Title:
Interface Management for Automating Finite Element Analysis Workflows

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Introduction:
Solving computational analysis problems requires a fit-for-purpose finite element mesh to be generated, usually on idealized analysis geometry, along with the application of any applicable analysis attributes such as boundary conditions, loading and material properties. Geometric interface definitions in multi-component assembly models describe the connectivity between adjacent components. In FEA assemblies any explicit interface definitions are translated to appropriate boundary and contact conditions to capture the physical and mechanical properties to be transferred between components. Fig. 1 (a) and (b) show a simple bolted flange assembly and the interfaces in the assembly respectively. The application of boundary conditions for large assemblies, like whole aero-engine thermo-mechanical models, can be a tedious and time consuming task due to the vast number of physical interactions present. The manual effort required to define boundary conditions becomes repetitive and does not add value during multiple design changes through the product development, where validating and updating the assembly feature interfaces becomes necessary to maintain the integrity of the analysis model. Fig. 1 (c) and (d) illustrate the transformation in interface definition once the dimensionality of the geometric representation of the fastened plates has been modified. The interfaces with the dimensionally reduced plates and the fastener assembly have either reduced in dimensionality, from a face to an edge interface (blue edges in Fig. 1 (d)), or no longer exist because there is no longer physical contact between the geometric component models, the plate-plate, plate-washer and plate-bolt interfaces highlighted from Fig. 1 (b). Solutions are needed to automatically identify these interface transformations and to determine the subsequent decisions on how they shall be treated in order to generate a valid analysis model. For example, where a shell meshed region meets a solid meshed region, multi-point constraint equations (MPCs) can be used to connect the meshes or constraints can be applied to achieve mesh conformity at the interface.

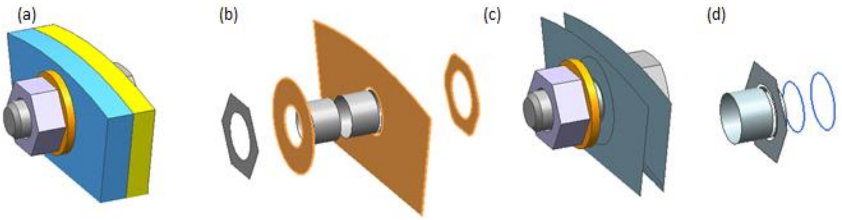

Fig. 1: (a) 3D fastened plate assembly; (b) Interfaces in 3D fastened plate assembly; (c) Mid-surface representation of fastened plate assembly; (d) Interfaces in reduced dimension fastened plate assembly.

In previous research activities Shahwan et al. [7] describe how interfaces are essential to derive the functional information required to progress from a Digital Mock-Up (DMU) to an appropriate analysis model. This work focused on using shape properties of geometric interfaces between components in assemblies to classify functional interfaces which in turn dictate the shape transformations, or connections, required to capture the behavior between components. Boussuge [1] used the geometric and functional interfaces derived by Shahwan [7] to generate user-defined templates for processing repetitive arrangements, such as fastener assemblies, for FE assembly modelling. Boussuge implemented template-based shape transformations on a 250 component assembly and reduced the analysis model preparation time from 25 days to 1.5 hours. It is evident that interface management is an essential aspect of automating the transformation process between design and analysis models. Gostaf [3] described the re-use of assembly topology to define interface regions for the application of boundary conditions in multi-component assemblies. Defining contact regions using assembly constraints requires post-processing, such as imprinting, in situations where only partial contact interfaces exist. Furthermore, there is no guarantee suitable assembly constraints exist, especially in DMU representations where components tend positioned at the correct location in 3D space, but the relevant spatial constraints are not explicitly known. An approach for the mixed-dimensional coupling of analysis models is described in [2]. Dimensional interfaces describe the connection between adjacent regions of mixed-dimensionality and are defined by using face-splitting techniques to create the topological link between adjacent regions, i.e. imprinting the edge of a mid-surface face on the bounding face of an adjacent solid, which dictates the mesh pattern on the adjacent solid domain. The imprinting procedure can be avoided using the equivalencing techniques presented in this paper.
In this work the aim is to automate many of the decisions required for treating interfaces and creating appropriate analysis models by using Cellular Modelling, Virtual Topology and Equivalencing to manage the dependencies between equivalent design and analysis models.

Transferring analysis attributes between equivalent model representations:
A precursor to this work was introduced in [9], where links between all of the design and analysis models of the same components are identified and stored in an independent data structure. Three technologies are employed to identify and process the dependencies between equivalent analysis configurations, Fig. 1 (a); cellular modelling is used to store the non-manifold representation of analysis specific decompositions of the design space; virtual topology techniques are used to record where partitioning and merging operations have been applied to a model; equivalencing describes the dependencies between equivalent regions of space, which may have a different geometric representation for different analyses, i.e. mid-surface representation of a thin-walled component. More detail on the identification of links between design and analysis models can be found in [9].

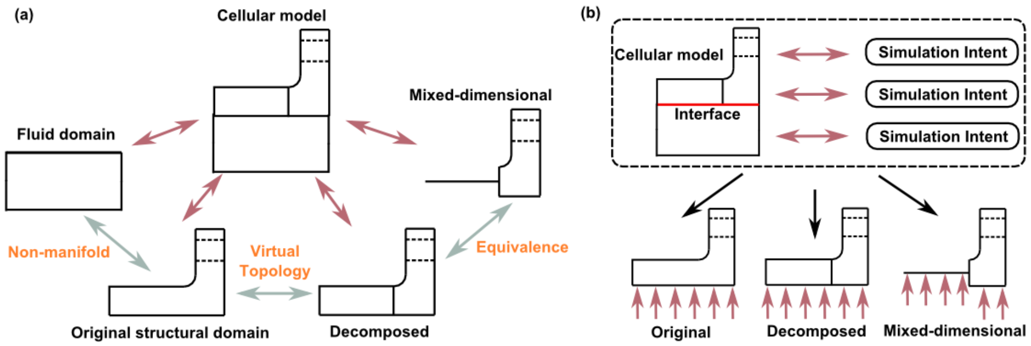

Fig. 1: (a) Technologies used to link analysis representations; (b) Linking with Simulation Intent to create fit-for-purpose analysis models at different levels of fidelity.

Simulation modelling and idealization decisions refer to the decisions made by an analyst in order to create a fit-for purpose analysis model. These input decisions can include, but are not limited to, the physics to be solved, the required accuracy, mesh type and dimensionality, mesh mating conditions and boundary condition application. The aim here is to specify high-level analysis decisions or 'Simulation Intent' [5] in a manner that is independent of the underlying geometry. This enables many low-level decisions and operations to be automated and manual rework to be avoided using the dependencies available through the use of Cellular Modelling, Virtual Topology and Equivalencing. For example, Fig. 1 (b) where boundary conditions are automatically transferred between equivalent abstract analysis models defined by applying different 'Simulation Intent' to the design model.

Transferring analysis attributes between analysis models at various levels of fidelity:
Interchanging between models at various levels of fidelity is required at different stages of a design process, or depending on the physics to be solved. Here it is demonstrated how boundary conditions can be transferred between the three different representations of the same component, shown in Fig. 2. The analysis decomposition of the structural casing component in Fig. 2 (a) is an automated process carried out by tools developed in [6] and [4], to isolate regions which exhibit certain geometric characteristics which lend themselves to specific meshing styles, namely thin-sheet (green), long-slender (blue) and residual (yellow) regions, Fig. 2 (b). The partitioning of the design space also includes fluid domains, Fig. 2 (b). The resulting decomposition lends itself to mixed-dimensional analysis modelling, where thin-sheet regions and long-slender regions are easily idealized to mid-surface and long-slender regions, Fig. 2 (c).

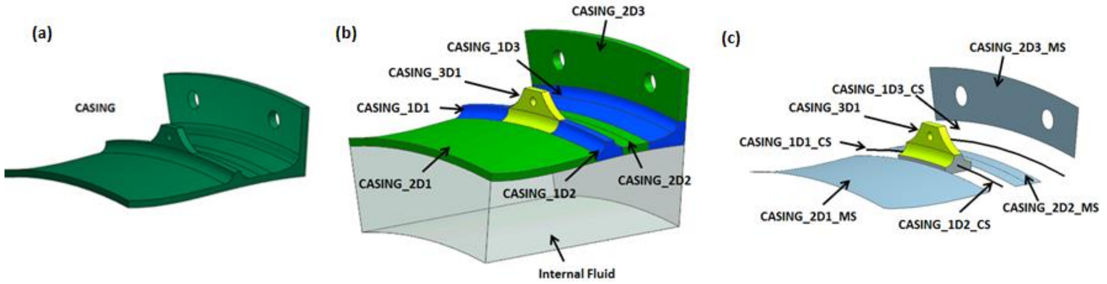

Fig. 2: (a) Aero-casing section; (b) Cellular model of analysis decomposition; (c) Lower fidelity model.

Explicit representations of fluid domains are essential for multi-disciplinary analyses where results from a CFD analysis can be supplied as the input to structural thermal or stress analyses. Another benefit of having an explicit definition of fluid domains within the cellular model is exploited in this work to automate the application of boundary conditions. As an alternative to manually specifying the boundary conditions it is possible to utilize a high-level Simulation Intent attribute that is independent of the underlying topological entities. Here, the Simulation Intent specifies that a pressure load has to be applied on the structural faces at the interface with the internal fluid domain Fig. 2 (b), where:

$$Pressure\ Interface = CASING\ \cap Internal\ Fluid \tag{1}$$

Non-manifold cellular modelling provides a geometric framework which can be conveniently used to identify the interfaces between interacting cells, highlighted interface in Fig. 1 (b). Shahwan [7] extracted interface using bounding boxes of components in a DMU to filter non-adjacent components and subsequently check for geometric interactions. Sung [8] used an octree approach to locate assembly interactions for disassembly sequence generation. These interfaces are readily available in the non-manifold cellular model described in this work. Interacting volume cells in the non-manifold cellular representation are bounded by the same faces at their interface, albeit with opposing orientations. Therefore, the definition of the interface is simply the set intersection, ∩, of both sets of bounding faces, Equation 1, carried out using SQL queries on the data structure generated in [9].
Interface calculation on the cellular model enables these interfaces to be transferred between the different representations in Fig. 2. Relationships between original and decomposed cells are managed using Virtual Topology, where decomposed cells are recorded as subsets of the original cell. The calculated pressure interface between the 'CASING' and 'Internal Fluid' domain is represented by the faces in Fig. 3 (a). These faces are considered equivalent to the collection of partitioned faces in Fig. 3

(b). Using this Virtual Topology information the interface information can be automatically transferred between the original Fig. 3 (d) and decomposed models in Fig. 3 (e). Identification of dependencies between the idealized entities and their equivalent entities in the detailed representation is described in [9] and illustrated in Fig. 3 (c), where the dependencies of all bounding entities of the mid-surface are defined. Although no explicit interface exists between the fluid domain and the mid-surface representations, equivalence links with 3D interfaces in the cellular model are used to transfer the pressure load to the idealized interfaces in the mixed-dimensional model, Fig. 3 (f). Fig. 3 (c) shows the equivalence between top and bottom faces of a 3D thin-sheet region and mid-surface face has an orientation attribute defining whether the surface normals point in the same direction. This allows the boundary conditions to be applied in the correct orientation on the mid-surface, inset Fig. 3 (f). This is an improvement from existing analysis workflows, where switches in model fidelity require boundary conditions to be manually updated.

Connecting independently meshed domains at their interfaces:
The extraction of topological interfaces provides the input required to couple independently meshed domains. Fig. 4 (a) shows the interface regions automatically returned from the cellular representation of a section of the aero-casing component from Fig. 2 (b). The interface characteristics and the associated simulation intent are utilized to automatically define the coupling strategy at the interface.

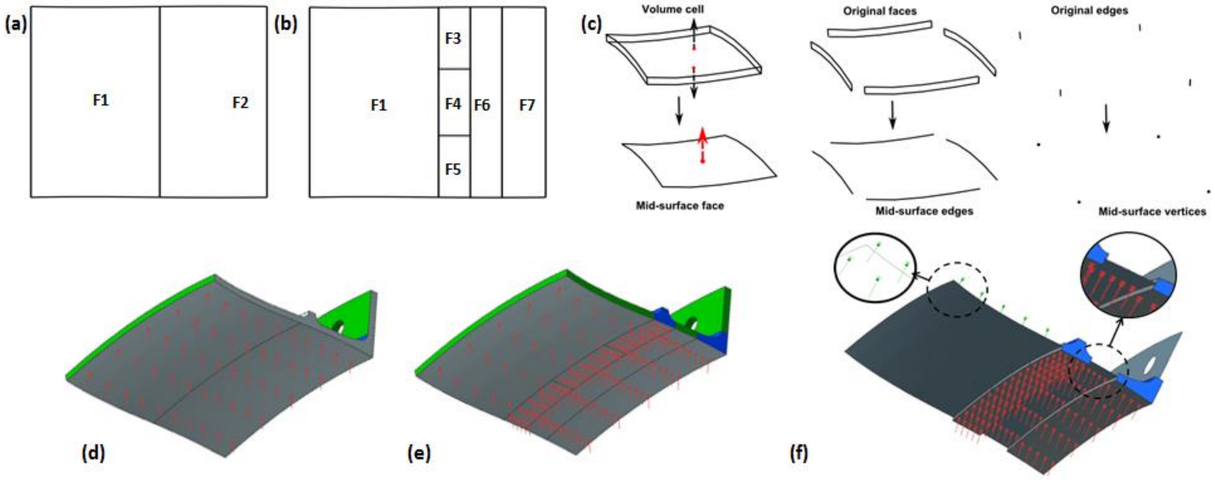

Fig. 3: (a) Original interface region; (b) Equivalent interface for decomposed region; (c) Equivalencing mid-surface; Pressure load on (d) original model; (e) decomposed model; (f) mixed-dimensional model.

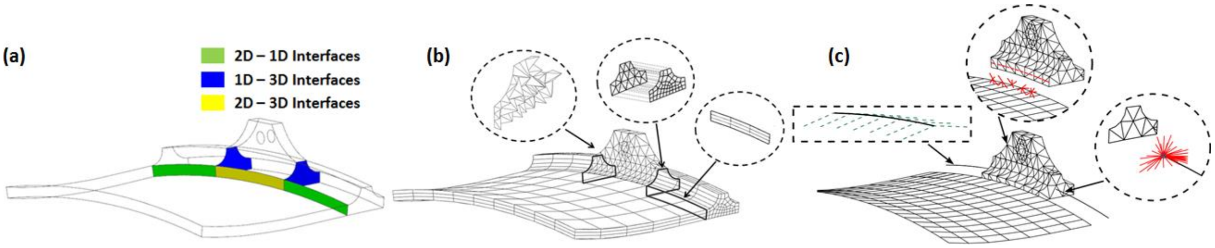

Fig. 4: (a) Highlighted interfaces of a section of the aero-casing component; Interface meshing for (b) mixed-solid mesh; (c) mixed-dimensional mesh.

One simulation intent definition may require a mixed-solid element mesh for a stress analysis, where thin-walled regions (referenced '_2D' in Fig. 2) and long-slender ('_1D') are automatically meshed with hex elements (by sweeping a quad mesh on a source face through the thickness, or along the length, of the region) and the residual region ('_3D') meshed with tet elements, Fig. 4 (b). Hex elements are more efficient than tet elements in thin-walled regions due the greater number of tet elements required to mesh the same domain. The interface characteristics, or simulation significance of an interface, are derived from the analysis attributes attached to the interacting cells. The analysis attribute of parent cells is automatically stored in its name attribute during decomposition, Fig. 2 (b). For example '_2D' signifies a thin-walled region that can be idealized to a mid-surface. Different strategies for coupling the mixed-solid mesh are automatically defined for each interface type in Fig. 2, where: 2D-1D interfaces signify hex-hex conformity and may be used to merge coincident nodes, Fig. 4 (b) inset right; 1D-3D and 2D-3D signify hex-tet interfaces which can be coupled using MPCs in situations where different mesh densities can be used either side of the interface, Fig. 4 (b) inset center, or using pyramid elements to transition from hex to tet in situations where a conforming mesh is required, Fig. 4 (b) inset left. Another simulation intent definition may require a reduced-order model for a modal analysis, Fig. 4 (c). Thin-walled regions are reduced to mid-surface and meshed with a shell mesh of quadrilateral elements, long-slender regions are reduced and meshed as beams with associated cross-sectional properties and the residual region is meshed with tet elements. The equivalence links and the 3D cellular modelling interfaces are used to define the mixed-dimensional coupling strategies required to account for the rotational degrees of freedom present in shell or beam elements, which are absent from the solid element models, where: 2D-1D interfaces require edge-to-edge MPC connections, Fig. 4 (c) inset left; 1D-3D interfaces require point-to-face MPC connections, Fig. 4 (c) inset right; 2D-3D interfaces require edge-to-face MPC connections, Fig. 4 (c) inset center, where the mid-surface does not need imprinted (red dashed line on 3D mesh) in order to connect the meshed domains. Robust management of model interfaces also allows mesh sizing controls to be assigned either side of an interface region in order to achieve mesh conformity, or to simplify any MPC connections.

Conclusions:

This research has shown that once high level analysis attributes have been assigned to individual cells in a non-manifold cellular model it is possible to use interface information to automatically generate desired analysis models and seamlessly transfer analysis attributes between equivalent model representations. Cellular Modelling, Virtual Topology and Equivalencing information are used to facilitate the capture of the Simulation Intent of an analyst in order to avoid unnecessary or repeated manual effort in setting up analysis models.

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