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METHODOLOGICAL DEVELOPMENT OF AN OPTIMIZED PRODUCT EMERGENCE PROCESS FOR FIBER REINFORCED POLYMERS

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ABSTRACT

Designing a lightweight composite part is always a trade-off between optimization, manufacturability and available time. Especially in an environment of many changing involved persons a concrete and practical process is a mandatory requirement to stay competitive and pass on knowledge and experience within the organization. Targeting this conflict, this research focuses on providing an overview of the available design tools for composite parts in the software *Altair Hyperworks* as well as *Siemens Fibersim* within the CAD software *CATIA v5 R2014*. The main task is to guide the designer through the development process and show the different available tools which support a sufficient and lightweight part. Using the German standard VDI 2221 (1993) for the development of the process an objective hierarchically method is generated. Divided into the four main stages “outer geometry”, “core”, “layup” and “manufacturing preparation”, different working streams are defined for the design process of a sandwich carbon fiber reinforced polymers (CFRP) part. In order to evaluate these steps, a generic monocoque is used in combination with stage-specific criteria corresponding to the individual objectives of the four stages. As a result the developed modular product emergence process (PEP) allows the designer to combine 76 tools with 42 modules to a part-specific PEP, matching the framework regarding timing, personnel and performance. Hence, the opportunity to make an objective decision on the ideal development process is generated with the possibility to even assess properties which are usually difficult or impossible to quantify like e.g. manufacturability. Future research should focus on these classification factors and the possibility to implement them into a product data management (PDM)-software to develop product specific PEPs computer-assisted.

Keywords: product emergence process, FRP, composites, optimization, software.

INTRODUCTION

The data exchange between designer and analysis engineer during the design process of a composite part is a crucial point. Which data should be available at which point during the PEP and in which format? These questions must be answered before the design process starts in order to set milestones and match the timing. Especially for the development of a prototype within a tight schedule, it is important to estimate the duration of optimization loops plus to know the interfaces and data formats within the different software. Information in literature like Potter (1997), Hennings (2011) or the AVK (2014) is mostly very generic and thus difficult to apply to every company and product. Many processes focus on the micromechanical behavior like stiffness, strain and fatigue. Failure criteria like Tsai (1984),

Tsai-Wu (1971) or Puck (1996) are often implemented in processes like the German standard VDI 2144 (2006) for the development of FRP components. Broader processes like Schürmann (2007), Bergmann (1992) or Morgan (2005) try to capture all aspects of the development but do not assign any software tools to deliver the different objectives. A detailed process with the specific software tools and their order within the PEP is usually a core competence of the part manufacturer and not openly communicated.

Recapitulatory, although composite parts are state of the art and vastly used, a concrete PEP including its implementation within software cannot be found in any technical literature. The demand of this research is to give an overview of currently available solutions and their possible combinations to support the development of a sandwich composite part within the previously mentioned programs. Obviously, this paper cannot deliver a comprehensive survey of all available tools but it tries to give a first approach to allocate defined software tools to defined deliverables within the development process.

Within this paper the PEP is divided into a hierarchical structure with different levels and modules consisting of individual tools. Several modules correspond to the same section of the process, delivering the same result but varying in performance, duration and main objective. These modules however allow the project manager to set up a part specific PEP and develop a high performance design within the given time. The chosen underlying case study is a prototype development of a CFRP sandwich monocoque, which defines the framework of the developed PEP. The process is geared around weight saving, time allocation and matching the required material properties (e.g. stiffness) under consideration of the producibility. It is assumed that the main geometry is already set and the starting point is the simplified CAD-data. The output of the process is the plybook and the design of the core, which is then passed on to manufacturing.

The importance of structural optimization in order to save weight has grown significantly over the last years. Especially when designing with composites the necessity to find the optimal material distribution is immense. Overlaid by the growing processing power of most working stations the question is not whether a part should be optimized but with which tool to which degree.

According to Bendsoe (2002), Kober (2011) and Christensen (2009), optimization can be divided into the three categories sizing optimization, shape optimization and topology optimization. During a topology optimization an algorithm finds the best material distribution for a given design space. The most common method is the **Solid Isotropic Material Penalization (SIMP)**-method, developed by Bendsoe (2002). The topology optimization gives the designer the highest degree of freedom and hence most work during the adjustment phase.

The shape optimization was developed by Cox (1965). In contrast to the topology optimization the shape optimization aims for the optimal shape within a design space with a constant volume. The sizing optimization is the oldest optimization and was already mentioned by Schmit (1960) in 1960. Where the topology and shape optimization will change the structure itself, the sizing optimization will find the optimal dimensions of the structure. Depending on the framework every optimization has its advantages and disadvantages during the PEP and it depends on the degree of optimization and the available time, which optimization is the most sufficient.

METHOD

The guideline for this research was the German standard VDI 2221 (1993), which led to a very methodical and solution-neutral approach. The first step within the standard is setting up the list of requirements for the product. Accordingly transferred on the development of a PEP this research is conducted under consideration of the following requirements:

Table 1 - Requirements for the developed PEP

Demand (D) Request (R)	Pos.	Requirements
D	1	Different alternatives are modular and hence combinable
R	2	Alternatives have different focuses: good results vs. fast execution
D	3	Starting point of the PEP: first draft of the outer geometry
D	4	PEP ends with the start of manufacturing
D	5	Output of the PEP: optimized outer surface, design of the core, layup, plybook
D	6	Software: Catia v5-6R2014, Hyperworks13, Fibersim15, AutoCAD 2016
R	7	Possibility to parallelize: designer and analysis engineer work to some extent parallel; design and analysis jobs are in part distributed among multiple engineers
R	8	Manufacturing can be performed by comparatively inexperienced staff

The requirement specification necessitates the PEP to be assembled from combinable modules. To identify these modules, the process will be structured into several levels. The approach is again based on the German standard VDI 2221 (1993), which demands to structure a system into subsystems and sub elements to support the identification of sub problems (Fig. 1).

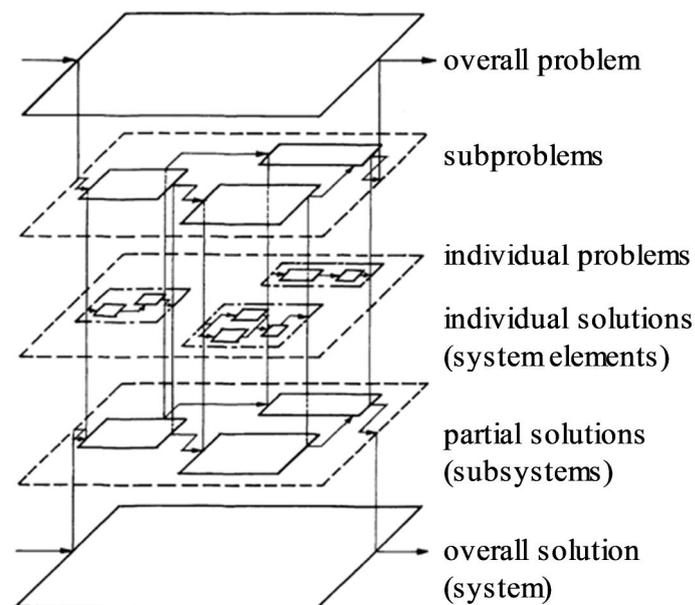


Fig. 1 - Method of subdivision and combination to structure problems and systems (c.f. VDI 2221, 1993)

The full product emergence process is shown in Fig. 8. In level 1 the process is divided into four strictly successive stages: “*outer geometry*”, “*core*”, “*layup*” and “*manufacturing preparation*”. The strict order is a result of the tight schedule in prototype-manufacturing: To achieve a brief production, the molds and the core have to be machined during the development process and therefore cannot be altered further along the line. The products of the stages form the output of the PEP and simultaneously act as input for the successive stage respectively.

The product emergence process is further sectioned in another two levels with the last one, level 3, containing sub elements which can be covered by specific software tools. These tools, representing possible solutions to the sub problems described by level 3, are positioned below the product emergence process in Fig. 8 as illustrated by Fig. 2.

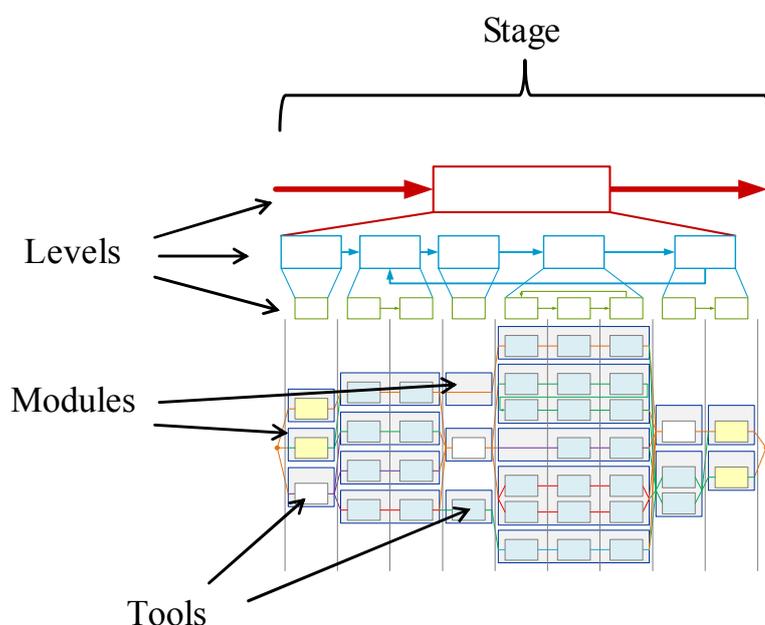


Fig. 2 - PEP: legend for the illustration of possible solutions

Tools, which can only be executed in conjunction or which represent very similar alternatives, are merged to one module. Taking the compatibility of the modules into account, main paths through each stage are identified, portraying the fundamental alternatives to configure a stage. Four main paths, one for each stage, compose a complete product emergence process. Table contains all identified main paths. The modules that form a main path are highlighted in black font.

Within the scope of this paper only the modelling and optimization strategies specific to FRP sandwich parts are described in greater detail.

Table 2 - Description of main paths

Main path	1. Outer geometry					
	1.1 Model Development	1.2. Optimization		1.3 Adjustment		
O_M01	1 shell global	Analysis Shape opt.		No transfer Punctual transfer Complete transfer	No adjustment Revise design	
O_M02	1 shell global	Analysis Shape opt.		No transfer Punctual transfer Complete transfer	No adjustment Revise design	
Main path	2. Core					
	2.1 Designing	2.2 Dev. discr	2.3 Dev. l-str.	2.4 Optimization	2.5 Adjustment	
C_M01	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M02	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M03	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M04	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M05	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M06	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
C_M07	Design space Preliminary core No core	3D elements 2 shells global 2 shells local 1 shell	No laminate Global laminate Zone laminate	Topology opt. Freesize-/Size opt. Analysis Shape opt. Size opt.	No transfer Punctual transfer Complete transfer	No adjustment Redraw core Smooth inner mesh
Main path	3. Layup					
	3.1 Model B.-up	3.2 Optimization	3.3 Adjustment		3.4 Final analysis	
L_M01	Properties	Analysis Freesize-/Size-opt.	Punctual transfer Complete transfer	Ply based Zone based Multiply based	Analysis	
L_M02	Properties	Analysis Freesize-/Size-opt.	Punctual transfer Complete transfer	Ply based Zone based Multiply based	Analysis	
Main path	4. Manufacturing Preparation					
	4.1 Designing solid body		4.2 Flat patterns		4.3 Plybook	
M_M01	Design from offsets Automatic body from layers		Brief definition Complete definition		Manual plybook Automatic plybook	
M_M02	Design from offsets Automatic body from layers		Brief definition Complete definition		Manual plybook Automatic plybook	

Modelling and optimization of a sandwich part

The first method to model a sandwich part is to use a single layer of shell-elements and assign the properties of a full laminate including a core ply in the center. An alternative method is to mesh the outer and the inner surface with shell elements representing FRP layers. For this case, the core is disregarded and the inner and outer FRP layers are not connected. Hence, forces or stresses in that region cannot be transferred from one laminate to the other. A third method is to model the inner and outer laminates with shell elements. In contrast to method two, the core is not disregarded, but modeled with 3D elements. All three methods are shown in Fig. .

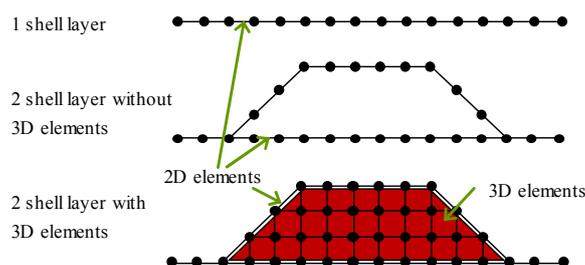


Fig. 3 - Modelling strategies in a FEA

The accuracy of the first and second method is highly dependent on the geometry and load case of the part. The third method can be considered as most accurate but also most complex. In case of geometry changes, the 3D elements have to be changed as well.

Using the example of the core design, a practical description of the optimization process is conducted. The simplest way of core optimization of a sandwich part is to perform several iterations of changing the core thickness globally or locally and executing simple FE analyses. The preferred modelling strategy is the *1 shell* approach. Hence, adding, deleting and moving of “core plies” is more or less a manual optimization of properties. The inner and outer laminate however, is maintained. Alternatively, a two-step parameter optimization called *freysize/size optimization* is used. Its goal is to calculate an optimized thickness distribution of the core ply for given boundary conditions in the first step and to reduce its complexity and recalculate thicknesses of automatically added core-ply in the second step.

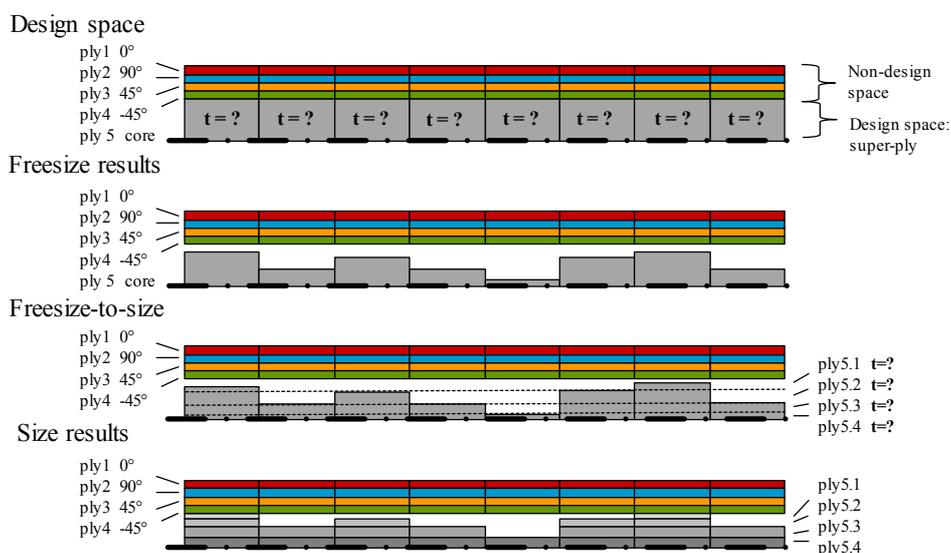


Fig. 4 - Freysize/size process

In the first step, the thickness (parameter t) of every element of the core ply is set as the design variable and optimized. As shown in Fig. 4 the thickness results are highly segmented and therefore difficult to manufacture. Thus, during the freesize/size step the complexity is reduced by combining plies of similar thicknesses to new core plies. This will be executed automatically by the software. Furthermore, a highly-segmented core can be combined to bigger plies by the user. After the combination of element thicknesses the result is not optimal anymore and the second step recalculates the optimal thicknesses of the newly added core plies.

A size optimization can be performed as sole parameter optimization and is particularly suited if the regions of different core-thicknesses are fixed. It can be utilized to optimize the thickness parameters of previously modelled core plies.

The most common optimization is a topology optimization, which implies a good overview of load paths in a part or in an available volume. The design space must be meshed with 3D elements and the material density will automatically be varied for every element. The normalized material density of each element should take a value of either 0 or 1, defining the element as being either void or solid, respectively. The objective of reducing mass is achieved by the optimization target of e.g. maximizing the stiffness under consideration of design constraints such as keeping only a fraction of the mass regarding the initial design space. The result is an optimized material distribution, showing the ideal load path within the design space (Fig.).

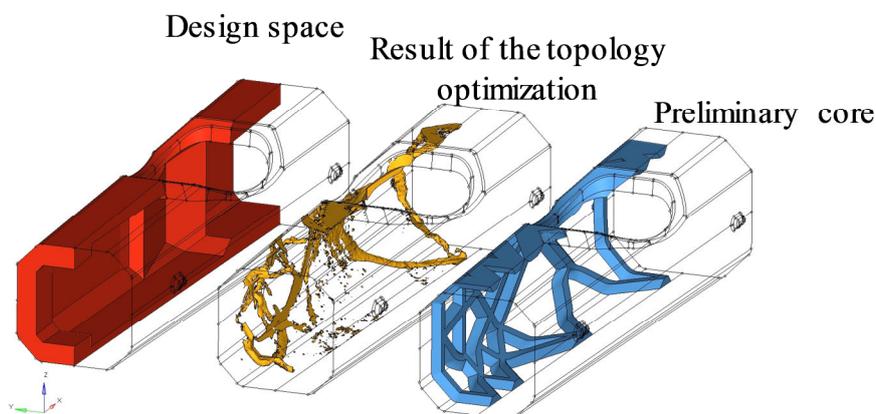


Fig. 5 - Topology optimization on a monocoque

Alternatively to the topology optimization, a shape optimization can be conducted. The technique of repositioning nodes to quickly change the geometry makes a shape optimization a fast tool to evaluate several small geometry changes.

Vectors, which define a direction in which nodes can be moved, are created in the preprocessor. A “morphing”-tool is used to directly manipulate the nodes in the preprocessor. Another option is a topography optimization which moves the nodes automatically during calculation in the solver after defining an objective and design constraints.

These tools can be used to change the inner geometry of a sandwich part like a monocoque with a global second shell layer (see Fig. on the right). The combination of a shape optimization and a parameter-optimization by using different sandwich modelling strategies offers the advantages of both sides. In regions, where an important design variable (e.g. stiffness) highly correlates with the geometry, discrete changes can be made by morphing a

second shell layer. In other regions, the freesize/size optimization can be used to calculate the ideal thicknesses automatically (see Fig. on the left). Another advantage of this combination is, that a second shell layer is only required locally.

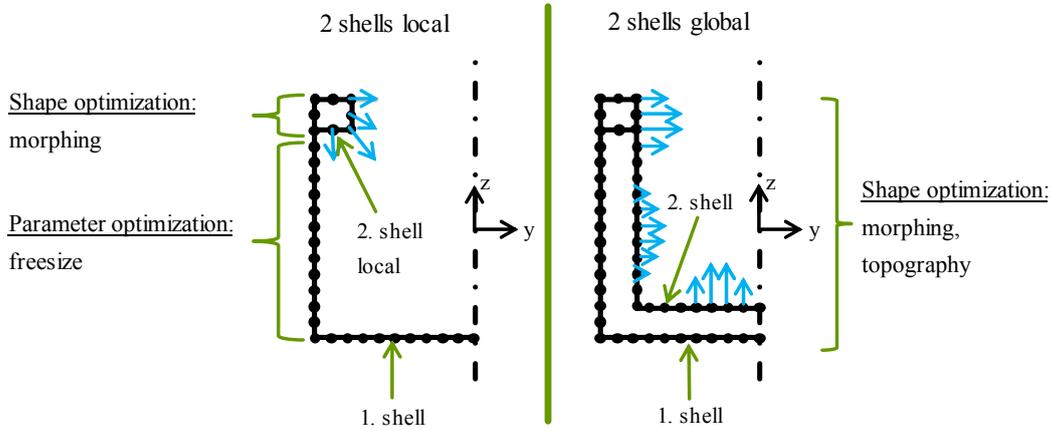


Fig. 6 - Difference between 2 shells local and 2 shells global

The evaluation of the possible solutions is carried out on main paths. Due to the following reasons this approach is chosen rather than comparing every single tool: The individual process steps have different objectives and can hardly be analyzed in isolation. An example for this is the shape optimization which can be applied in combination with a preliminary core or with no core specified. While the functionality is the same, the effort and possibly the result can differ tremendously. Evaluating complete processes with only one module exchanged at a time would cause more precise results but at the same time increase the number of alternatives to be examined, which would not be sufficient enough.

The assessment of main paths represents a good trade-off between taking the interactions of the tools into consideration and temporal expenditure. During the assessment process, the performance of the main paths is determined in a preliminary step (Fig.) before a complete process is assembled incorporating the process durations.

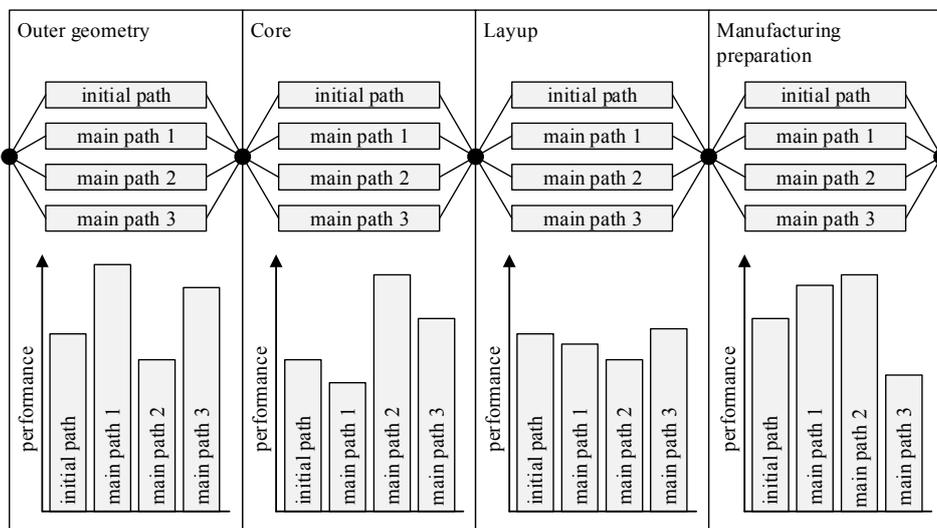


Fig. 7 - Evaluation procedure for main paths

The main paths are compared to initial paths which represent a very basic PEP. For the outer geometry, the initial path simply implies that the preliminary design of the outer surface remains unchanged. For the core, the initial path embodies a global core with constant wall thickness using a 1 shell discretization. The initial path of the layup contains a quasi-isotropic layup whose thickness is increased until the stress and stiffness requirements are fulfilled. The initial path of the manufacturing preparation is equivalent to the main path M_M01 (see table 2) apart from the body design which is solely performed in CATIA.

The evaluation criteria are based on the individual objectives of each stage. For this matter requirement specifications for each stage are formulated with demands that must be met by the main paths and requests which represent the performance criteria. The main paths are each awarded 1-10 points corresponding to their improvement relative to the initial path with 10 points for the highest performance and 1 for the lowest performance accordingly. Since stiffness enhancements do not have to be bought dearly with increasing weight during the outer geometry stage, the main paths are judged on torsional stiffness. The objective of the core stage is to increase the stiffness without disregarding the weight. Therefore, the main paths of the core stage are evaluated on their stiffness-to-weight-ratio. The stage layup aims to reach the target stiffness at a minimum weight by additionally producing a good manufacturability. Before specifying evaluation criteria, it has to be determined how manufacturability can be quantified. For this purpose, a *manufacturing parameter* F is defined, which rates the manufacturability depending on the size of the part, the sizes of the plies, the number of plies and the distortion angle. The distortion is evaluated based on drape simulations with *Fibersim*. For each ply, the highest distortion angle is judged with an evaluation scale taking into account the angle at which a material wrinkles. The size of a ply is rated based on how well a ply with the respective size is manageable. This consideration is premised on individual experience in prototype construction.

The pursued approach includes determining the total area of plies to be placed. This area will be divided by the classification of ply sizes. Hence, the number of plies will be considered high, if the respective part is manufactured solely with very small plies and vice versa. Equation 1 (Eq 1.) shows the definition of the *manufacturing parameter* F. The manufacturability is regarded better, the higher the parameter is.

F: manufacturing parameter
 E_n : evaluation: number of plies
 n_{plies} : number of plies
 E_A : evaluation: size of plies
 E_γ : evaluation: distortion of plies

$$F = E_n * \frac{\sum_{n_{plies}} (E_A * E_\gamma)}{n_{plies}} \quad (1)$$

The stage layup is finally evaluated on the criteria *mass* of the part and *manufacturing parameter*, each weighted 50%. The stage *manufacturing preparation* is rated depending on the quality of the plybook. To determine the quality of a plybook, a requirement specification is created and its requests weighted with a ranking method. The *plybook quality parameter* P is composed of the sum of met criteria multiplied with their weighing factor.

RESULTS

The full PEP is shown in Fig. 8. (upper picture). In an exemplary manner, the modules 2.2, 2.3 and 2.4 are shown in greater detail (picture below).

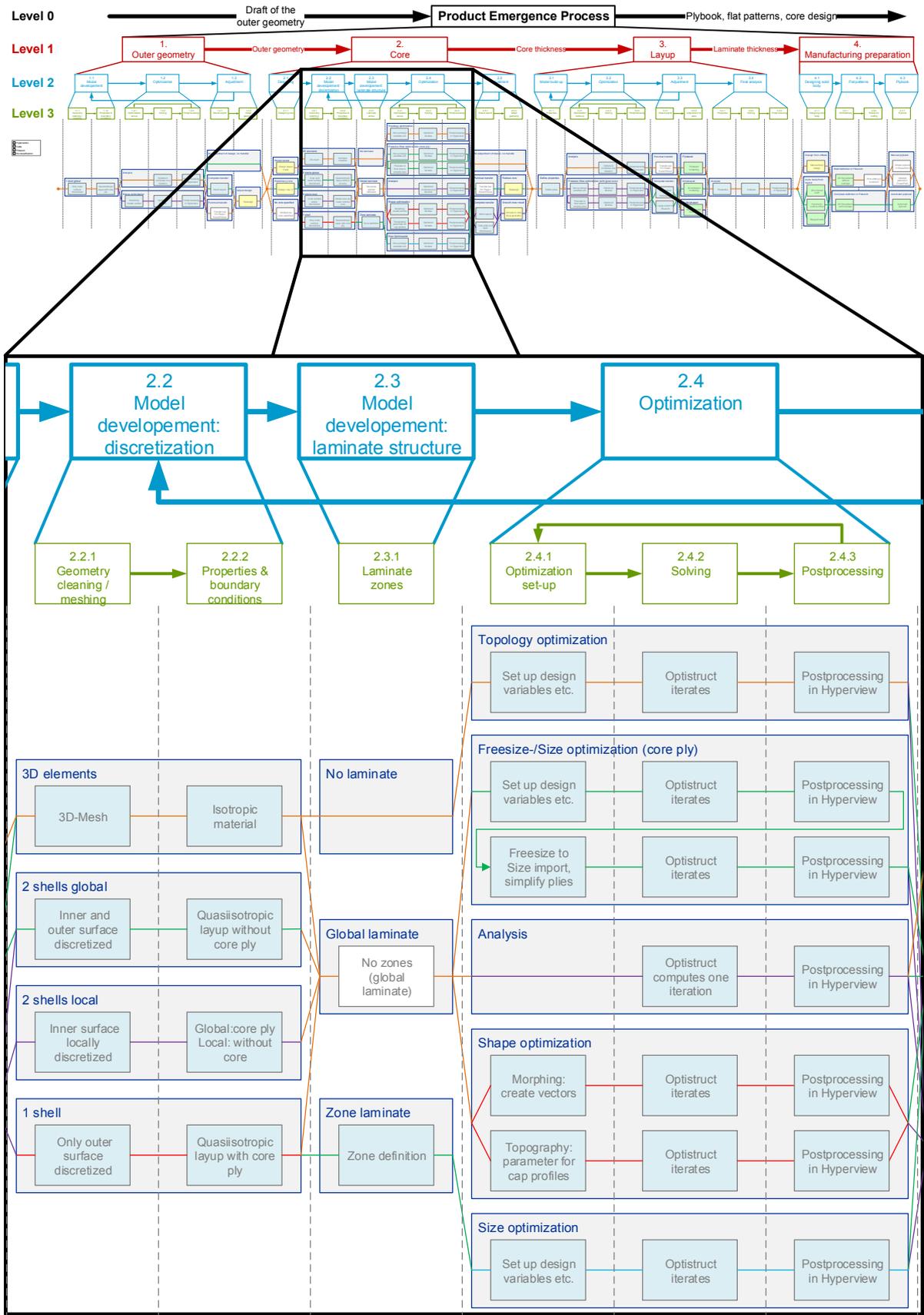


Fig. 8 - Developed PEP with four major levels, here: detail of the core design

The evaluation scheme produces the following results for the main paths. The table illustrates the discretization, performance, duration and efficiency of all main paths.

Table 3 - Main path of all stages

Main paths	Discretization	Performance	Duration [h]	Efficiency $\left(\frac{\text{Performance}}{\text{Duration}}\right)$
Outer geometry				
O_M00: <i>Initial path outer geometry</i>	1 shell	1	9	0.11
O_M01: <i>Analysis</i>	1 shell	10	14	0.71
O_M02: <i>Shape optimization</i>	1 shell	10	13	0.77
Core				
C_M00: <i>Initial path core</i>	1 shell	1	0,5	2
C_M01: <i>Analysis</i>	1 shell	2	5	0.4
C_M02: <i>Freesize/Size optimization</i>	1 shell	7	12	0.58
C_M03: <i>Size optimization</i>	1 shell	1	6	0.17
C_M05: <i>Analysis of optimized topology core</i>	3D	10	28	0.36
C_M06: <i>Topology shape optimization</i>	3D	1	31	0.03
C_M07: <i>Shape optimization</i>	2 shell local	3	2,5	1.2
Layup				
L_M00: <i>Initial path layup</i>	1 shell/2 shell/3D	5.5	7,5	0.73
L_M01: <i>Analysis</i>	1 shell/2 shell/3D	6.5	8,5	0.76
L_M02: <i>Freesize/Size optimization</i>	1 shell/2 shell/3D	9	10,5	0.86
Manufacturing preparation				
M_M00: <i>Initial path manufacturing preparation</i>	-	3	5	0.6
M_M01: <i>Brief laminate definition</i>	-	9	6.5	1.38
M_M02: <i>Complete laminate definition</i>	-	8	5.5	1.45

For every stage of the process there is a most performing and a most efficient main path. The main paths with the shortest duration is always the initial path.

For the *outer geometry*, the main path O_M01 and O_M02 have the highest performance but not the shortest duration. The main path with the best efficiency is O_M02 *shape optimization*, because the user can quickly iterate shapes of the geometry. Even combinations of different shapes can be investigated automatically. To successfully and quickly execute the mentioned paths, some software and morphing skills of the user are required.

The *analysis of the optimized topology core* (C_M05) has the highest performance for the core stage. The discretization with 3D elements and the possibility to optimize the layup of the inner mesh/geometry in the next stage assures a high accuracy. On the other hand, this discretization takes a lot of modelling time which results in a semi efficient process. The most efficient main path is the C_M02 *freesize/size optimization*. The accuracy is a little bit lower but still good and the speed of this two-step optimization method is tremendous.

In the *layup* stage, the *freesize/size optimization* (L_M02) is not only the main path with the highest performance, but also the most efficient one. Finding the right optimization

parameters requires some experience, but leads to a very light part in a small amount of time. An integrative simulation by coupling the structural with the process simulation in form of a drape simulation can be used to reduce the deviation of fiber orientations between the digital and the real part.

In the stage *manufacturing preparation*, the main path M_M02 *complete laminate definition* is the most efficient one due to an automated tool within *Fibersim*. The missing function of adding individual information to an automatically created plybook downgrades the performance of the main path M_M02, so that the *brief laminate definition* (M_M01) achieves a higher score.

The information about performance, duration and efficiency of all tools can be used to assemble a customized PEP. The durations of the main paths can simply be summed up. The following diagram (Fig.) illustrates exemplary three different total paths through the whole PEP which concentrate on different goals: A fast process, an efficient process and the best performing process.

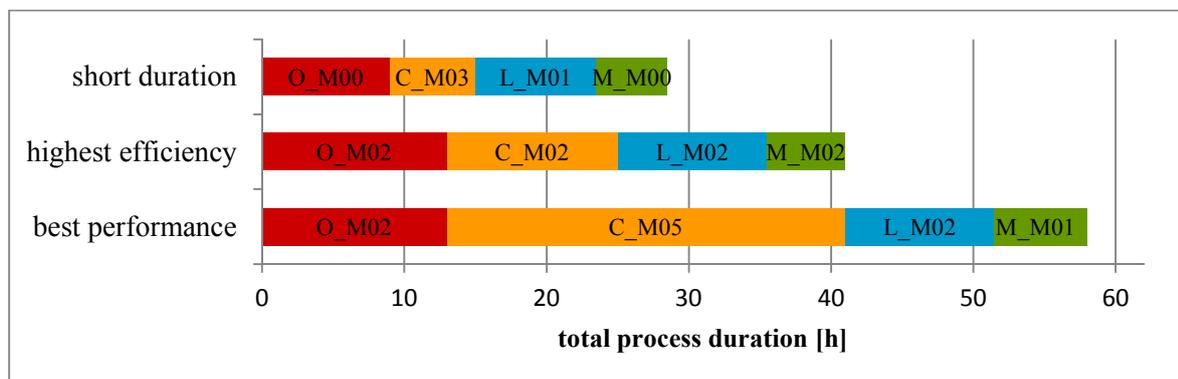


Fig. 9 - Exemplary PEPs

CONCLUSIONS AND OUTLOOK

The previous results have shown that a generic PEP for sandwich composite parts is feasible and that it can help to quantify and assess several design steps before the development starts. The example of the *manufacturing parameter F* has shown, that an experience based indicator is a way to quantify and consider subjective facts like the manufacturing within the compilation of a PEP. In order to prove the approach and validate the figures the example of a generic monocoque was used and lead to three exemplary PEPs with different objectives. With this information an evaluation, whether a sandwich composite part is an alternative to existing parts or structural components is possible. The potential of estimating the development time in advance and the gained benefit in regard of weight saving can lead to a significant cost reduction due to the avoided design of inefficient composite parts.

However, the presetting regarding the used software and hence the limited timeliness of the data lead to a constricting framework. Thus, the results reflect the current state of the art under the given restrictions and do not claim to be exhaustive. But it allows an organization to store and pass on experience regarding the development of sandwich composites and make decisions based on this information.

Future research will focus on the data management system and the possibility to attach META-data to every module in order to generate a preliminary PEP by implementing the CAD-Data into a PDM-System.

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