Feasibility study on time saving potentials of automated workflows in the early design stage of bus body structures

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Abstract

The huge variety in the commercial vehicle segment leads to an enormous amount of work during the development process as structural components or assemblies like bus body structures have to meet the requirements of different vehicle variants. In this case automated workflows provide an option to connect individual process steps and to accelerate development times. A segmented bus body structure is used to allow an easy representation of variants for structural simulations and to simplify the overall problem for a topology optimization. A feasibility study is conducted to investigate the time saving potentials of an automated workflow considering the total process time as well as required man-hours. Additionally, the break-even point of this method is determined.

Keywords

Product Design, Automated Workflow, Bus Body Structure, Topology Optimization, Variety Management

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| DOI: 10.35199/dfx2023.07

1. Introduction

Since many products are used in different application areas, they are often offered in multiple variants to meet specific requirements in the best possible way. During the development process, it must be ensured that each variant fulfills these requirements and complies with applicable boundary conditions. When developing variants of structural components like bus body structures, it is particularly important to investigate whether they withstand the various loads that can occur during their use phase. Before prototypes are built, this is usually done by structural simulations using the finite element (FE) method, whereby a corresponding FE model must be built for each variant, being a time intensive process [1, 2]. In addition, the effort even increases if the development of common parts for different variants is intended for economic reasons. In this case, common parts must be validated with regard to the loads of all variants. If a structure does not meet the requirements, it needs to be modified before a new FE model is built and a new structural simulation is performed. This iterative process is repeated until the structure withstands all loads. If these recurring process steps are performed manually, this leads to large efforts and long development times [3]. For a more goal-oriented development process, tools such as topology optimization can be used at this point to identify the load paths within a given design space to create a basis for further development steps [4]. However, in this case the different variants must be taken into account as well, which also leads to recurring tasks during the preparation of such optimizations.

For this reason, there is great interest in automating these recurring tasks to reduce development times as well as development costs and to make the entire process significantly more efficient. In addition, the development process becomes more dynamic, to be able to react quickly to changing boundary conditions, which particularly occur during the early design stage.

2. State of the art

2.1. Automation during the product development process

The product development process can be divided into the four main phases of clarification, conceptual design, embodiment design and detail design, whereby the product is continuously refined and revised in an iterative process [5]. The greatest amount of design freedom exists during the early design stages. In order to ensure the functionality of the concepts as early as possible during the individual phases, FE simulations are commonly used for structural simulations to evaluate their mechanical behavior [6].

To automate recurring tasks like the generation of FE models or the setup of optimization models, different approaches are described. De et. al. make use of Python scripts to build a parametric optimization model to reduce the mass of a truck chassis. The wall thicknesses of the longitudinal beams are varied in sections and corresponding FE models of the truck chassis are automatically derived in order to determine its stiffness and bending frequency. [3]

Schwinn, on the other hand, utilizes a toolbox based on the Ansys Parametric Design Language to generate geometries and meshes for FE Models of airplane fuselages. He is pointing out the advantages of parametric and automated tools to evaluate various concepts "[…] in a fast and efficient way". [1]

Herrmann et al. as well as Li et. al. describe the so-called generative parametric design approach (GDPA) to adapt existing designs to new requirements or to create product variants. In this case, product structure and model structure are separated and product models are assembled from various design elements stored in a library with each of them being parametrically adjustable. Compared to solely parametric models, it does not only allow the scaling of features by modifying parameters, but also changing the topology by exchanging design elements. This model can be embedded into an analysis-synthesis-process and linked to an optimization algorithm. Thus, it is allowing the representation of more variants and the exploration of a wider design space. [7, 8]

2.2. Bus body structures

As buses can be used in a very wide field of different application areas with each of them having special requirements, bus body structures are produced in numerous different variants. The configuration of city buses is massively influenced by the intended application area. Depending on how many passengers have to be transported on certain routes, how frequently stops are approached and how narrow or twisty the travelled streets are, city buses can have various lengths, wheelbases and axle or door arrangements, for example. [9]

These characteristic features must be considered for the load bearing bus body structures, also known as bus frame structure or superstructure, which are nowadays predominantly assembled from welded square tube profiles and sheet metal parts [10]. Only few components mainly in highly loaded areas are manufactured by casting or milling.

3. Research problem and objective

Because development steps have to be run through repeatedly during the development of components with a large number of variants, a manually executed process leads to long development times. Therefore, the use of automated processes is desired at this point. In preliminary or detailed design stages, in which concepts are getting more and more detailed and refined, the use of scripts for example is established to automate recurring activities such as the creation of FE models as much as possible. In this case, characteristic features and properties of the structure are already fixed, so that an automation can be developed and applied according to them.

During the early design stage, however, in which only few design restrictions exist and in which innovations shall be made possible, automation is more difficult to implement. In order to be able to investigate disruptive solutions, the automation must be flexible enough to allow the handling of unusual structures and should also restrict the solution space as little as possible.

Therefore, an automation approach similar to the GDPA is applied on an example of different bus body structures during the early design stage. Thereby the following question arises:

- Which impact has an automation during the early design phase on the development process of bus body structures?

It is assumed that in addition to time savings, automation can also open up a wider solution space.

4. Approach and Methodology

A feasibility study is conducted to determine the time saving potentials by the application of automated workflows on a variety of bus body structures. For this purpose, the software Synera is used, which offers a low-code platform to create automated, algorithm-based workflows. It allows to connect the required tools for various development steps like FE simulations or topology optimizations, avoiding manual data conversions between them [11].

For the feasibility study, exemplary 10 variants of different bus body structures are considered, covering the range of 10 - 14 m long solo city busses with two or three axles and different door arrangements. In this case, the structure in the lower area of the sidewalls shall be optimized for a lighter and commonly suitable design.

4.1. Segmentation

Similar to the GDPA the models are split into segments along the longitudinal vehicle axis according to recurring structural features, although the segments are not parametrically adjustable in this case. As described by Herrmann et. al. product structure and model structure are separated from each other [7]. This means that the product does not necessarily need to be assembled from segments, but it might be an option if desired. On the one hand, segmentation allows to represent different variants with very little effort by combining these segments. It also simplifies the comparison of concepts as only certain segments can be modified and exchanged in the model of the overall bus body structure. On the other hand, segmentation divides the bus body structure as an overall problem into several subproblems that can be solved easier [12].

4.2. Automated Workflow

The automated workflow is split into two phases (Figure 1). The first phase is used to evaluate existing concepts and to generate data for the second phase. During the second phase the optimization of certain segments is performed.

Segments are stored in a library in form of CAD models a) to be imported into the automated workflow. The bus body structure in this example is primarily built from square tube steel profiles and is reduced to its main structural features as this is sufficient during the early design stage. Mesh settings can be defined by the user.

In this case, profiles are represented by their midsurfaces and meshed with 20 mm first order quad elements while for a few volumetric bodies a first order dominantly hexahedral mesh is used. Thus, the FE models of the 10 bus body structures contain about 250.000 to 330.000 nodes each. The material behavior is described by a linear-elastic model.

The meshed segments are automatically assembled to FE models for various bus body structures b) according to a user-specified configuration. Multiple configurations can be set at once which are seamlessly processed one after another by the automated workflow. The load cases to be analyzed are stored in a database and are pre-selected by the user. Four linear static load cases are simulated for each variant during this feasibility study. Areas in the CAD model on which forces, supports or point masses have to be applied are automatically identified by the workflow. To ensure that this process step works reliably for all kind of segments and variants, reference points are systematically named and surfaces colored within the CAD model before they are stored in the library. Freeze Contacts are automatically generated between adjacent parts depending on their shell thickness and the gap size. After completing the solver run, results of interest are automatically evaluated and summarized with supplementary graphical representations in a report.

For the second phase, the user has to define a design space within the CAD model of the segment to be optimized. The optimization can be performed on an entire segment or only on certain areas. The loads acting on this specific segment are automatically extracted from the result files of the first phase for all corresponding variants and installation positions to be then projected on one optimization model c).

A topology optimization using the solid isotropic material with penalisation (SIMP) method is performed aiming to minimize the compliance while keeping a volume fraction of max. 30%. Consequently, a common structure for different variants and installation positions is obtained d). In the next step, the amorphous structure generated by the topology optimization needs to be manually transferred into a manufacturable design by the engineer e).

Finally, the optimized segment can be stored in the library as well. Due to the segmentation the original structure can be easily replaced by the optimized one to run through the first phase again f). Thus, the mechanical behavior of the new structure as well as the effect on its surroundings can be evaluated.

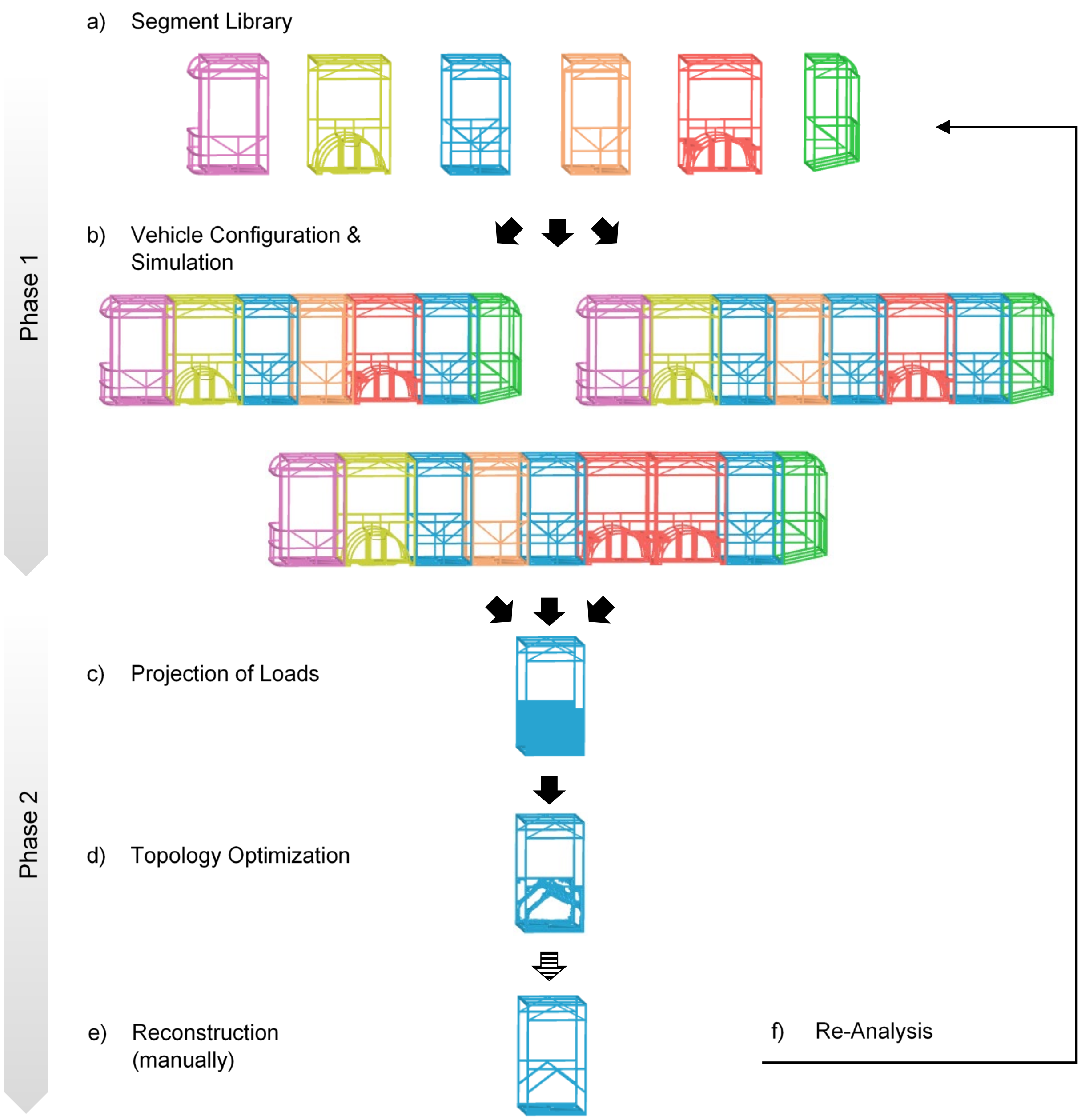

Figure 1: Main steps of the automated workflow applied on bus body structures (exemplary illustration)

4.3. Determination of time saving potentials

To identify the time saving potentials for the considered use case, the time requirements by an automated workflow are compared to the conventional process. Additionally, the break-even point of an automated workflow is determined. The comparison is differentiated according to individual process steps to get a detailed view on strengths and weaknesses of each method. The different process steps for the first and second phase are summarized in Table 1 with a list of included tasks for each step. Tasks printed in bolt letters are performed manually.

Following assumptions regarding the comparison are made:

- For both methods the CAD models of the various segments already exist.
- The time requirements for mesh generation and solving the FE model are considered identical for the automated workflow and the conventional process as the same models are compared and these steps are automated in both cases.

- During the conventional process only the first FE model is built up from scratch. The FE models for the remaining nine variants are created by modifying an existing model, for example by cutting or duplicating parts
- During the conventional process the topology optimization is performed for each vehicle variant separately within the corresponding FE model of the overall bus body structure, as the manual extraction of the relevant data and the projection on one single segment is too time-consuming.

Table 1: Process steps of automated workflow and conventional process (manual tasks printed in bold letters)

Process steps		Included tasks	
		automated workflow	conventional process
Phase 1	Pre-Processing	▪ **Storing CAD models in library** ▪ **Coloring reference surfaces** ▪ **Preparing vehicle configurations** ▪ **Defining load cases in library** ▪ Assembling of body structures ▪ Meshing geometries ▪ Applying loads & supports ▪ Creating point masses, connector elements & contacts	▪ Meshing geometries ▪ **Applying loads & supports** ▪ **Creating point masses, connector elements & contacts** ▪ **Modifying model for other vehicle variants**
	Solver Run	▪ Solving FE model	▪ Solving FE model
	Post-Processing	▪ Capturing images of results ▪ Extracting values for displacements & eigenfrequencies ▪ Creating a report	▪ **Capturing images of results** ▪ **Extracting values for displacements & eigenfrequencies** ▪ **Creating a report**
Phase 2	Pre-Processing	▪ **Preparing a design space in CAD model of segment** ▪ **Selecting result file from phase 1** ▪ Meshing geometries ▪ Applying loads & supports ▪ Creating point masses, connector elements & contacts ▪ Optimization setup	▪ **Preparing a design space in overall body structure** ▪ Meshing of design space ▪ **Optimization setup**
	Optimization	▪ Topology optimization process	▪ Topology optimization process
	Post-Processing	▪ **Transferring result into manufacturable design**	▪ **Transferring result into manufacturable design**

The time requirements for the individual process steps are measured for the automated workflow. For the conventional and mainly manually executed product development process values based on experience are used for this feasibility study.

5. Results

The results are evaluated in terms of total process time on the one hand and on the other hand in terms of required man-hours. This differentiated comparison is of interest as for example tasks like solving an FE model are already automated and occur equally within the automated workflow and the conventional process.

The total process time is important in order to be able to assess how long it takes until results are available. Consequently, this also affects how fast individual iteration loops can be performed and how dynamically reactions to changing boundary conditions during the development process are possible. The required man-hours are of interest as they describe for how long one person is engaged in a certain process step impacting significantly the development costs.

It is important to note that the following values refer to the exemplary bus body structures considered in this use case and are not representative for other cases. Time saving potentials may vary depending on factors like the size of the FE model, the amount of connector elements, contacts and other features, the number of load cases as well as the number of vehicle variants.

Figure 2 illustrates the comparison of the total process time for an automated workflow and the conventional process according to the individual process steps. When comparing the total process time, the automated workflow leads to time savings of 84 %. Major time savings can be achieved by the automated workflow during pre- and post-processing as many tasks which are executed manually in the conventional process can be accelerated by automation. The time for the solver run is identical as it is already automized for both methods.

Regarding the second phase, segmentation allows to optimize a certain segment for all variants in an isolated model without surrounding structures. Firstly, this results in a smaller optimization model with less elements and a shorter calculation time in comparison to the conventional process, where the topology optimization is performed within the overall body structure of each variant. Secondly, the structure obtained from the automated workflow is commonly suitable for all variants and installation positions while the structures generated during the conventional process only suit one specific variant and installation position and need to be merged to a common structure by the engineer. The post processing of the second phase which contains the reconstruction process of the topology optimization result into a manufacturable design needs to be performed manually for both methods as mentioned before.

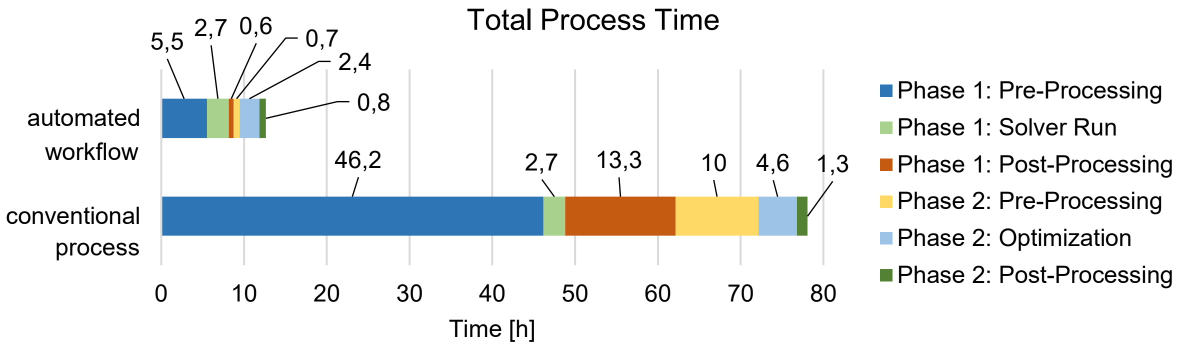

Figure 2: Total process time according to process steps for conventional process and automated workflow

The optimized structure obtained during this use case leads to a weight reduction of about 4,3 – 12,9 kg per bus body structure depending on the configuration while slightly improving the stiffness and maintaining the desired stress level.

Analyzing only the proportion of manual work, the automated workflow allows to reduce the required man-hours by even 96 % compared to the conventional process. These significant time savings are achieved since mainly preparational tasks like setting vehicle configurations and selecting load cases as well as reconstructing the optimization result need to be executed manually for the automated workflow (Figure 3).

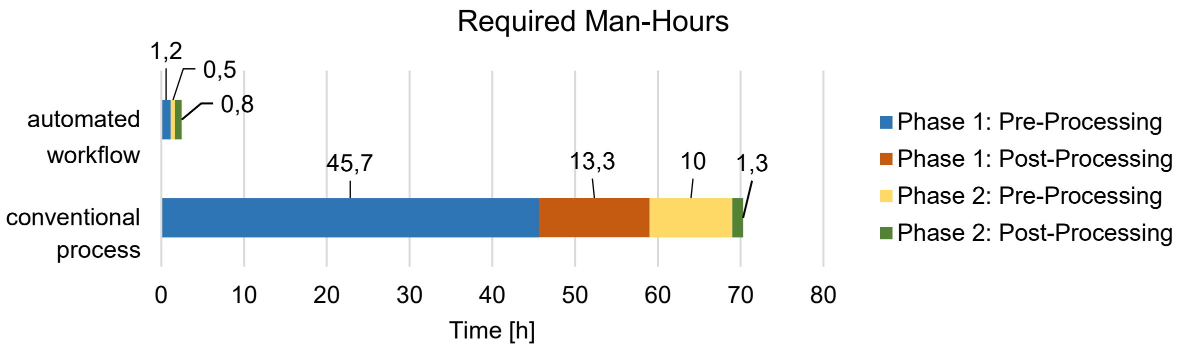

Figure 3: Required man-hours according to process steps for conventional process and automated workflow

Although significant time savings can be achieved by the use of an automated workflow, the development time of such a workflow has to be taken into account as well. For this reason, the break-even point of this method is to be determined. In this use case the development of the workflow takes about 500 man-hours. This value is not representative for other cases as well as it strongly depends on the range of tasks to be automized and their complexity.

The break-even point is determined based on the total process time and on required man-hours (Figure 4). Considering the total process time, the development of an automated workflow pays off after handling 77 variants or conducting 77 iterations. With regard to required man-hours the break-even point is reached after 74 variants or iterations.

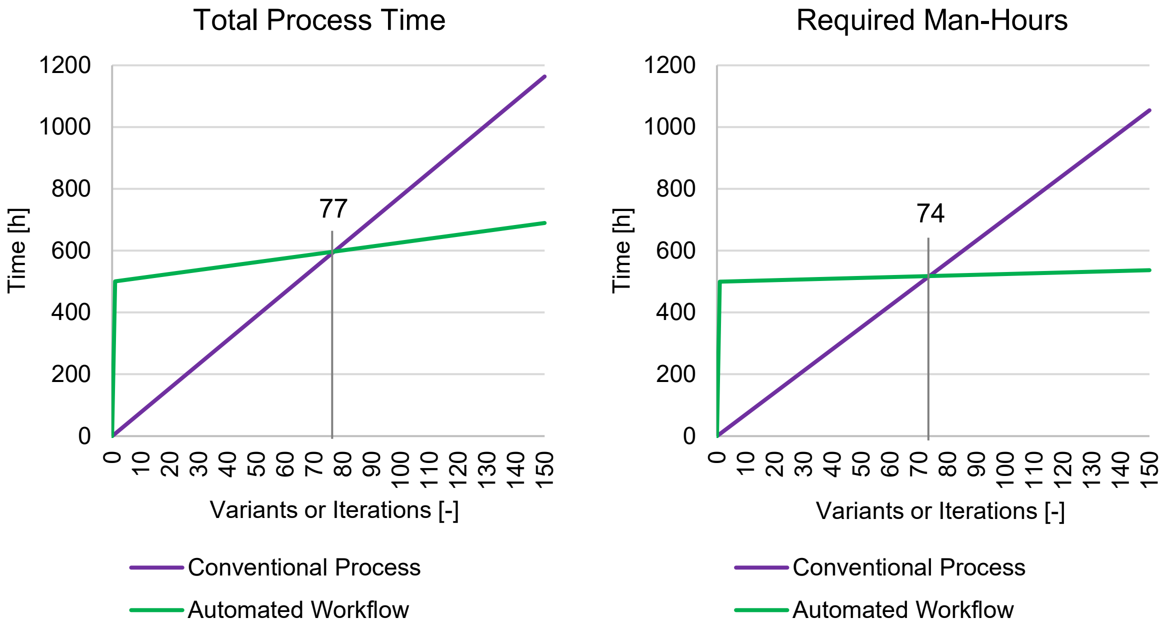

Figure 4: Break-even point for the automated workflow according to total process time and required man-hours

6. Discussion

The results show that the application of automated workflows during the early design stage of bus body structures lead to major advantages. Nevertheless, some downsides have to be discussed in the following as well.

First of all, the described method makes it possible for a wide variety of variants to be represented, calculated and analyzed by minimal effort due to segmentation, whereby knowledge about their mechanical behavior can be gained in a significantly shorter time compared to the conventional process. This is particularly important during the early design stage in order to be able to quickly calculate, evaluate and compare different concepts or variants and to draw conclusions. Overall, iteration loops can be shortened, which allows a more dynamic response to new findings or changing boundary conditions. In addition, the high degree of automation and the greatly reduced amount of manual work gives engineers the opportunity to focus on tasks such as creating concepts or evaluating results.

Secondly, the described method enables a very goal-oriented development process since segmentation directly promotes the generation of common structures for different variants during the topology optimization process. In comparison, the various results of the topology optimizations performed for each individual variant during the conventional process have to be merged into a common structure by the engineer himself. The result is then strongly depending on the engineer’s individual skill level and creativity. Consequently, a much wider solution space can be explored by the automated workflow as the designs are based on a computer driven optimization process and do not depend on the engineer’s creativity. Hence, better concepts can be generated as a basis for the following design process.

Thirdly, the high degree of automation and the reduced number of manual tasks in combination with the possibility to prepare simulations of numerous variants in advance which are processed automatically one after another allow the automated workflow to run without any additional input or breaks for multiple hours so it can be used even out of working hours. Thus, available computing capacities and software licenses can be used very efficiently.

Furthermore, a good comparability of the results is ensured as the routine executed by the automated workflow is always identical. A final advantage is the possibility to conserve expert’s knowledge in an automated workflow and to make it accessible to other engineers.

One clear disadvantage of an automated workflow is the high time invest for its initial development. Therefore, the use of an automated workflow only pays off if it can be used for a sufficient number of variants and iterations. However, once the workflow has been created, it can be reused in total or even only in parts for future developments, achieving significant benefits over longer periods of time. Moreover, the automated workflow can rather be seen as an enabler to evaluate more concepts in order to develop better products, which would not be realistically achievable in a manual process.

Another disadvantage of the automated workflow is that it always starts to assemble a new FE model based on the segments stored in the library, regardless how much of the structure was actually changed. The conventional process on the other side allows to manipulate only the affected areas of the FE model. FE models for similar variants can also be derived from each other by adaptations without starting from scratch. Nevertheless, there are still significant time advantages achieved by the automated workflow due to the much shorter process time compared to the conventional process.

On the one hand, segmentation of the overall structure offers some big advantages as mentioned before and may be an enabler to modularize products or even portfolios. But on the other hand, it creates a restriction that structures must be splitable into segments. This can be seen as a limitation, if this method shall be transferred to other application fields.

7. Summary and outlook

The feasibility study clearly shows that automated workflows can be profitably applied on products with numerous variants such as bus body structures during the early design stage. Considerable time reductions are achievable as recurring process steps like the generation of FE models can be carried out automatically. Consequently, the total process time can be reduced by around 84 % compared to the conventional process regarding the described use case. The required man-hours are even reduced by about 96 % due to the high degree of automation, which allows engineers to spend more time on developing concepts or evaluating results. It has to be noted that these values relate to the considered use case and are therefore not representative for other cases.

Moreover, a much wider solution space can be explored by such an automated workflow compared to a conventional process, allowing to generate better concepts as a basis for following design stages. However, automated workflows do not immediately lead to time savings as their initial development is time-consuming. Accordingly, the application of an automated workflow is only worthwhile, if there is a sufficiently large number of variants to be evaluated or iteration loops to be carried out.

The segmentation of the overall bus body structure makes it possible to represent a wide variety of variants with little effort in order to gain knowledge about their mechanical behavior and to compare concepts. In addition, segmentation of the bus body structure enables the development of common parts for numerous variants.

Using this method in other fields of application is possible and particularly suitable for structures that shall be composed of segments or can be divided into such. A transfer to the construction industry might be evident, with applications on bridges, industrial halls or multi-storey car parks, for example.

A further research need is seen in the area of production-oriented reconstruction for pipe structures or sheet metal constructions, as this step needs to be executed manually so far.

Acknowledgement

The author thanks MAN Truck & Bus SE for funding this research project. The statements and information in this publication do not necessarily represent the opinion of MAN Truck & Bus SE.

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