DESIGN OF AN INTEGRAL PRE-PROCESSOR FOR WING-LIKE STRUCTURE MULTI-MODEL GENERATION AND ANALYSIS

Teodor-Gelu Chiciudean and Cory A. Cooper
Delft University of Technology

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Abstract

This paper introduces an improved approach to support the modeling of wing-like structures. This approach utilizes knowledge based engineering and extends previous methods of geometry generation and analysis for various disciplines. A KBE application known as a multi model generator was developed to facilitate parametric modeling. In previous methods, preparation of structural models for analysis required multiple trimming operations. Trimming is an important primitive operation in geometric modeling; however, these operations are also the cause of many problems in modern CAD systems. This research seeks to exclude these operations through the use of parametrically referenced sub-surfaces allowing the new model pre-processing activities to be accomplished in a more integrated and reliable manner. This enables the direct export of a quad element mesh for aerodynamic and structural analyses. The proposed framework and an initial multi-model generator for airplane wings and wind turbine blades are presented.

1 Introduction

The modern aerospace designer has to deal with a daunting number of new requirements, technology, and constraints. Also, the design process must occur within tighter program schedules and budgets, where risk-mitigation through design analysis is valuable. It is well recognized that “there are technical challenges in modeling and analysis capability and major work is required in refining the understanding of the relationships between system entities and the analysis models that are used to represent them” [1]. With many design analysis tools available and computer processing speeds increasing, there should be an increase in designers’ efficiency and the resulting quality of their designs. Unfortunately, many design engineers are still spending a great deal of time on the mundane, repetitive tasks within model preparation and analysis.

The field of Knowledge Based Engineering (KBE) supports a model-centric approach to design by capturing and automating the routine rules and actions of the designer. The Design and Engineering Engine (DEE) concept, developed at the Technical University of Delft, provides a modular framework facilitating interaction among the various design steps (Fig. 1).

“The DEE is defined as an advanced design environment, where the design process of complex products can be supported and accelerated through the automation of non-creative and repetitive design activities… In practice, a DEE consists of a collection of commercial off-the-shelf (COTS) [and developed] components connected by a framework.”[2]. KBE applications are embedded within the DEE to provide expert logic, traceability and design intent.

The DEE is a general framework, made specific by the amount and type of knowledge included within its Multi Model Generator (MMG), the selection of tools, the types of optimization selected, and the overall arrangement.

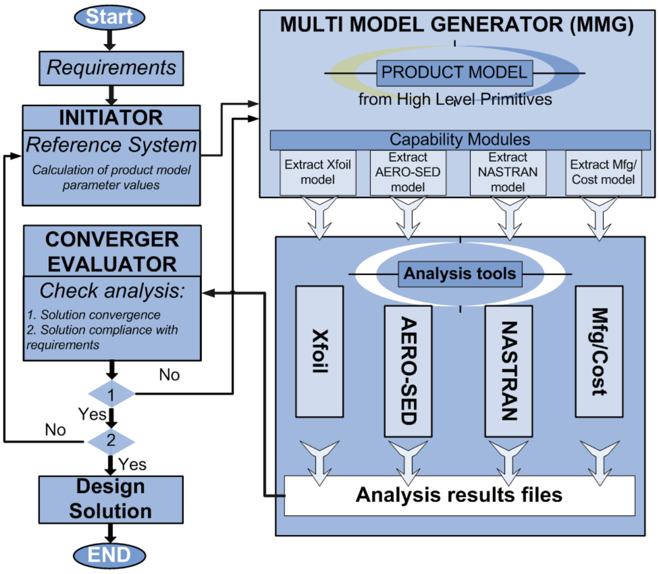

Fig. 1. Instantiation of the Design and Engineering Engine [3] concept

The MMG is the KBE application within the DEE and its modular architecture allows for functional expansion. As discussed in [3] and [4] the MMG architecture is built around two main types of components: the High Level Primitives (HLP) and Capability Modules (CM). The HLPs are responsible for the model parametric generation and the CM's are employed to communicate and provide the required views of the modeled product with respect to the analysis tools.

In recent work at TU Delft a series of new CM's were added to cover a range of design areas. For instance, CM's for aerodynamic analysis (2D and 3D), structural finite element analysis, manufacturability, cost estimation and others [5-10] have been developed for use in various MMG's. The capability module for structural analysis, *SurfaceSplitter,* developed by La Rocca and van Tooren [8], added a valuable tool interface for the aircraft MMG. However, surface trimming procedures within *SurfaceSplitter* in combination with the use of an external program to prepare and discretize the geometry (PYCOCO [6]) limited the model's efficiency. Operations performed by *SurfaceSplitter* and *PYCOCO* effectively prepared the model for third party structural analysis; however, the ability to trace analysis results back to the original HLP required use of additional geometry mapping and search functions.

The goal of the current research is to further develop the previous works and overcome their disadvantages by including new knowledge procedures to avoid surface trimming and external preprocessing. Such new features will enable design traceability down through the full product design. The current approach will seek to contain all model pre-processing activities within the KBE application. The goal will be to produce a MMG for basic wing-like structures (e.g. wind turbine blades and aircraft wings). The new capability will allow direct model export to third-party analysis tools and re-import of analysis results.

2 The Approach

The authors seek to further develop the tools and methods of ongoing KBE research at TU Delft under G. La Rocca and Prof. M.J.L. van Tooren. The work presented in this paper has started with an in-depth analysis of the current design practice of wing-like structures in combination with a knowledge based engineering approach. Within this study, the works of La Rocca and van Tooren [8], Amadori et al. [11], and Price et al. [1] were key references. This review identified process improvement opportunities for the current KBE approach, specifically in the full utilization of the MMG as the central geometry operator. The selected improvements deal with the elimination of surface trimming operations and improved traceability to native product structure in combination with multiple material allocations (e.g. composite materials). It was concluded that an alternative method to surface trimming could be a surface subdivision procedure [12, 13].

The current work begins with the design of interface modules for common, third-party finite element analysis (FEA) tools. The multi-model generator's capability module for FEA preparation should be able to export model information to the analysis environment without a series of segmentations or loss of core model knowledge. By working backwards from what the analysis tools directly require, the dedicated

CM can be designed to more effectively prepare model information.

In order to analyze the structural behavior of a complex structure, its CAD model must be prepared and discretized, or meshed, in a preprocessing program. To support the meshing process within the preprocessing program, models must normally be separated into discrete parts and regions. These trimmed surfaces may maintain their geometric connection information, but they lose their overall traceability to higher-level parametric logic. Rather than viewing a set of discontinuous panels – chopped and separated, the suggested approach views a wing-like structure as a total subsystem, requiring continuity of part referencing. This paradigm shift allows for model processing without altering the core geometric model. As observed by Nawijn et al. [6] knowledge transfer can significantly degrade between development stages and changes in tools/formats. Therefore this research seeks to maintain the native Non-Uniform Rational B-spline (NURBS) geometry within the core MMG and perform non-destructive element referencing as opposed to segmented panel exportation. The geometry used for the mesh generation is the native NURBS model without any trimming operation applied to the parametrical surface. The previous segmentation approach used by La Rocca and Nawijn, and the proposed, logical referencing model are presented in Figure 2.

The previous method creates a wing structure through use of an HLP. The SurfaceSplitter CM prepares the original model by segmenting the structure into meshable panels and subsections. These parts are created through Boolean (i.e. adding, subtracting, and/or intersecting) operations and then exported in initial graphic exchange specification (IGES) files. The use of these Boolean operations retains excessive and redundant information about the original surface with each cropped sub-surface. These operations are also highly dependent on tolerance settings which can greatly affect the adjacency of split surfaces in later operations.

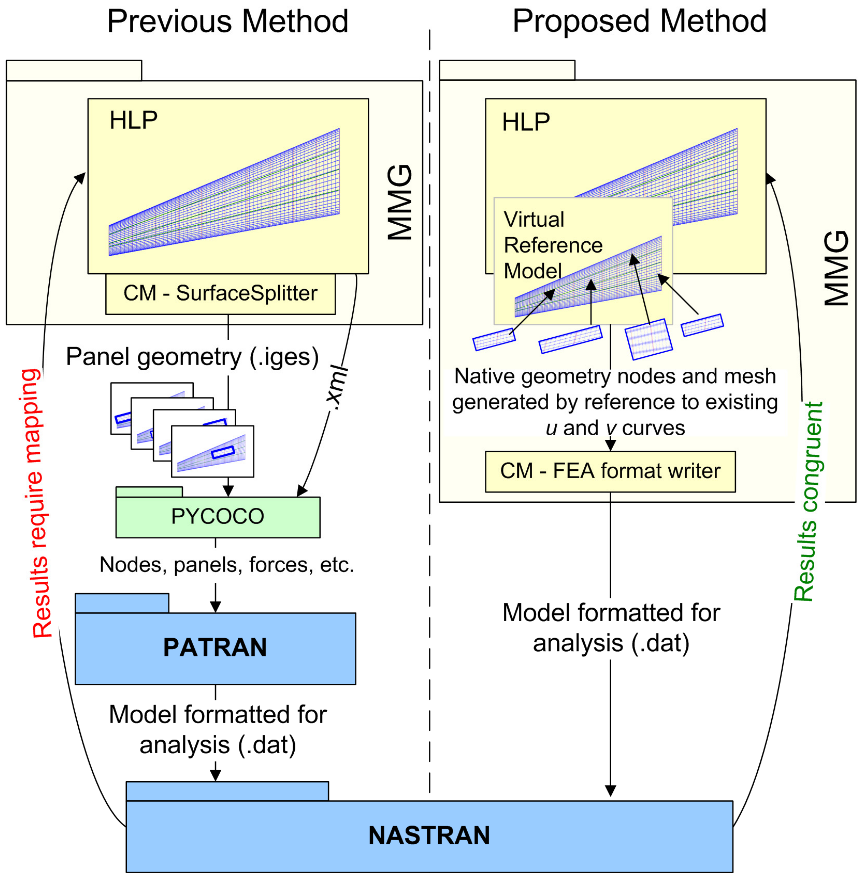

Fig. 2. Comparison of structural analysis pre-processing methods

The IGES format can transfer only geometric information about each part, so an additional application (PYCOCO) and .xml files are required to pre-process the model for analysis. This pre-processing was performed within PATRAN. Because the node generation occurs outside of the original geometry environment, the analysis results based on these nodes must be remapped to the original geometry afterwards. Additionally, the MMG from this method was developed in a currently unsupported KBE system. This has encouraged the current development of improved methods, HLPs and CMs in the new KBE system in use at TU Delft.

The proposed method is able to perform the preprocessing activities in the native MMG environment. Loss of model data integrity is reduced by eliminating the export through IGES format. The proposed method uses a subdivided surface method developed in-house. It creates bilinear Coons surfaces (a special case of Gordon surfaces) [14] interpolating the new boundary curves with respect to the original basis surface definition. This method does not retain the basis surface information for each sub-surface. It computes new individual patches directly which have the local properties of the original basis surface.

For structures composed of surfaces which are largely planar, the Coons patches are nearly identical. Even with surfaces that have uni- and bi-directional curvatures, the Coons surfaces are extremely good approximations. Only when there are local, out-of-plane curvatures (i.e. bumps) in the original surface do the Coons surfaces not match exactly. As this type of surface is rare in the design of wing-like structures it was felt that the use of Coons surfaces was appropriate and offered several benefits in the proposed method. Because this method uses NURBS geometry, which is supported by most existing CAD software, it can be widely implemented. Regardless of the CAD software adopted, the proposed method can provide reliable, traceable, platform interchangeable results.

Once the subdivided surfaces are established, the mesh generation based on native surface u- and v-directional curves [14] can be performed. With this and other user input data, a capability module is used to write out analysis data files directly, formatted as required by NASTRAN.

The overall process for the MMG to generate a NASTRAN input file can be summarized with the following steps:

1) The user inputs desired parameters for the wing to be instantiated (e.g. span, airfoil shape, component placement, etc.).
2) The MMG creates a parametric wing model. Panels, segments and elements are all defined with respect to the this virtual reference model.
3) Material properties are allocated for each of the model components (e.g. skins, spars, ribs, etc.).
4) Constraints, loads and other properties are defined through user selection and logical operations.
5) The analysis data file-writing function is executed. The file-writing call requests the instantiation of the actual geometry and produces the NASTRAN input file.

The implementation of the improved method will be discussed in more detail in the next section. The features of the proposed method and sub-processes will be addressed.

3 Design of the Multi Model Generator

The new MMG currently under development at the Faculty of Aerospace Engineering at TU Delft is built using the General Declarative Language (GDL) KBE platform by Genworks [15]. GDL is an object-oriented functional programming language which uses a Common LISP compiler in combination with a powerful NURBS-based geometry kernel, developed by Solid Modeling Solutions (SMS) [16]. This platform allows much of the engineering knowledge to be stored in the form of HLPs. Structural analysis was chosen as the driving type of analysis for this research. The finite element analysis tool used to test the output and compatibility with our new capability module is MSC/NASTRAN [17].

Figure 3 illustrates the data structure for an aircraft MMG with its components. When FEA is desired, the FEA-writer capability module is used to pre-process and format the geometry generated by the wing HLP. In general the HLP is responsible for initially generating and maintaining all core model information. The capability modules are responsible for model data formatting for use in analysis programs. To ensure backwards traceability, the CM should not change the HLP geometry; only translate it to a format that can be analyzed by outside programs.

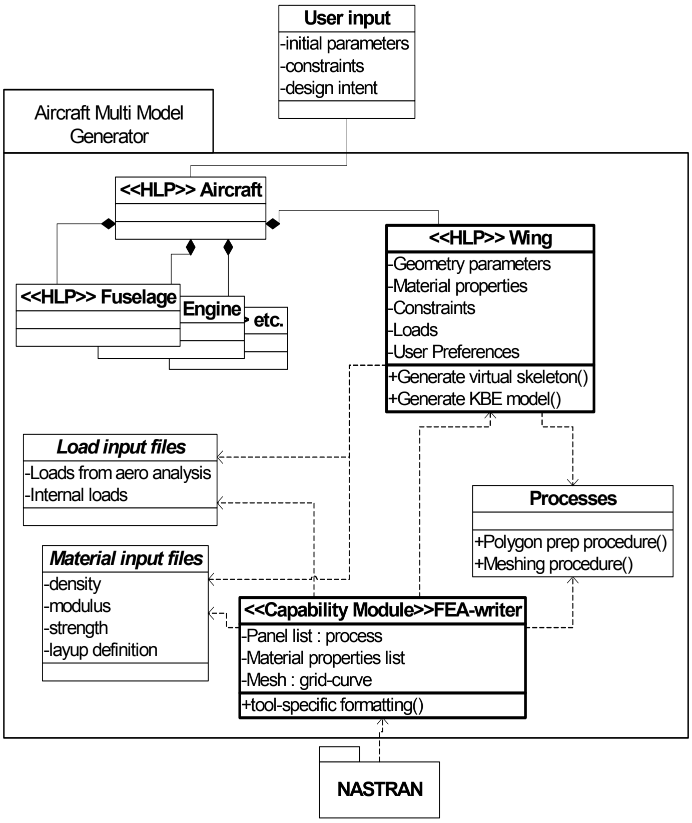

Fig. 3. UML class diagram representing the wing multi-model generator

The MMG accepts user input through either a developer interface or an eventual designer interface. Parameters are accepted for both the aircraft and wing levels of design. Example wing parameters are span, airfoil types at various locations, number/position/orientation of spars, number/position/orientation of ribs, material allocation, constraints, and other user preferences. These user preferences can direct the MMG in its generation and analysis preparation activities.

From these user inputs, a virtual wing reference model is generated by the MMG. Critical structural intersection points (see Figure 4a) are generated based on the rules established for the wing HLP. For analyses requiring a surface definition, further model pre-processing can now occur in the capability modules associated with analysis packages. See Figure 4 for an illustration of this process for a simply constructed wing trunk.

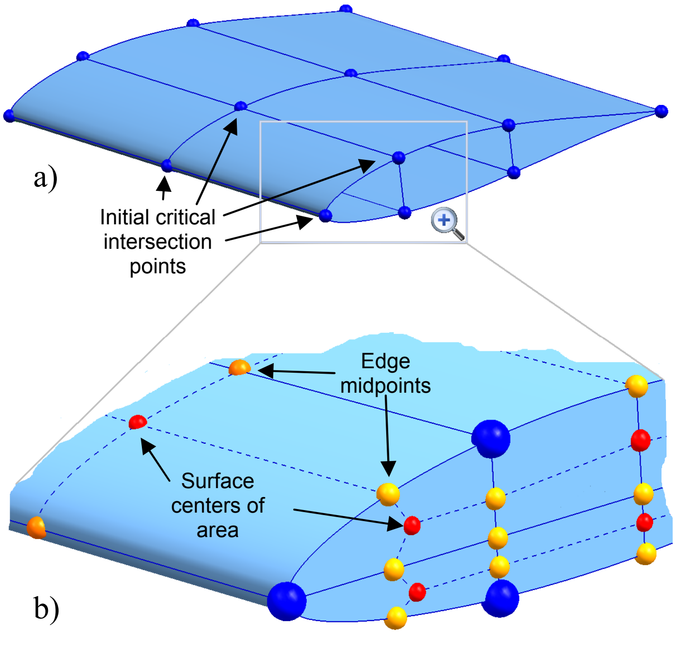

Fig. 4. Wing trunk a) virtual reference model from user input and b) preprocessed for sub-surface generation

The following discussion describes the activities required to convert the virtual skeleton to surface definitions composed of elements for use in FE analysis. The proposed method takes advantage of native *u*- and *v*- directional curves created along the control points and knots of the generated NURBS surfaces. These *u* and *v* curves are easily accessible from within the GDL environment supported by the SMS surface modeling kernel. The access time to retrieve these curves for a common surface is less than a millisecond. However, these *u* and *v* curves require surfaces with four edges in order to provide appropriate grid points for quad-element meshing. For a wing of multiple components and surfaces, the numbers of edges of each surface could be three or more depending on how they are positioned and oriented.

To use the *u* and *v* curves to create quad elements, the surfaces must be prepared to guarantee sub-surfaces with four edges. The method developed and implemented for this research can be seen in Figure 5. Beginning with the initial structural surfaces, the method uses the centers of area (also readily available within the GDL environment). Next, lines are created between the original surface edge midpoints and the centers of the surfaces. Then, new sub-surfaces are defined by the original edge halves and the new lines to the surface centers. These new sub-surfaces are lightweight Coons surfaces and can be queried for their *u* and *v* curves. Equi-spaced points along these *u* and *v* curves can then be used to generate quad element meshes.

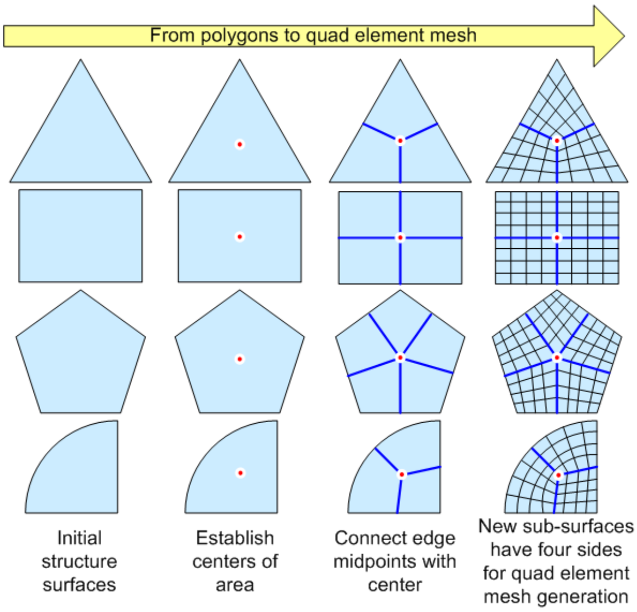

Fig. 5. Sub process for preparing all polygons for quad element generation

In a similar way, surfaces that have holes in them can be divided about the hole, thus creating four sub-surfaces each with continuous inner regions for further processing. Such a hole sub-division process was outside the scope of the current research but is planned for implementation in a future version of the MMG.

Since this process of generating four-edged sub-surfaces can be applied to polygons of any number of edges, it can be applied as a general process for all initial structural elements, even surfaces that originally have four edges. While at first, this may seem redundant to apply this to four-edged surfaces, there is a good reason to still perform it. By sub-dividing each surface based on centers and edge midpoints, the process is guaranteeing that each pairing of surfaces with adjacent edges will have a common curve intersection at their edge midpoint, regardless of the initial number of edges.

Figure 6 illustrates why general application of the sub-process shown in Figure 5 is required. Surfaces that do not connect only at their outer nodes (i.e. one adjacent surface ending in the middle of another’s edge) have connectivity errors in many FEA tools. This would normally require the engineer to manually re-divide surfaces until all adjacent surfaces have congruent edges. Also, depending on the exact length of the original edge length and the parameters given for *u* and *v* curve generation, the distribution of curves on adjacent surface edges could vary by one *u* or *v* curve. For this reason it is better to apply the center subdivision process for all surfaces. In this way the *u* and *v* curve generation is operating on adjacent edges that always have the same length, and will always result in identical *u* and *v* curve spacing.

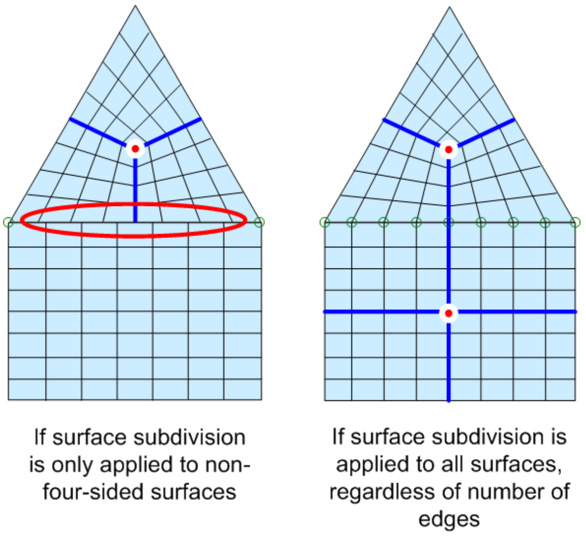

Fig. 6. Illustration of how applying the sub-surface processing steps is beneficial, even initially four-edged surfaces

The sub-surfaces are assigned material properties (also layer properties in the case of composite structures) and loads from aerodynamic analysis. Various user analysis preferences are also captured (type of analysis to be performed, output preferences, etc.). Some key steps of the material allocation procedure can be summarized as follows.

- The materials are defined within an external standard library.
- The materials are imported and exported within the system as symbols.
- For each sub-surface the materials are allocated using a logical, or declarative, procedure. This allows reference to the materials in an L_n x P_m map. See Figure 7.
- This material data is stored with the sub-surface definition and is available at request of other objects, including the FEA writer capability module.

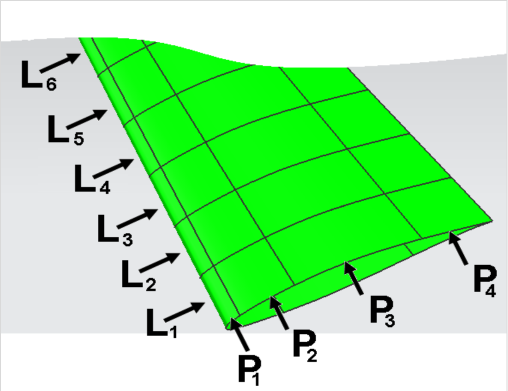

Fig. 7. Illustration of material allocation referencing

The capability module for FE analysis continues by using the *u* and *v* curves to generate nodes for each of the sub-surfaces. Then, the newly defined nodes are mapped to quad elements throughout the model. Now the capability module has data for elements and materials. Next, aerodynamic and other loads are allocated to the nodes. If the model preparation method presented here is used for aerodynamic analysis as well, the loads can be taken directly from CFD analysis and assigned directly to the nodes. If the aerodynamic loads are produced from a different mesh of the original structure, methods exist to map those loads from one mesh to another.

The output produced by the capability module is a data file properly formatted for direct input and analysis by a NASTRAN FE program. The call for execution of the FE program is also controlled from within the MMG. The data file with its nodes, elements, materials, and loads are all directly traceable to the original structure.

4 Results of Initial Implementation

The implementation of the proposed approach is found to have versatile application. Various wing-like structures are able to utilize the developed capability module. MMGs that have high level primitives related to wing-like structures are able to use the developed capability module directly. Other high level primitives are also likely to benefit from this approach as well.

Figure 8 illustrates how the current capability module applies two similarly constructed, yet different in purpose, product systems (i.e. a wing and a wind turbine blade). This method was seen to handle the material complexity, yet structural simplicity of wind turbine blades. Many wind turbine blades currently utilize composite material for their skin and simple spars for bending strength. The proposed method also can handle the relative material simplicity and structural complexity of current aircraft wings. As wing structure designs begin to include more complex material combinations, this method should be able to easily accommodate the more complex models. As wind turbines are scaled up for increased power generation, the blades will also increase in size and structural complexity. The turbine blades and aircraft wings will therefore both benefit from this improved design framework.

During implementation of the proposed method several issues were noticed and addressed. Initially the meshing method relied on the assumption that there would be a constant number of grid points (*u* and *v* curves) along any sub-surface edge. This ensured that all opposite edges would have an equal number of curve end points throughout the model. Changes in orientation of the sub-surfaces that changed *u* and *v* directions were not affected with this approach. However, this constraint of equal number of grid points along all edges had undesirable effects on sub-surfaces with high aspect ratios, such as skin panels and spars.

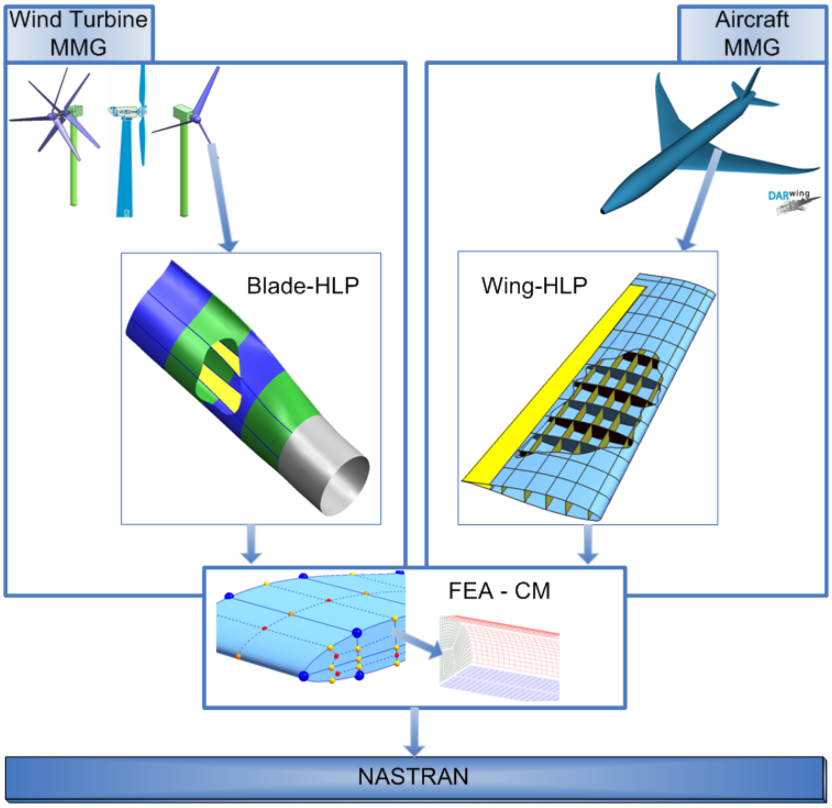

Fig. 8. FEA capability module for various wing-like structures

The new sub-surface curve constraints are assigned by the MMG through a KBE approach. The curve constraints are based on the type of structure that is being instantiated. For instance, skin panels and spars will be allowed to have a different number of grid points in the *u* and *v* directions. This will allow the mesh generation to produce quad elements with lower aspect ratios.

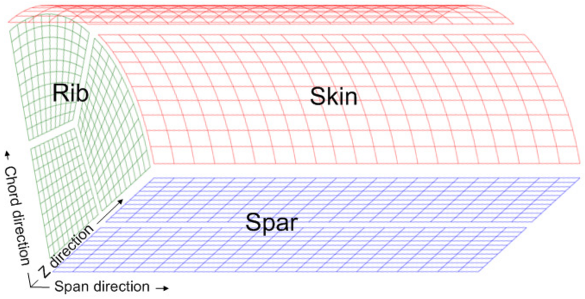

Fig. 9. Illustration of sub-surface *u* and *v* curve alignment

In order for the rib sub-surface mesh to align with the skin and spar sub-surface meshes, their number of *u* and *v* direction grid points should be equal to each other, to the chord-wise direction of the skin panels and the z-direction edge of the spar panels. See Figure 9 for an illustration. However, if a structure does not utilize ribs, as in the case of the present wind turbine blades, the user will have the option to use a different quantity of *u* and *v* curves in order to better control the aspect ratio of the finite elements.

With knowledge of how wind turbine blades and wing trunks are actually constructed, sub-surface creation was designed to accommodate this for aerodynamic, structural, and manufacturability considerations. Each sub-surface represents a topological component of the wing or blade assembly thereby allowing direct cost estimation and other component-based analysis. Attributes such as volume, area, or weights can be directly queried for use in such analysis modules with high precision. Also in the case of composites manufacturing the composite layup planar estimation can be easily produced by flattening the sub-surfaces. This is very feasible through the retention of the native surface mathematical representations.

5 Discussion and Conclusions

Increased understanding of the relationship between system entities and the tools used to model and analyze them is still required. This research sought to achieve a more effective balance between the creative generative activities and the analysis preparation activities within the design of wing-like structures. The presented approach aims to improve the existing methods for model pre-processing within a knowledge based engineering framework. The design of an improved multi model generator was completed with goals to improve efficiency and allow backwards traceability of analysis model preparation activities. Using a method which takes advantage of native surface control points and lightweight surface manipulation, these goals were achieved.

Traceability in a design and engineering engine is critical to allow for rapid and diverse changes to the core design model. The ability to map analysis results directly to the original surface control points allows more freedom in the multi model generation capabilities. Because the nodes used in the analysis tools are also mathematically linked to the surface control points for the original geometry, the results can be directly used to adjust that geometry. This could facilitate free-form deformation and allow full, direct and efficient control of the entire structure. This capability, coupled with knowledge based design rules, will allow much freedom in early design stages – still linked to sophisticated first principle analysis tools. Currently this method is being investigated for direct use in several system-level multi model generators with promising results. The presented method shows promise in unifying the approach to modeling various wing-like structures from diverse application domains.

Further research is still needed to fully implement the proposed approach presented here. Structures that have design features such a holes and more intricate substructure (e.g. stringers, clips, and fastening hardware) will drive the need for a more capable MMG. While the use of Coons patches and surface subdivision for quad element production is sound in theory, implementation within the current KBE environment requires close attention to tolerance settings. As these issues are addressed in further research, the proposed method can become even more beneficial to other researchers in the field of structural modeling and KBE applications.

As analysis tools improve the interface of imported model formats, this method could direct basis surface definitions (the mathematical surface representation – not just nodes) for analysis. This has the potential to reduce the need for interim steps of mesh generation/visualization all together.

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Corresponding Author

c.a.cooper@tudelft.nl

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