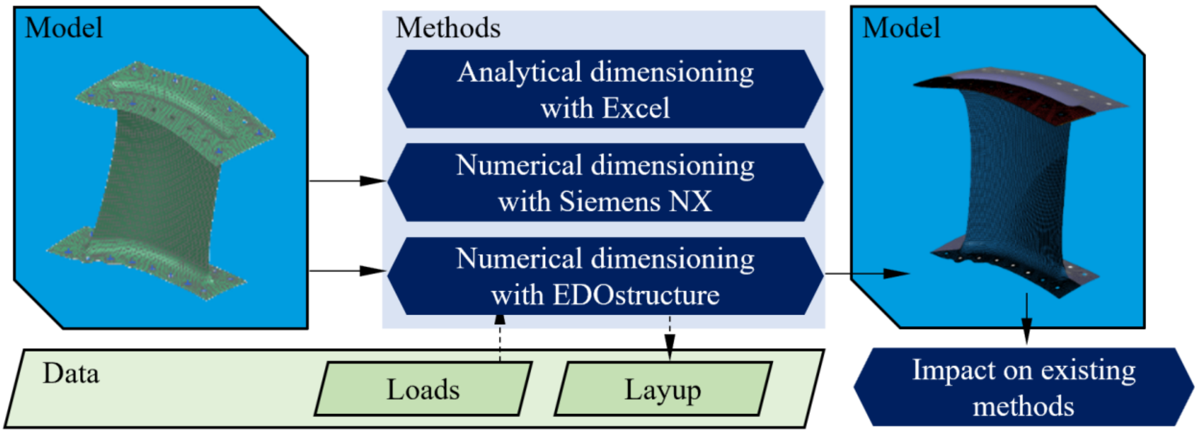

Figure 7: FE-Model of structural vane as part of dimensioning process step with different associated methods, input and output data

The FE model with its real fibre conditions is used by different software tools to transform the input data “Loads” into the output data “Layup”. The software is chosen specifically to the underlying dimensioning method and the data was exchanged in-between the dimensioning and the manufacturing process. The numerical dimensioning with Siemens NX returned the data directly back to the input model, while the dimensioning in EDOstructure created a new, more complex and three-dimensional model. Hence the complexity of the further development process steps linked to this model increased ultimately and the model input of the defined modelling levels changed. Therefore, the corresponding methods had to be reviewed and adapted to ensure a proper model transition and compatibility.

3.2 Process Modelling of the Manufacturing

The material-oriented design and dimensioning process provided the required ideal material architecture. Furthermore, the manufacturing development process identified the technological capabilities. In interaction with the individual disciplines of design, material development and dimensioning, a manufacturable structure is developed. In interaction with the dimensioning process, an aero- and load-compatible Tailored Fiber Placement (TFP) fibre architecture (cf. Figure 8) is derived. The resulting conditions are interactively exchanged with the dimensioning process and the load-bearing capacity is evaluated. This results in a design that is manufacturable and loadable, and in which the resulting material properties are respected in the design and dimensioning process.

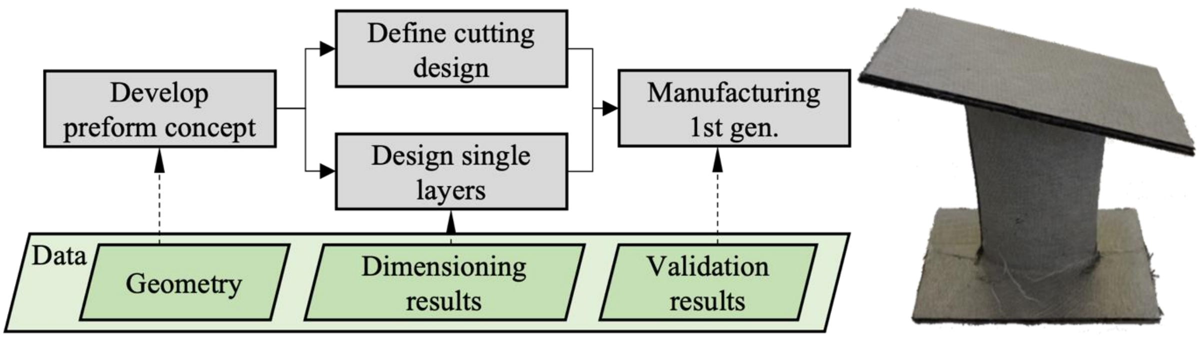

Figure 8: TFP-manufactured preform for a structural vane with its design process

The EDP of the vane showed relevant correlations of the methods, the models and the data. The complete process and sub-processes are, where possible, depicted as a model with focus on the MMD approach and detailed down to the smallest element. For each process step, the time distribution of the work steps as well as the time required to create and use the models is determined. By that, time- and cost-consuming work steps and iteration were identified.
The models used within the EDP are stored in a variation monitor (cf. Table 1) and the underlying method(s) to create the model are recorded there.

Model

Model Nr.	**Phase/ Process step**	**Level**	**Method**	**File Name**	**File Format**	**File Path**	**Software**	**Purpose**	**Model Type**	**Manu-facturing**
0	P1/PS1.0	L0	M1	Model_v00	.xlsm	C:\Documents	Excel	CLT model	Analytical 2D/3D	Patch
…	…	…	…	…	…	…	…	…	**…**	…

Table 1: Models within the PDP

All process steps were documented including their corresponding models, methods and data. The data was stored in a data catalogue (cf. Table 2) in order to make the required data visible. This results in possibilities for data management, transfer and analysis of single process steps as well as for the whole EDP.

Process Step	Phase/ Process step	Level	Data Name	Data Type	Software	File Format	Accessing Software	Automation
				Data				
Specification of requirements	P1	L0	Requirement	List	Excel	.xlsm	-	No
…	…	…	…	…	…	…	…	…

Table 2: Data within the PDP

Based on the data catalogue, the relevant software and their interfaces were derived (cf. Figure 9). It showed the diversity of different software within the EDP and identified existing and missing interfaces. In case of a changed process, it allows the evaluation of existing interfaces and the exchange of information towards their compatibility. The interface to the data level is implied.

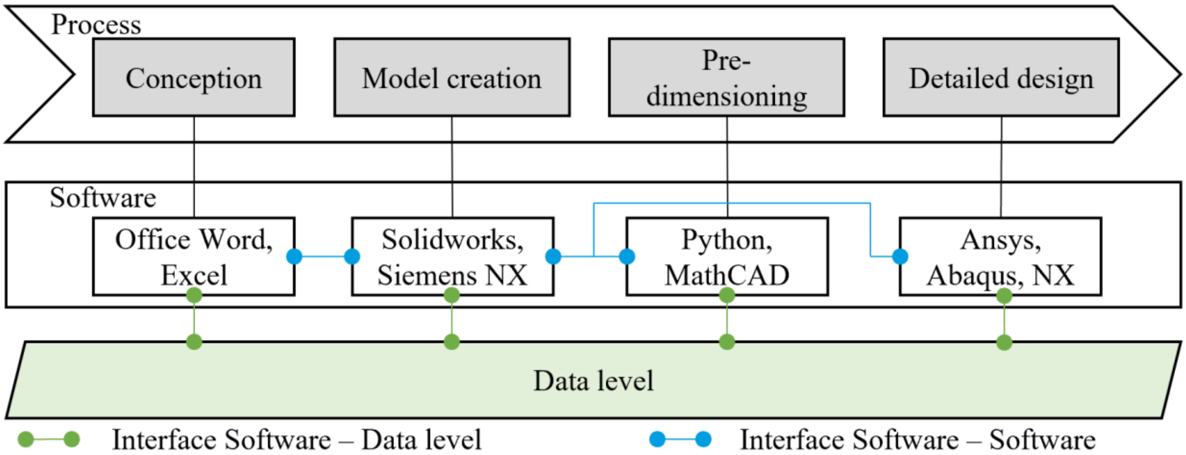

Figure 9: Software correlation for the process steps and their linkage

Finally, the single process steps were combined into one process MMD diagram, which is exemplarily shown in Figure 10 for a three-level section of the virtual development process of the vane. For the process step 1, three sub-processes were identified. The sub-process-step 1.2 was further detailed on level two (L2). It shows the required data for each (sub) process step and data dependencies along the process chain.

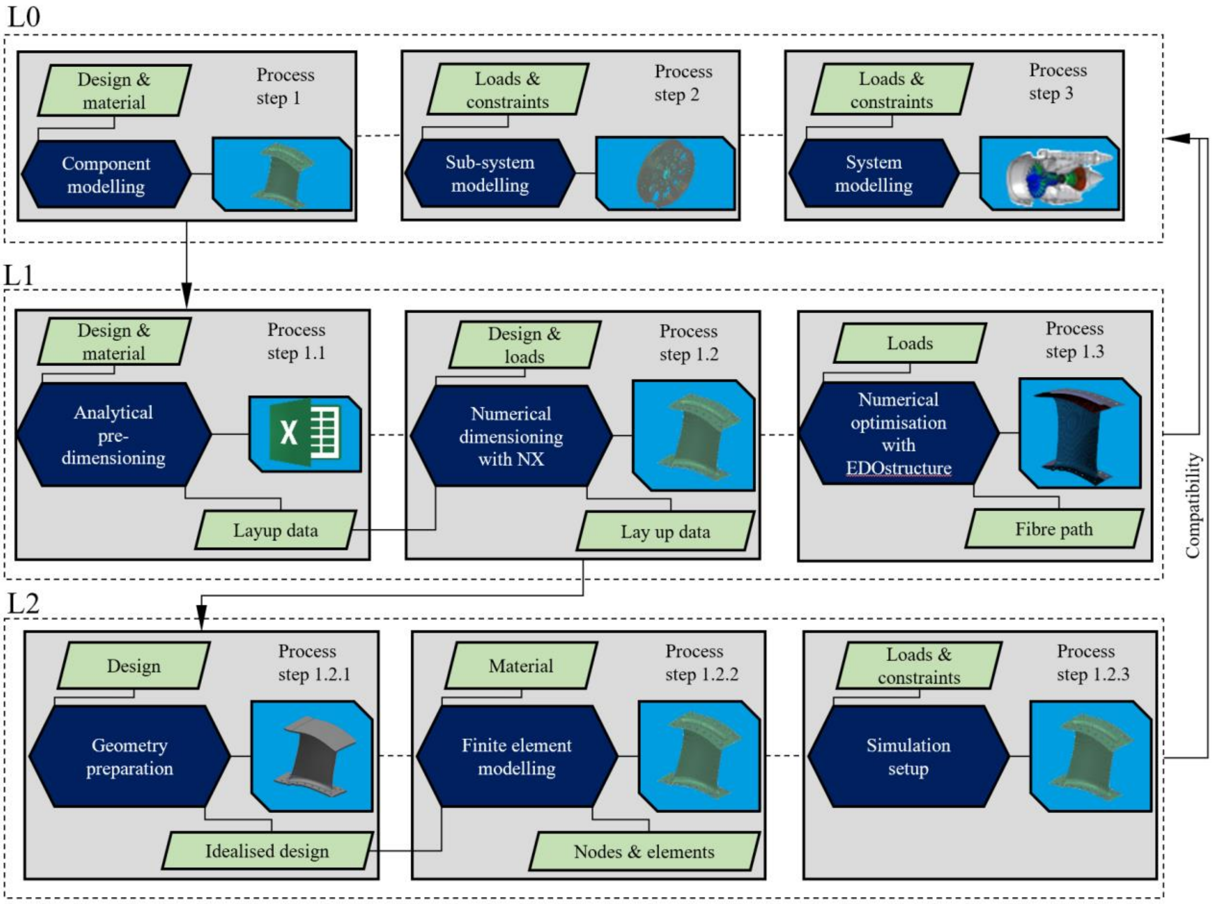

Figure 10: MMD process step diagram for a section of the vane development

4 DISCUSSION AND OUTLOOK

In this paper, we propose to divide the degree of digitisation of an EDP into four levels, based on a formalised model representation of the process (level 1). A well-known approach in the literature, according to FELDHUSEN [5], divides the individual steps of a development process into the interaction of models, methods and data. Using the development of a lightweight engine component as a case study, the transferability of the MMD approach to the development process of high-performance lightweight structures and systems is examined. Our findings demonstrate the feasibility of implementing this approach in such scenarios.

The conducted work demonstrates the capability of the process model to identify relevant correlations. It effectively distinguishes between digital and analogue process steps, allowing for the identification of both pre-existing automated correlations and those with potential for automation, specifically within the digital steps.

The required data become visible, which helps to plan the process and to develop data management and analysis concepts. The interface of the software with the data layer and the linkage of the data within the data layer was also implied, where further work is needed to increase the data linkage and the efficiency of data-driven decisions in the PDP.

Furthermore, the process modelling approach shows that the level of detail of the MMD can be high even in the early stages of the PDP. A lot of input data is needed to properly define the processes, which is often difficult to ensure. Agility is reduced by defined methods, which can be a barrier and limit innovation. Therefore, the introduction and consideration of MMD within already established PDPs is recommended. For new product development, it should be used carefully in the definition, selection and development of methods.

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