Geometry-Based Topology Optimization - Improving Head Impact Performance of an Engine Hood

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Summary:

The actual paper introduces the integration of LS-DYNA and CATIA V5 into automatic geometry-based topology optimization of an engine hood regarding pedestrian head impact.
In current design processes, such Computer Aided Engineering (CAE) tools, along with structural optimization, have become essential elements to provide efficient and reliable structures. However, the required iterative process of adjusting steps between simulation and design engineers is still a time-consuming task. In recent years therefore, automatic multi-criteria and multi-disciplinary optimization simultaneously considering different simulation disciplines have drawn increasing attention. For structure creation or topology variation, FE-based concepts have been developed working on a discretized design space, whereas geometry-based parameter variation on CAD models has been mainly used for shape and size variation.

Although being a first step toward design process automation, both concepts are a trade-off between accuracy and creativity. The final goal would therefore be to combine the topology variation ability of the FE-based method with the ready-to-use solution of the parameter concept.
Hence, extending the idea of parameter variation with the addition and removal of entire geometrical features, automatic topology variation on CAD structures is introduced. However, applying such geometry variation implies further considerations regarding a fully automated optimization loop such as accurate CAD build-up, update-stability, high quality batch meshing and a rapidly increasing number of free parameters.

The project this work is based on aims at full automation of a geometry-based optimization loop for optimum structure generation using CATIA V5 and LS-DYNA. The concept is applied to pedestrian safety considerations, analyzing different engine hood topologies regarding their head impact performance.
In a first step, parameter studies and simplified impactor load cases are run using the automatic CAD-FE loop as a pre-stage to a full multi-criteria optimization. The paper's focus is set on the concept's applicability to industrial processes. Hence, solutions regarding automated CAD-FE transition for evaluation are discussed as well as general limitations of CAD-based topology optimization. In particular the demanding task of batch meshing for varying topologies and sensitivity analyses to reduce the number of free parameters are addressed.

Keywords:

Structural optimization, geometry-based topology optimization, CAD, specification tree, Evolutionary Algorithms, pedestrian safety, head impact, batch meshing

1 INTRODUCTION

In nowadays industrial design process demands such as *first time right*, *efficient testing* and *concurrent engineering* are increasingly met by a shift from hardware to virtual verification and testing. Such digital mock-ups (DMU) reduce the number of costly hardware prototypes and enable economic concurrent simulation and flexible adaptation along the design process.

Using the benefit of such high flexibility, virtual structure optimization has become an increasingly addressed issue. The prospect of creating an ideal structure before the first hardware prototype is manufactured has yielded numerous simulation disciplines being applied to these DMU. However, such simulations still bear high time-saving potential as the required iterative steps between design and different simulation engineers are still mainly carried out manually. In recent years therefore, *automated* structural optimization has gained of importance. Further extensions are multi-disciplinary and multi-objective optimization to consider several requirements at the same time.

To perform automated structure optimization, a dedicated optimization algorithm as well as a suitable structure variation concept is needed. In the present case, Evolutionary Algorithms (EA) were chosen, providing a useful environment for such an optimization.

Regarding structure variation, two different concepts are available - both being a trade-off between creativity and accuracy or reusability. The *FE-based* method applies changes to a discretized design space, using little initial knowledge and therefore allowing for greater creativity. The drawback in this case is the necessity to rebuild the discrete solutions in CAD and uncertainties concerning material removal or addition [13]. Using already existing CAD models, *geometry-based* variation provides an alternative method, resulting in optimized ready-to-use CAD geometry. However, working on such knowledge-rich models greatly limits the search and solution space, rather allowing for shape and size optimization than structure creation. The choice has therefore to be made between *creation* of a rough initial draft, requiring transition to CAD (FE-based) and *improving* the shape of an existing CAD model by parameter variation (geometry-based).

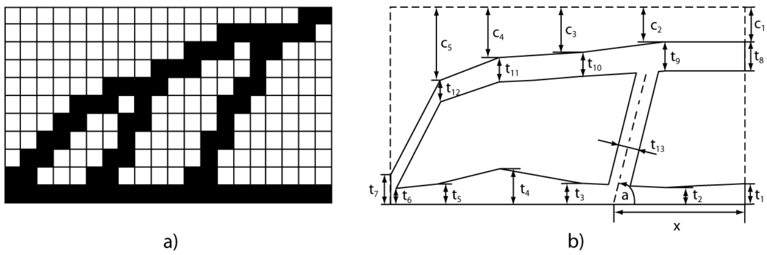


Figure 1: a) FE-based structure creation, b) Geometry-based structure variation [16]

The presented project is focussed on the geometry-based method. Exploiting its ready-to-use CAD solution and considerably extending the search space, feature[1]-based *topology* variation is introduced (section 3.1). However, including this method in an industrial optimization loop poses several additional difficulties concerning variation and evaluation.

To automatically vary a highly constrained CAD model, it has to be fully parametric-associative and therefore update-stable against any parametric changes. Additional topology variation through feature addition/removal increases update instability in history-based[2] CAD tools (e.g. CATIA V5) and needs particular attention.

In addition, automated high quality meshing (batch meshing) is still an unresolved task that needs to be considered in such an optimization loop. An according solution for parameter-based optimization using enriched CAD models has been described by [15]. However, with additional topology variation, an extended concept is needed.

In the following sections, we will introduce a new concept for geometry-based *topology* variation on complex CAD structures. Solutions to a fully automated optimization loop in industrial design processes will be provided especially considering CAD build-up and batch meshing. The presented optimization problem considers an engine hood sub-structure and its head impact performance applying LS-DYNA and CATIA V5. The case involves the application of the presented concepts to a

[1] A feature in CAD-context is an object that contains mathematical information (geometry), attributes (material) and associativity information (parents/children) [4].

[2] History-based CAD provides a history tree that stores relationships and parameters along with the creation order of each component created by the designer. Changes of a component propagate through the entire tree [8].

Design of Experiments (DOE) for parameter impact evaluation by automatically generating and evaluating a large number of varied engine hood sub-structures.

2 CASE OUTLINE

Pedestrian safety has become an increasingly important issue in vehicle design during the last few years due to an advanced testing routine added to the European vehicle authorization procedure[3]. The routine includes tests concerning lower leg, upper leg and head impact on the vehicle's front parts [3], Figure 2.

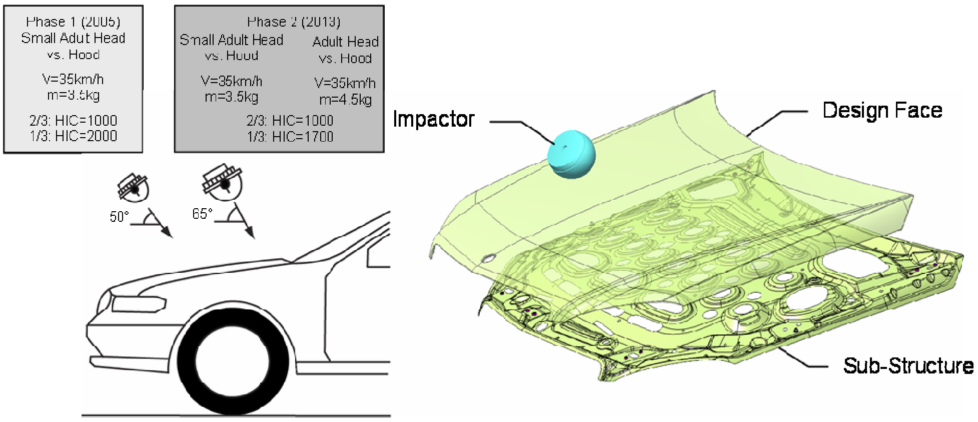


Figure 2: 2003/102/EC testing configuration and engine hood assembly with impactor

In the current project we focus on head impact on a *passive* alloy engine hood. The study case eventually aims at evaluating the new concept of combined topology and parameter variation in the context of multi-objective optimization. The preliminary study includes only a few specific impactor[4] points to reduce calculation effort. We assume that the outer hood regions have already been approved and use the variation process to evaluate according topologies and parameters for the selected impactor points (Figure 3).
The target value is a minimized Head Injury Criterion (HIC) lying well below 1000, which is derived from head deceleration simulations with LS-DYNA.

$$HIC = \sup_{t_1,t_2}\left\{\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)\right\} \tag{1}$$

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{2}$$

$[t_1,t_2]$ is an interval of ≤ 15ms, yielding the highest HIC value. *a* is the resulting acceleration of the impactor's centre of gravity, measured in *g* (9.81m/s^2) [2].

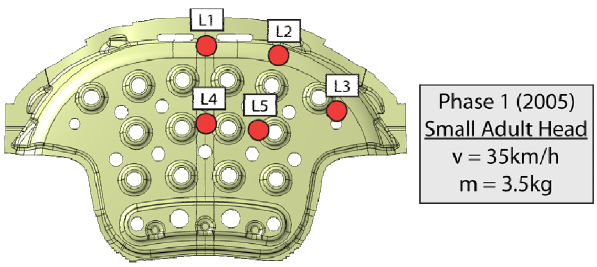


Figure 3: Parameter study load case

[3] Regulation 2003/102/EC [5, 1] amends directive 70/156/EEC introducing the entire test routine in two phases until 2010. Recently, the introduction of phase II has been postponed to 2013 [6].
[4] small adult head, 3.5kg, 35km/h

Commercial tools integrated in the loop are LS-DYNA (LSTC), CATIA V5 (Dassault Systèmes) and MEDINA (T-Systems). One of the major challenges therefore is reliable data interchange between these tools, including the mentioned FE information for high quality mesh.

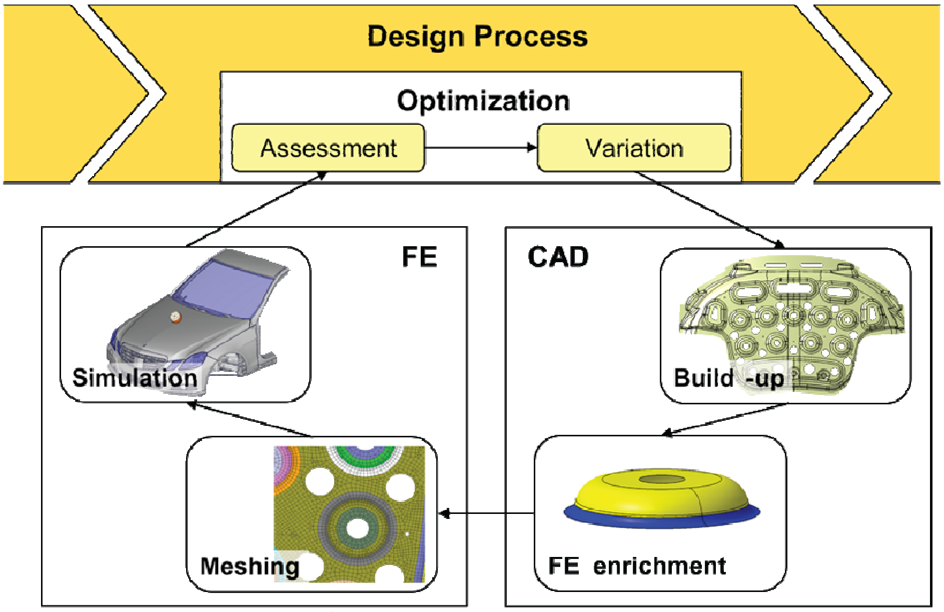


Figure 4: Optimization loop in design process

2.1 OPTIMIZATION ISSUES

Standard optimization methods usually operate on real-valued vectors of a fixed length. As long as geometry parameters apply to scalar measures such as lengths, radii, or angles, they can be directly mapped to optimization parameters suited for most algorithms. To a certain degree, even topology variation can be mapped to a fixed number of parameters [14, 11]. For more general geometry optimization, however, algorithms are required that allow for direct operation on the natural representation of the given problem. In the case of geometry-based optimization, graph representations are most suitable [9, 10, 11, 6], which cannot be processed by derivation-based mathematical methods. Order-based methods, e.g. Evolutionary Algorithms, however, have been shown to operate well on such non-standard representations [10, 7, 11, 12, 16].

3 CAD-BASED TOPOLOGY VARIATION

A prerequisite for geometry-based structural variation is an already existing parametric-associative CAD model that can be updated automatically after parameter changes. Since subsequent conversion of existing CAD geometry into such an update-stable model is usually a laborious task, the parameters required to cover the desired design space should be known and regarded during the creation of the initial CAD model.
With such an update-stable model, mere parameter variation is state-of-the-art and has been performed in numerous examples [10, 11, 7, 15]. The parameters in the CAD model (Figure 5) are adapted in batch via Excel sheets or simple Visual Basic (VB) script without changing the specification tree’s structure. Topology variation, however, is a major intervention in the structure's hierarchy and needs a more sophisticated approach.

3.1 Feature-Based Topology Variation

Generally, creation of a CAD model is done by aggregation, intersection and splitting of different basic geometric components – e.g. a perforated plate can be created by splitting the plane with corresponding cut-out geometries (Figure 5). Every such sub-component and operation of the entire CAD model, including its relations, appears in the corresponding CAD specification tree: single parameters become leaf nodes and geometric components are represented by single internal nodes or entire tree branches (Figure 5: `Sketch.3` or `Cutout.2`).
Feature-based topology variation benefits from this tree-shaped representation of CAD structures to easily retrieve components (features) of the CAD model. Such simplified access to structural

components enables addition or removal of specific features, extending the original pure parameter optimization to a combined parameter and topology optimization. As a result, the previously mentioned disadvantage of highly restricted shape optimization of geometry-based approaches is mitigated. The search and solution spaces are considerably widened by the newly introduced topology variation.

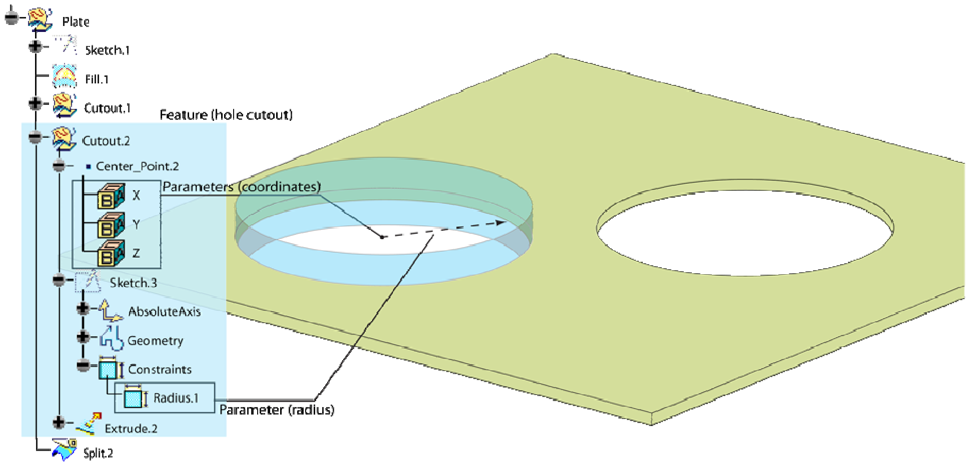


Figure 5: Features and parameters in CAD specification tree

However, insertion of entire sub-branches into the specification tree frequently causes substantial changes of inter-structural dependencies. New associativities have to be created along with intersections and sequential topological operations. Hence, a dedicated procedure is needed to perform such operations yielding a valid and update-stable resulting CAD geometry. For such an automatic CAD build-up, two basic approaches can be distinguished:

- incorporating the entire CAD build-up knowledge into an external algorithm
- dynamically acquiring the internal CAD knowledge provided by the specification tree

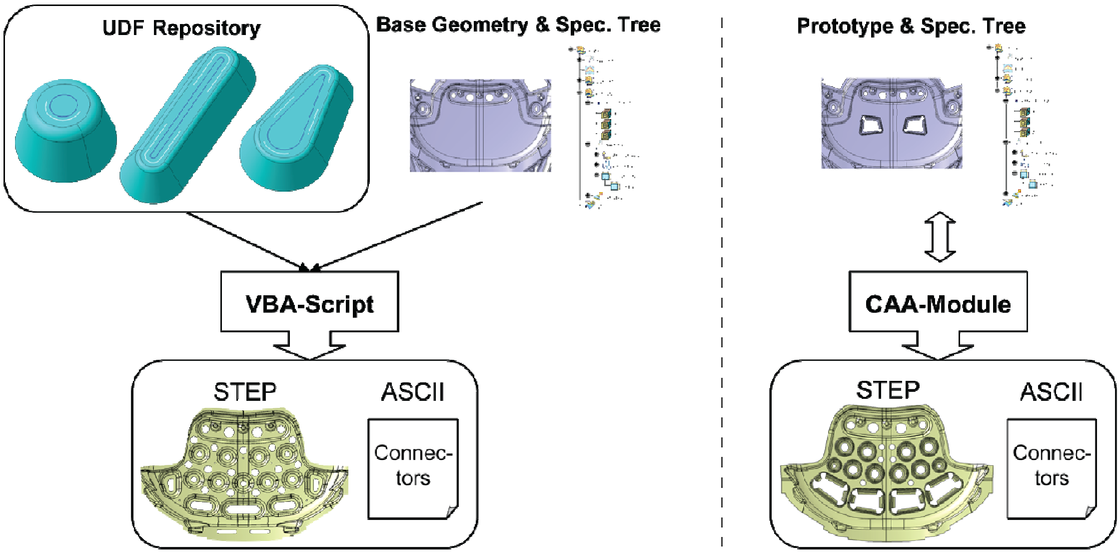
These concepts allow for efficient automatic topology variation on CAD structures, however, they are both a trade-off between generality in application and ease of maintenance.
Although only the first concept was used in the actual study case, both concepts have been implemented and will be shortly described.

3.1.1 Incorporated Knowledge

This approach requires a dedicated algorithm adapted to specific variable geometric components and containing the entire build-up knowledge [11]. The idea is to implement manual CAD design steps, e.g. in VBA, and thus virtually automating manual geometry build-up. Figure 6 a) shows the principle using predefined User-Defined Features (UDF) for variable components and CATIA's VBA scripting language to insert these components into the specification tree, i.e. the CAD structure. The algorithm instantiates the UDF as many times as required and updates their relations and operations including them into the base geometry. VBA is comparatively easy to maintain and therefore most suitable for corporate use where different engineers may apply and adapt the implemented tool. Its drawback, however, originates from the 'hard-coded' knowledge. As the build-up procedure is specifically designed for the actual CAD model and its predefined variable UDF it has to be adapted every time a different CAD geometry is processed.

3.1.2 Dynamic Knowledge Acquisition

Realizing that the entire build-up knowledge is already given by the historically structured CAD specification tree of CATIA V5, a more general approach can be derived. With the knowledge left in the CAD model, the algorithm triggering the CAD variation can be implemented in a rather general way. The specification tree is not only used anymore for simple geometry access but also to interactively extract needed build-up information and relations to correctly insert the instantiated variable features. Such a hybrid approach requires closer collaboration with the CAD tool, which is granted for CATIA V5 by the CAA RADE interface. As a result, the algorithm contains no hard-coded knowledge proper to only a specific optimization problem. Thus, it is applicable to a great variety of CAD structures without any additional adaptation [16]. In this case, however, a grave drawback is the necessity of a complex programming language (CAA), requiring expert knowledge and expensive software environment even for smallest adaptations.



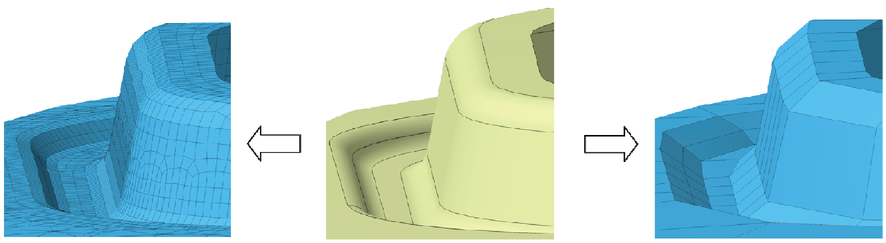
a) b)

Figure 6: CAD build-up - Incorporated knowledge a) and interactive knowledge acquisition b)

In the current case study, the *incorporated knowledge* concept has been used in combination with a layout assistant as described in section 5. The varied features are pot-shaped entities inserted into the engine hood sub-structure.

4 BATCH MESHING

Automated high quality meshing is still an unresolved task in industrial design processes. Nevertheless, such batch meshing is indispensable for any optimization loop to evaluate the newly generated CAD geometry. The difficulty in nowadays commercial meshing tools is their unreliability in completely detecting specific geometric entities and missing general criteria for mesh quality evaluation. An approach is therefore to provide enough geometric information for the meshing tool to reliably detect corresponding features and areas using *enriched* CAD models. The idea is to predefine separate meshing areas by already dividing the according CAD geometry into different partitions. Such areas allow to apply specific local mesh properties, e.g. to prevent unwanted shape simplification.



a) b)

Figure 7: Individual meshing properties a) and shape simplification due to global rough mesh b)

Hence, in the actual case, an additional task performed by the CAD build-up algorithm is the allocation of the resulting geometry's faces to according mesh areas for 2D meshing.
For simple parameter variation, i.e. static topology, such parametric-associative face compounds can be predefined during the optimization problem set-up. These compounds are automatically adapted to parameter changes and provide the according face partitioning [15].
With the newly included topology variation, such static groups loose their purpose. Hence, concepts for feature detection and dynamic group retrieval during CAD build-up have to be introduced. An according approach can be derived from the presented concept of topology variation using UDF instantiations. In addition to the geometry UDF, specifically partitioned face features are previously

defined to be inserted along with their standard geometrical counterparts. These entities are equally immersed into the base geometry and adapted to accurately represent the final geometry. The resulting geometry is a partitioned facial representation of the topologically varied CAD structure (Figure 8, a)). The faces are grouped according to their represented geometric feature and the mesh properties to be applied.

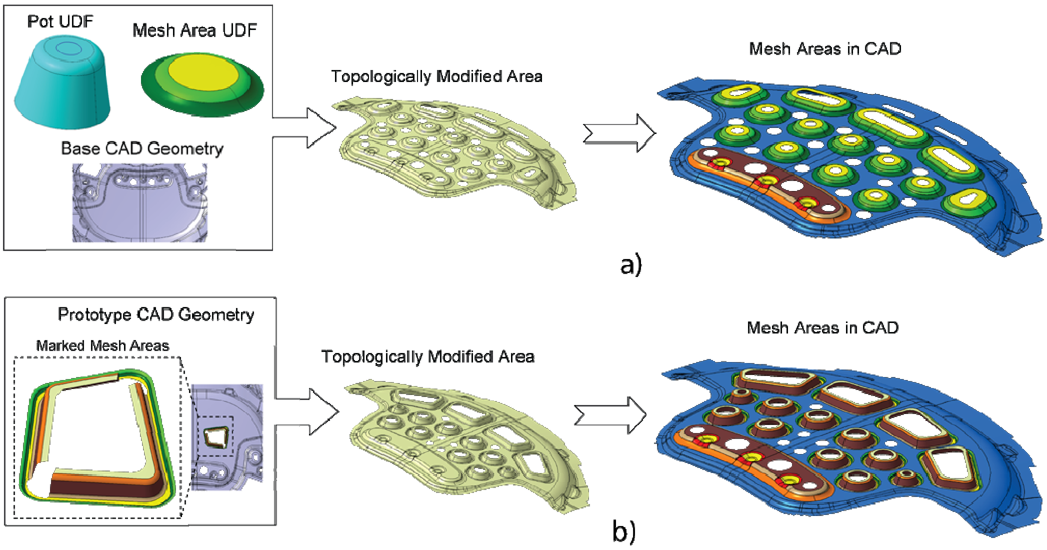


Figure 8: UDF-based a) and Filter-based b) FE-view generation

The major disadvantage of such an approach is the time-consuming and intricate preliminary build-up of the supplementary adaptive face UDF. Thus, in addition to the according geometry UDF, for each new variable feature type, an according face UDF has to be provided. This approach further contributes to the algorithm's optimization problem dependency.

An alternative is again provided by the CAA RADE interface of CATIA V5. Returning to the idea of *dynamic knowledge acquisition*, a corresponding concept can be derived for face retrieval and grouping. Prior to the optimization run, the user composes the desired groups by interactively selecting the corresponding faces on the prototype CAD geometry. The idea is to include face partitioning directly into the geometrical entity to be instantiated. During later topology variation, i.e. instantiation of the variable prototype features, according similar faces are collected via the generated filter and grouped (Figure 8, b)).
Due to such a non-UDF-based approach, this method is less problem-specific and thus again more general in its applicability. However, although no face templates are necessary anymore, the filter build-up and subsequent internal information retrieval still require pre-processing effort and a dedicated supporting CAA algorithm. Therefore, requiring again CAA knowledge to maintain such a module, this approach is hardly suitable for widespread corporate use. It may rather be a suggestion to extend CATIA V5 functionality with a new interface for CAD enrichment. The advantage in this case being less pre-processing effort, increased generality in application, and the use of already existing (internal) knowledge for CAD enrichment.

With the addition of the FE view to the CAD model, such enriched geometry can easily be exported via STEP format. The face groups can be retrieved through specifically named geometrical sets by any meshing tool supporting this format. In the actual case T-Systems' MEDINA is used for batch meshing. Assigning the named groups to separate mesh areas and applying dynamic MEDINA protocols for a variable number of these areas, high quality mesh generation is ensured.
Connectors (spot welds and glue lines) are considered in a similar way. In CAD, according UDF are inserted to explicitly hand over their information to MEDINA.

To reduce meshing time in the current project, varied and static geometry are separated. As only the inner part of the hood's sub-structure is altered, the according area is automatically cut out, varied, re-meshed and inserted into the hood assembly. For FE analysis, the assembly is further on included into the supporting vehicle front via the LS-DYNA include file framework. Thus, high flexibility is achieved allowing for variable head impactors and positions, material (aluminium or steel), and the mentioned independent hood geometry variation without any manual intermediate steps.

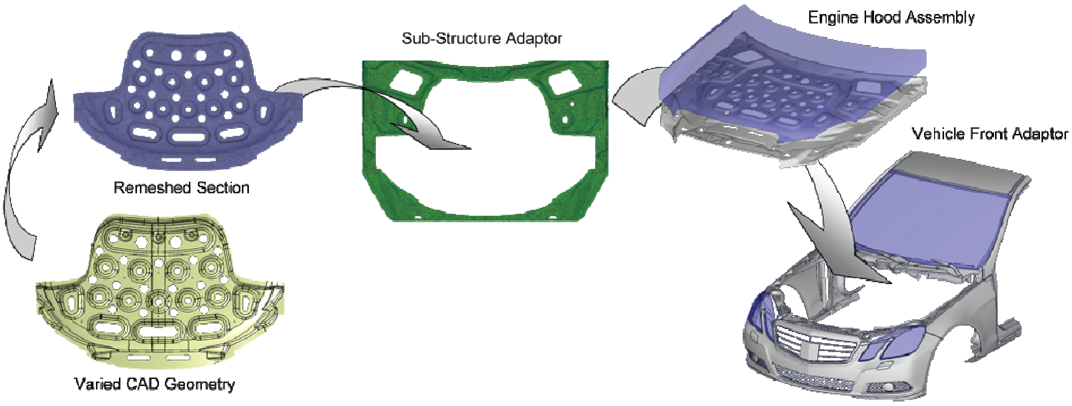


Figure 9: Partial re-meshing and inclusion into reduced FE vehicle model

5 OPTIMIZATION PROBLEM SET-UP

Having defined the process automation framework, the parametric-associative CAD model for the actual optimization problem can be set up. In this section, we suggest an according approach to cover a largest possible search and solution space while keeping the free optimization parameters at a minimum. These parameters can be divided into *shape-* and *topology-relevant* values according to their impact during optimization.
We define a simple circular pot entity as variable feature to be distributed in a predefined area of the engine hood sub-structure (Figure 10, red border). Each pot carries two shape-relevant parameters to be varied during optimization (radius R_p and inclination α). An additional *global* parameter is added to the CAD model to vary the distance between sub-structure and hood, i.e. to control the height of the pots.

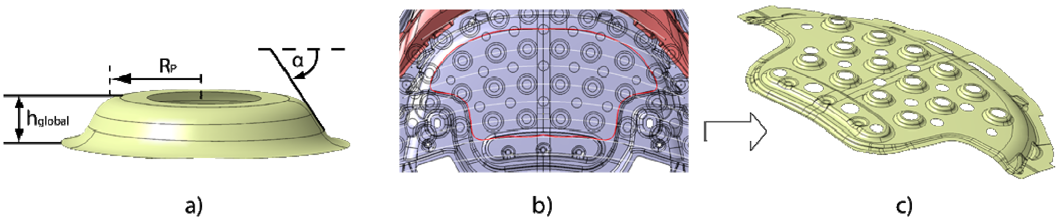


Figure 10: Free parameters a) and CAD build-up after pot exclusion through layout assistant b), c)

To vary the number of pot entities, a layout assistant is added prior to the CAD build-up process. In a first step, the variation algorithm generates new parameter combinations, influencing both shape and position of each variable geometric entity and stores the values in an XML file. Before the actual build-up is started, the entities are pre-processed by the layout algorithm to merge or ignore certain topological features. Hence, the number of variable features is not controlled in the first step (the actual variation algorithm) but by subsequent merging of intersecting features or by neglecting features on or outside a given 'border' of the considered area. Hence, position parameters become *topology-relevant* entities.
The intermediate layout stage is crucial for strong causality in optimization. The variation/optimization algorithm will always 'see' the same amount of features. Rather than suddenly disappearing, the features are continuously moved around the design space. The final build-up stage will nevertheless receive a varying number of components due to the intermediate layout module merging or deleting them according to the mentioned criteria (Figure 11).

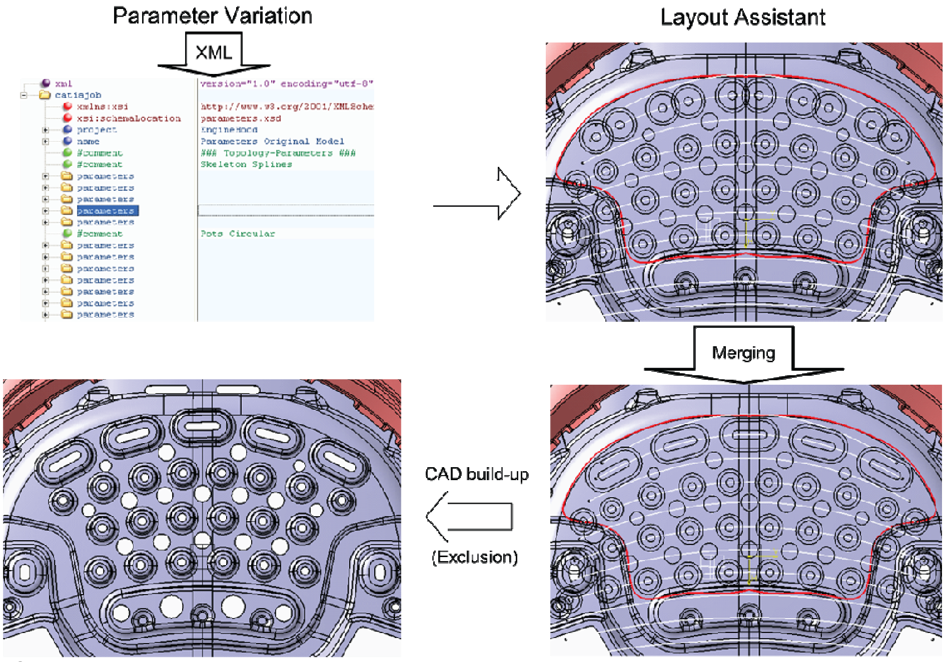


Figure 11: CAD build-up - topology variation through parameter variation combined with merging and exclusion.

The additional introduction of pot position coordinates, however, would considerably increase the number of free parameters. Therefore, a spline-based skeleton is introduced on which the variable entities are attached. Similar to an elastic cloth, the entire skeleton can be stretched or compressed to vary the distances between its splines. For basic topology variation, this elastic skeleton allows to simply use two global parameters to scale the entire pot arrangement (Figure 12, a)) and thus to move pots around the sub-structure. If individual pots are to be moved, a ratio parameter can be added to each pot, defining its position on the actual spline (Figure 12, b)). This however, increases the number of parameters considerably. Alternatively, the control points of the splines may be parameterised to individually vary each spline with all its pots.

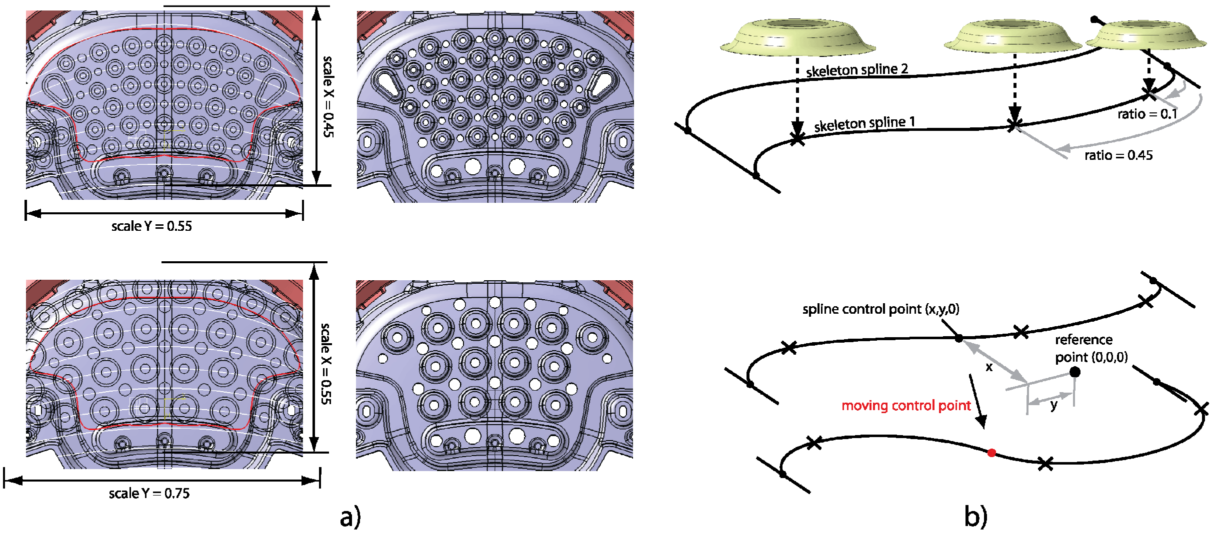


Figure 12: Pot number variation by scaling a) and spline skeleton concept for parameter reduction b)

With this set-up, a highly flexible CAD model is provided covering largest possible search and solution space and allowing for individual settings concerning the number of free optimization parameters.
The parameters are saved in an XML and the optimization or DOE loop can be started (variation, layout-stage, CAD build-up, evaluation).

6 CONCLUSIONS

In response to current corporate developments towards multi-disciplinary optimization, process automation and continuous design verification, we addressed major difficulties common to all such processes.
Using the study case of head impact performance of an engine hood, we introduced automatic CAD-based topology variation, an approach to high quality batch meshing and a fully automated optimization loop incorporating LS-DYNA and CATIA V5.
Applying the feature-based concept, topology variation has been successfully added to CAD parameter optimization, considerably extending search and solution spaces of *geometry-based* structure variation. The presented concepts are a trade-off between ease of maintainability (incorporated knowledge, VBA) and generality in application (dynamic knowledge access, CAA). Both approaches, however, invariably require a highly parametric-associative CAD model to apply parametrical and topological changes with granted update-stability.
To provide reliable FE evaluation results by high mesh quality, the concept of enriched CAD geometry has been introduced. Predefined faces are additionally included to retrieve and group the resulting structure's faces in order to provide separated mesh areas. The resulting STEP file transfers the additional information to the meshing tool for accurate meshing. However, such enriched geometry is gained at the cost of either high pre-processing effort (additional UDF set-up) or a dedicated and hardly maintainable algorithm (CAA).
Summarizing, a fully automated geometry-based parameter and topology variation/optimization loop has been implemented, yielding ready-to-use CAD geometry and reliable simulation results. This prototype setup is a step towards design process automation in general and particularly towards the automation of nowadays manual iteration steps between design and simulation engineers. First validation runs have already proven the accuracy and efficiency of the applied concept. The automatically generated meshes are consistent with the original manually applied mesh and a large number of varied designs has been generated by simply varying a few parameters.
However, considering the required framework for such automation, extensive work has still to be done:

- Suitable parametric-associative geometry rarely exists in today's design process
- History-based CAD software (CATIA V5) is highly sensitive to update-stability
- High pre-processing effort or low maintainability of the presented frame work complicate industrial applicability
- The required patchwork of intermediate scripts between CAE tools further complicates maintainability

Additional difficulties especially regarding full-scale optimization are calculation effort for FE analyses and the formulation or detection of target values for certain simulation disciplines (e.g. mode tracking not yet fully automatable).

Hence, although being a considerable step towards multidisciplinary optimization, omni-objective optimization of entire products (car, aircraft etc.) still remains utopia. Nevertheless, the application to small-scale parts and even assemblies in CAD has been proven and is highly welcome in design processes.
Future efforts will focus on providing ready-to-use optimization packages and their introduction into series production for specific simulation disciplines.

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