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An Analysis of the Transformation Requirements for Digital Mock-Ups of Structural Assembly Simulations

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Abstract

In order to set up a framework dedicated to the transformation of digital mock-ups (DMUs) into simulation models, this paper exposes the problem of simulation assembly model preparation. It analyses the differences between standalone component and assembly preparations to justify the reasons for the time consuming tasks specific to assemblies. To this end, the content of a DMU is analysed to explain why information about interfaces between components is missing in DMUs and how to derive the shape idealization of industrial assembly models, resulting in categories of DMU transformations. There, repetitive configurations emerge as a key issue to process large assembly models and the use of functional data appears to be critical to automate assembly transformations. Then, starting from the concepts of simulation objectives, user-specified hypotheses and connections between them, shape transformation categories are analysed to extract dependencies. As a result of these dependencies, a model preparation methodology is derived that address the shape transformation categories specific to assemblies. This methodology is already a means to improve the efficiency of an assembly simulation preparation process.

Keywords: CAD-CAE integration, assembly simulation, digital mock-up.

1 Introduction

Aeronautical companies face increasing needs in simulating the structural behaviour of product sub-assemblies. It becomes an essential issue to optimize these subsets. The goal is to increase the scope of physical observation in order to not only analyse standalone component, but to get the behaviour of an entire assembly containing up to thousands of components (such as wings or fuselage sections of an aircraft). The development and use of DMUs in a product development process (PDP), even with large assembly models, make 3D models available for the engineers. The DMU is regarded as a reference tool of detailed 3D geometric representation, which offers new perspectives for analysts to approach more complex geometry and speed up the simulation model generation.

The DMU was initially developed for design and manufacturing purposes as a digital representation of an assembly of mechanical components. Consequently, DMUs are good candidates to support a virtual analysis of e.g. part assembly processes. At the manufacturing level, engineers can quickly generate and simulate trajectories of industrial robots and are be able to set and validate assembly tolerances [1]. During project reviews of complex products such as aircrafts, their DMUs contribute to the periodical technical analyses conducted by the engineering teams. Connected to virtual reality technology, a DMU can be at the basis of efficient collaboration tools to prevent interferences among the various systems involved into a product [2, 3]. Also, the local or global, linear or nonlinear, static or dynamic analyses of structural phenomena using finite elements (FE) are now highly deployed in industry. Commercial software already provides some answer to the interaction between DMU and CAE for single components. Fewer, like GPure [4] offer capabilities to process specific configurations on large facetted geometric models. Unfortunately, a rather automated generation of complex assembly simulation models still raises large difficulties and is far too tedious to process groups of components as well as sub-assemblies. Shape transformations are needed because designers and analysts have different target models, resulting in the fact that DMUs cannot be easily used to support the preparation of structural analysis models. Today, the operators available in CAD/CAE software allows either interactive geometric transformations leading to very tedious tasks, or automated model generation adapted to very simple models only. These operators are still not adapted to analysts' needs, especially when idealizations of components or assemblies must be processed. Indeed, it is common practice for analysts to generate interactively their own models. Consequently, some simulations are not even addressed because their preparation time cannot fit within the schedule of a PDP, i.e. simulation results would be available too late.

To reach the needs of large assembly simulation, improvements in processing DMUs are a real challenge in aircraft companies. This work characterizes and analyses some specific issues of assembly simulation model preparation. To handle larger models, it is mandatory to speed up and to automate as much as possible the DMU transformation required. Prior to any automation, a first step stands in identifying the key content of interactive preparation processes and how these processes could be structured and formalized. For this, we must:

- Analyse the differences / similarities between simulation objectives of assemblies and that of standalone components,
- Identify the simulation hypotheses and validation criteria specific to assemblies,
- Identify the characteristics of DMU data, as available input to initiate a simulation process and specify the major geometric transformations required to meet simulation objectives.

In a second step, differences between assembly and standalone component preparations must be highlighted. Shape transformation requirements specific to assembly simulations preparation are addressed in the scope of user-defined simulation objectives (the analysis of data integration will be highlighted between user's hypotheses, simulation objectives and shape transformations). Finally, the analysis of dependencies between components' shape transformations applied to assemblies will help formalizing a methodology for the preparation of assemblies. Another contribution of the present work is the formalization of the concept of detail, adapted to the context of idealized assemblies.

The paper is organized as follows. Section 2 reviews previous work on CAD-CAE integration related to data integration and shape transformations. Section 3 points out shape transformation differences between structural simulations applied to standalone components compared to assembly ones. Section 4 analyses the interactions between shape transformations and underlines the existence of dependences between categories of shape transformations under given simulation objectives and hypotheses. Section 5 synthesizes the paper and outlines the ongoing development of a platform to automate the assembly simulation preparation process.

2 Tasks versus Data Integration

Prior work in CAD-CAE integration can be classified in two separate categories [5, 6]:

- Integration taking place at a task level: It refers to integration of activities of design engineers and analysts, hence it refers to methodologies and knowledge capitalization in simulation data management,
- Data integration level: It covers data structures geometric algorithms performing shape transformations on 3D models of standalone components.

Design and structural behaviour simulation are not regarded as two independent disciplines any more. Eckard [7] showed that the early integration of structural simulation in a design process could improve a PDP leading to a shorter time-to-market. Badin [8, 9] proposed a method of knowledge management used in several interacting activities within a design process. There, analysts and designers collaborate and exchange design information. However, the authors assume that relationships between dimensional parameters of CAD and simulation models of components are available, which does not currently exist. Additionally, they refer to configurations where the shapes of components are identical in the design and simulation contexts. To help analysts, Bellenger [10], Troussier [11] and Peak [12] formalized simulation objectives and hypotheses applied to a design model when setting up simulations to capitalize and reuse them in future model preparations. This approach underlines the influence of simulation objectives and hypotheses without setting up formal connections with the shape transformations required.

Research about data integration can be categorized in:

- Details removal performed either before or after meshing a part [13-15],
- Shape simplification applied to facetted models [16],
- Idealization of individual components [17, 18, 19] using surface pairing or MAT.

It has to be noticed that contributions addressing idealization transformations don't address explicitly the relationship between detail removal and idealization, i.e. parts are free of details that were removed using global mesh size criteria without considering the impact of details on the choice of the idealized areas (categories of details are shortly reviewed at section 4.1.1). Armstrong and Donaghy [20] and Fine [21] define details as geometric features which do not influence significantly the results of an FE simulation. This definition has been set up for volume models and it does not establish any relationship with assembly models or idealization transformations. It characterizes an error derived from the influence of the discretization at the mesh generation stage over the solution fields.
Another result of this paper is also to analyse the definition of details applied to an assembly incorporating idealization processes (see Section 4.1).
In industrial CAE or CAD software, a set of geometric approaches are available to apply shape transformations to solids. Although automated operators exist, they are currently effective on simple configurations of standalone components. To process complex models, the user interactively modifies the object using shape transformation operators according to his/her appreciation priori appreciation of the simulation model created. There, a model preparation reduces to a global geometric operator without connection to criteria derived from simulation objectives and hypotheses.

Recently, to address the problematic of complex parts, researches concentrated on the identification of specific regions to automatically subdivide a complex shape before meshing. Robinson and Armstrong [18] use the MAT to decompose thin/thick sections and produce a mixed-dimensional shell as simplified model. Makem [19] proposed shape metrics to analyse a part and identify automatically long, slender regions within a volume body. Chong [22] propose operators to decompose solid models based on concavity shape properties before the mid-surface extraction to reduce dimensionally the model. These researches enforce the significance of region decomposition for simulation model preparations. However, these decompositions are only available for specific configurations extracted from isolated components and essentially incorporate geometric criteria. These approaches still face difficulties to obtain consistent results on single mechanical components ; issues about assembly models have not been addressed yet.

Few authors have studied the problem of assembly simulation preparation. Either the feature suppression method of Gao [23] or the surface simplification of Andujar [16] considers an assembly as a single solid and not as a component structure with functional junctions. To avoid the interactive generation of component interfaces, some CAE software are able to automatically detect interfaces into an assembly. However, the algorithms look for face pairs characterized under a global tolerance of geometric proximity to define contact areas and are not defining the non-manifold interface area. It appears also that component interfaces in DMUs are not restricted to contact areas [28]. Clark [24] proposes to detect these interfaces and create a non-manifold representation of the assembly with CUBIT software before meshing. This paper underlines the importance of the interfaces between adjacent volumes to generate conformal assembly meshes. However, it does not consider the relationship between interfaces and the simplification and/or idealization part processes. Quadros [26] proposes a framework to generate size functions controlling assembly meshes, other authors, Lou [25] and Chouadria [27] identify re-mesh contact interfaces in polyhedral assemblies. However, these methods are used directly on already designed mesh without establishing a link between CAD and CAE models and are restricted to contact interfaces.

The above review shows that CAD-CAE integration is currently focused on standalone components; preparations of assembly models have not been addressed in depth under global simulation objectives. Assembly simulation models, not only suppose the availability of geometric models of components, but they must also take into account the kinematics and physics of the entire assembly as needed to reach simulation objectives. This suggests that the entire assembly must be considered when specifying shape transformations rather than reducing the preparation process to a sequence of individually prepared parts that are correctly located in 3D space. When processing large assemblies, this cannot be performed interactively to meet PDP requirements. An automated approach of assembly simulation models preparation becomes mandatory.

3 Analysis of assembly simulation preparation processes

3.1 Analysis of DMUs content as starting point

In the aircraft industry, a product is digitally represented in a part data management system (PDMS) as a product structure which contains an amount of information about processes, data, organizations, etc. The high complexity of the product containing nearly millions of objects performing many different functions requires adaption to different user’s needs and knowledge.

Today, a DMU stands for the reference geometric representation of a product used by structural and systems engineers. It is the input model of the analysts to generate their simulation model. However, the information available for analysts into an aircraft DMU reduces to a set of CAD components positioned in space with respect to a global reference frame and a tree representing a logical structure of the product [29]. This originates from:

- The size of a DMU: It contains a large amount of components created by different design teams during a PDP, e.g. in aeronautics, the extraction of a DMU from the PDMS requires one day (no centralized data),

- The ‘robustness’ of a DMU: Positioning constraints between components are not available. Components are standalone objects in a common reference frame. A DMU is an extraction from the PDMS at a given time. The evolution of a PDP cannot maintain interfaces between the geometric models of components; the corresponding geometric constraints have to be removed. For example, if a component is removed, the removal of its corresponding geometric constraints can propagate throughout all the assembly. The choice is to locate all components into a global coordinate system. Consequently, each component is positioned independently of the others, which increases the robustness of the DMU.

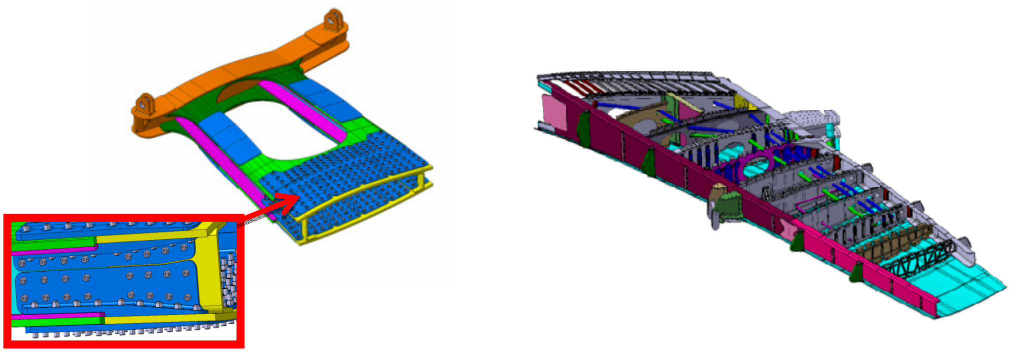

Figure 1: Complex assembly DMU from Alcas project[30].

The small amount of assembly-related information in a DMU makes the CAD-CAE link even more complex. To address this challenge, a first task observes the preparation of assembly models interactively generated by structural engineers. This analysis allows us to derive an initial set of shape transformations and analyse their dependences.

3.2 From DMU to FE assembly models

An assembly can be regarded as a set of components interacting with each other through interfaces. These interfaces contribute to mechanical functions of components or sub-assemblies [31, 32]. An assembly simulation model derives from shape transformations interacting with these functions to produce a mechanical model containing a set of domains discretized into FEs connected together to form a discretized representation of a continuous medium. Connections are of type kinematic or physical ones and associated with physical data (stiffness, friction coef., etc.), material parameters.

3.2.1 Interactions between sub domains in assembly models and hypotheses

An assembly simulation model is not just a set of meshed sub domains positioned geometrically in a global coordinate system. These sub domains must be connected to each other to generate global displacements and stresses fields over the assembly.

The selection of connectors is subjected to user's *hypotheses* regarding the relative behaviour of sub domains, e.g. motion and/or relative interpenetration. Here, a sub domain designates an entire component or a subset of it when it is idealized. These connections can be synthesized using Table 1.

	With relative motion	Without relative motion
With interpenetration	Junctions models : Used to model complete mechanical connections, i.e. ball joints, springs, dampers , welds, rivets, bolts, …	Kinematic constraints: used to model relationships expressed as displacement/velocity between nodes, eg tie constraints, rigid body
Without interpenetration	Normal and tangential contact : Used to model the normal and tangential stresses (friction) transmitted between two solids in contact during the simulation.	Normal Contact : Used to model the normal stresses transmitted between two solids in contact during the simulation.

Table 1: Available connector entities in CAE software

3.2.2 Simulation objectives interacting with the preparation process

Simulation objectives drive the shape transformations and interact with the hypotheses to model connections between components. Three simulation objectives are taken as examples in Table 2 to illustrate some of the possible interactions.

Simulation interest	Pre-sizing and design choices	Validation of mechanical tests	Contribution to phenomenon understanding
Simulation objectives	Determination of the number of junctions, the part thickness or material, …	Analyse the distribution of stress field in the structure Locate possible weaknesses	Understand the behaviour of the structure following unexpected results after physical tests
Internal Connections (Interfaces)	Physical junction simplified, no Contact (Rivet and Pin model associate to fasteners)	Physical junction simplified or use of volume patch model. Introduction of contact.	Complete physical junction, use of volume model with contact interaction
Component shape	Large number of components. Idealized: Thin parts associated to shell models.	Simplified (shell models) for large assemblies, volume model or mixed dimensional model accepted if rather small number of components.	Small number of components. Complete volume model
Job	Linear	Linear or non-linear	Non-linear

Table 2: Interactions or even dependencies between simulation objectives and interfaces, component shapes.

3.2.3 Idealization: a critical transformation in assembly models

Shells and beam elements can significantly reduce the number of unknowns in FE models leading to much shorter computation times than volume models. Using idealized representations can become mandatory for complex assemblies if license bounds (in terms of number of unknowns) are exceeded when sub domains are not idealized. From this perspective, idealization eases the integration of simulations in a PDP.

The use of idealized sub domains is nevertheless kept under physical hypotheses:

- The simulation objectives must be compatible with the observation of displacement or stress field distributions over the entire idealized sub-domains, i.e. there is no objective related to a local phenomenon taking place in the thickness or section of an idealized domain,

- The sub domains satisfy the shape proportions of idealization hypotheses, e.g. a thickness at least 10 times less than the other two dimensions of a sub domain.

However, even if the idealized sub domains reduce the analysis time, today they are obtained through a very tedious preparation process. All the time spent to prepare these simplified models should not balance the time saved during the FE computation. To process large assemblies with hundreds of parts, an automation of the preparation process is mandatory to insert assembly simulation in a PDP. To automate this process, it is necessary to identify the origin of lengthy operations.

4 Some major characteristics of preparation processes of FE assembly models

Now, the purpose is to highlight and formalize some of the operations explaining the difficulties contained in the preparation of simulation assembly models. This analysis focuses on structural assembly analysis (statics and dynamics). The simulation objectives fall into the “Validation of mechanical tests” category (see Table 2). Sub domains can be idealized to meet the level of abstraction named “functional macro view”, which expresses the transformation a group of components sharing a similar *function* in an assembly.

4.1 Particularities of assembly transformations vs component ones

In order to characterize the transformation of an initial DMU containing thousands of components, this section starts with a short description of the transformations related to a standalone component.

4.1.1 Transformations applied to a standalone component

To transform an initial B-Rep CAD model of a standalone component into a simulation model, the analyst in charge of pre-treatment applied sequentially different stages of analysis and geometric transformations. Based on the simulation objectives reduced to this component, the analyst evaluates, a priori, the interactions between boundary conditions and the areas of simulation observation (e.g. possible areas of max displacements or max stresses) to define whether sub domains can be idealized or not. Then, interactive shape transformations take place starting with idealizations because they are of highest level. Details removal comes after with topological and skin detail categories [21] (see Figure 2) that can be also grouped to refer to the common concept of form feature. Mesh requirements leading to volume partitioning is the last step of shape transformations.

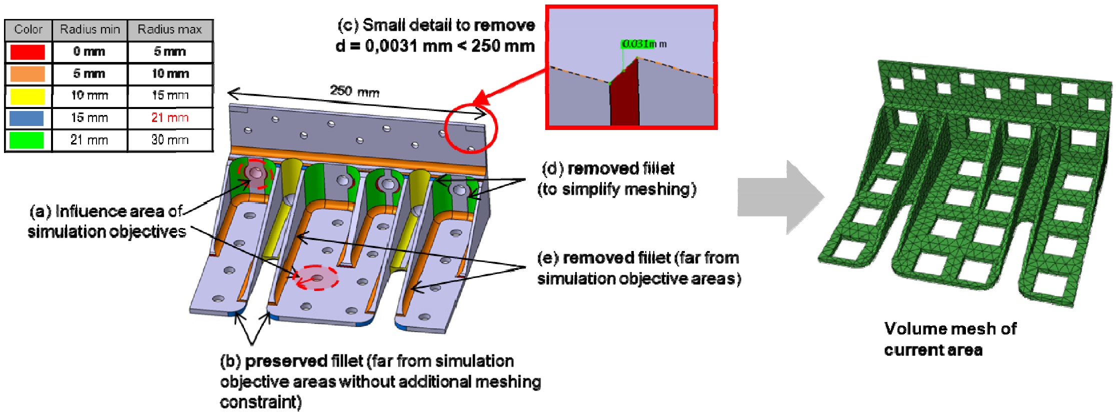

Figure 2: Detail removal on a standalone component.

The amount of shape transformations to be performed increases significantly for an assembly. The analyst has to reiterate numerous similar interactive operations on other components, often a large number of components. Avoiding the *repetition* of these similar operations is a first objective in assembly transformation.

4.1.2 Effects of interactions between components in assembly transformations

Unlike modeling a standalone component having no adjacent component, an assembly model must be able to transmit displacements/stresses from one component to another. Therefore, the preparation of an assembly model compared to a standalone component implies a preparation process of *interfaces* connecting components together. Consequently, to obtain a continuous medium, the analyst must be able to monitor the stress distribution by adding either kinematic constraints inside the assembly model or prescribing a non-interpenetration hypothesis between components by adding physical contacts. Thus, modeling hypotheses must be expressed by the analyst at each interface of the assembly.

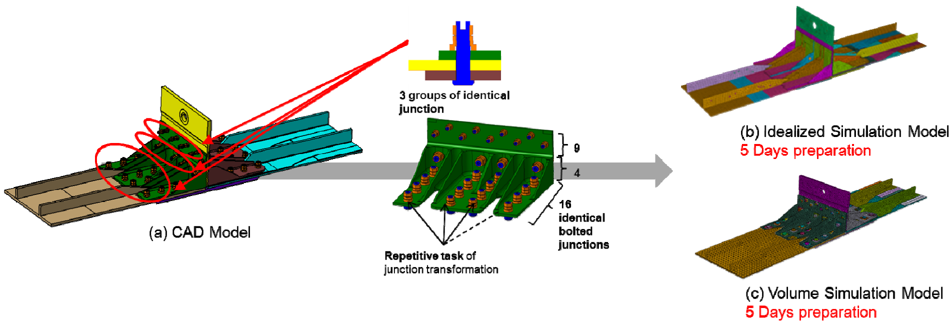

Figure 3: Use-case of assembly model of type aircraft wing/fuselage junction.

Today, the interactive preparation of the assembly depicted at Figure 3 requires 5 days of preparation to produce either an idealized model or a simplified solid model. When looking at this model, some repetitive patterns of groups of component can be observed. Indeed, these patterns are 45 bolted junctions that can be further subdivided into 3 groups of identical bolt junctions. The components forming each of these attachments belong to a same function: holding tight in position and transfer forces between the plates belonging to the wing and the fuselage. While a standalone component contributes to a function, an assembly is a set of components forming several functions between them. During an interactive preparation process, even if the analyst has visually identified repetitive configurations of bolts, each component of each bolt has to be transformed successively. The property that some components interact with each other and could be grouped together because they contribute to the same function cannot be exploited because there is no such functional information in the DMU. Thus, the analyst has to repeat similar shape transformations for each component. However, if the geometric entities contributing to the same function are available and grouped together before applying shape transformations, the preparation process could be improved. For instance, bolted junctions would be located and transformed directly into a fastener model through a single operator. Further than repetitive configurations, it is here the *impossibility to identify and locate* the components and geometric entities forming these repetitive patterns that reduces the efficiency of the preparation process.

4.1.3 Processing contacts

Hypothesizing the non-interpenetration of assembly components produces non-linearity and discontinuities of the simulation model. In this case, the analyst must locate the potential areas of interpenetration during the analysis. Due to the lack of explicit interfaces between components in the DMU, all these contact areas should be processed interactively. At each contact interface, the analyst has to delimit are as over both components and associate mechanical parameters such as friction. In the use-case presented in Figure 3, every bolted junction contains between 5 and 7 interfaces at each of the 45 junctions, which amounts to 320 potential contact conditions to define interactively. To avoid these tedious operations, in a context of nonlinear computations, there is a real need to automate the generation of contacts models in assembly simulations. It can be addressed on DMUs with the:

- Determination of geometric interface areas:
    - Localize geometrical interfaces between components likely to interpenetrate during the simulation,
    - Estimate and generate the extent of contact areas over component boundaries. Meshed areas of the two components can be compatible or not depending on the capabilities of CAE software,

- Generation of functional information to set the intrinsic properties of contact models:
    - Define the friction parameters,
    - Define the kinematic relations between component meshes in the contact area with respect to the dimensional tolerances between surfaces. Figure 4 exemplifies a contact between a shaft and a bearing. Commonly, a DMU exhibits a *conventional interface* [28] where the component representations share the same diameter, yet

they can have different functions according to their fitting (clearance, loose fit, snug fit) requiring different settings in their FE contact model.

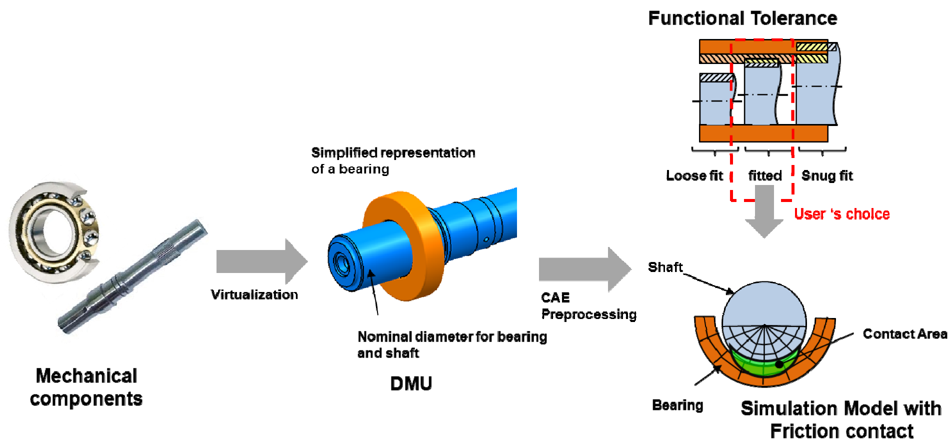

Figure 4: Example of contact model for FE simulation.

As a result, DMUs don't contain enough information to automate the generation of contact models. FE models need geometric and functional information about components interfaces to delineate contact areas as well as to set contact model parameters.

4.1.4 Functional macro view

To automatically handle these repetitive configurations related to components contributing to the same function in an assembly, the preparation process should be able to identify these functions from the DMU input. Currently, the analyst is unable to automate these repetitive tasks because he/she has no information readily identifying connections in the assembly.

Simulation models chosen by the analyst in a CAE library to replace the junctions are geometrically simple; simple interactive operators are available to achieve the necessary shape transformations. As shown in Figure 5, an idealized model of a bolted connection modeled with a fastener consists in a set of points connected by line elements. Using a mesh-independent fastener, the points representing the centers of the bolt holes do not even need to coincide with a surface mesh node. These idealization transformations are rather simple locally, given the component shapes. Hence, the challenge is neither the geometric complexity nor the mesh generation. Indeed, it holds in the term "bolted junction" to identify this geometric set of components. The issue consists in knowing the function of each component in an assembly in order to group them according to identical functions and to make decisions on modeling hypotheses (simplification, idealization) on geometries associated with these identified functions.

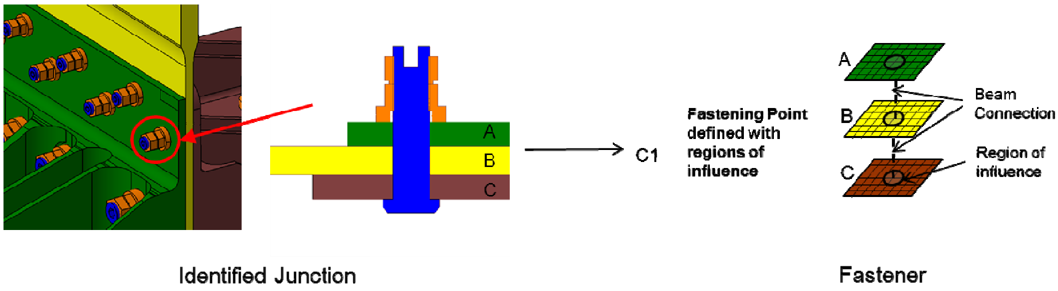

Figure 5: Identification of bolted connections to model them as fasteners.

4.2 Need for geometric and functional information in DMUs

4.2.1 Identification of functional interfaces and component functional designation in DMUs

PDMS technology provides information about component names referring to their designation, e.g. a component starting with ASNA 2536 refers to a screw of type Hi-Lite with 16mm diameter. However, information about each component designation does not identify its relation with others within the scope of a given function. How to know which component is attached to another to form a junction? Which screw is associated with which nut? There is a large range of screw shapes in CAD component libraries, how to identify specific areas on these screws through names only? Indeed, the word screw is not a *functional designation*; it does not convey an accurate connection with functions because a screw can be a set screw, a cap screw, ... To determine rigorously the functional designation of components, the neighborhood of a component is a fundamental information [28].

The extraction of functional data from a DMU through a bottom-up approach as the one conducted by Shahwan [28] demonstrates its efficiency in characterizing functional interfaces in a mechanical assembly. His approach identifies the functional designation of components through a combination of their geometric interactions with a qualitative mechanical reasoning process. This approach shows that the geometric interactions between components in a DMU are not only contacts and clearances but can be interferences, which leads to the concept of *conventional interfaces*. These results are a first step in the enrichment of DMUs to help automate the shape transformations of components and interfaces during an assembly preparation process. Geometric entities locating functional interfaces combined with functional designation of components enable the identification and location of groups of components to meet the requirements identified in section 4.1.

5 Analysis of dependencies between shape transformations: toward a modeling methodology

According to section 4, shape transformations taking place during an assembly simulation preparation process interact with simulation objectives, hypotheses, shape transformations applied to components and to their interfaces. Figure 6 shows interactions between shape transformations and modeling hypotheses. These interactions can be roughly seen as an iterative process with internal loops. The purpose is now to analyse and structure the interactions between shape transformations, leading to the emergence of a methodology structuring an assembly preparation process.

5.1 From simulation objectives to shape transformations

The purpose of is to analyse how shape transformations emerge from simulation objectives and interact between themselves. It is not intended to detail interactions to fit within the space allocated for the paper, rather the focus is placed on issues helping in structuring the shape transformations. Criteria related to time that may influence simulation objectives and shape transformations are not relevant in the present context since the purpose is to structure shape transformations to save time and improve the efficiency of preparation processes.

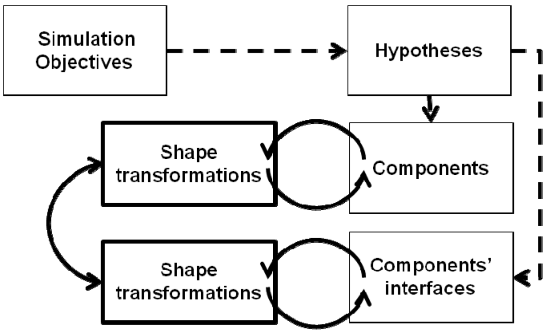

Figure 6: Interactions between simulation objectives, hypotheses and shape transformations.

5.1.1 Observation areas

From the simulation objectives, the structural engineer derives hypotheses that address components and/or interfaces among them, hence the concept of observation area.

Even if the analyst has to produce an efficient simplified model of the assembly to meet performance requirements, anyhow he must be able to claim that his/her result is correct and accurate enough in critical observations areas that are consistent with the simulation objectives.

Therefore, the mechanical model set up in these regions must remain as close as possible to the real behaviour of the assembly. Thus, the geometric transformations performed in these areas must be addressed in a first place. As an example, in Figure 7, the simulation objective is to observe displacements in the identified region (circled area) due to the effects of local loading configurations, the section of the domain being complex. A possible analyst's hypothesis can be to model precisely the 3D deformation in the observation area with a volume model and a fine mesh and set a coarse mesh or even idealized sub domains in other regions. To explicit this hypothesis over the domain, the circled region should be delimited before meshing the whole object. During a preparation process, setting up observation areas and thus subdividing an assembly into sub domains, independently of the component boundaries and their interfaces, acts as prominent task.

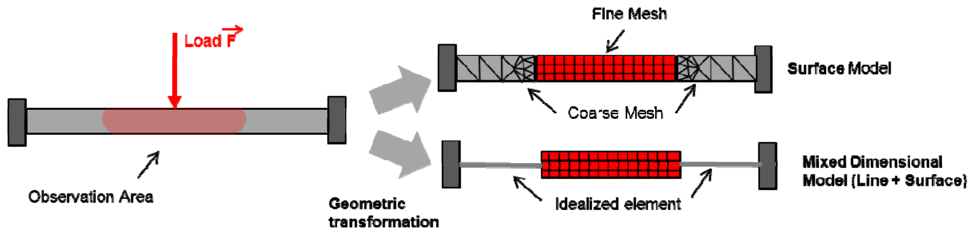

Figure 7: Setting up an observation area consistent with simulation objectives.

5.1.2 Entire idealization of components

As illustrated in section 4, idealizations have inherently a strong impact on shape transformations because of their dimensional reduction. Applied to a standalone component, idealization is meaningful to transform 3D domains up to 1D ones. In the context of assemblies, to meet simulation objectives, performances and reduce the number of unknowns, the analyst can idealize a component up to a point (0D), e.g. a concentrated mass, or even replace it by a *pre-defined solution field*, e.g. a rigid body behaviour or a spring-damper field. Such categories of idealizations can be also applied to a set of connected components (see Figure 8). In either case, such transformations have a strong impact on the interfaces between the idealized components and their neighboring ones.

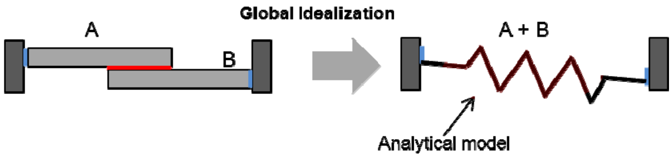

Figure 8: Entire idealization of two components.

Consequently, interfaces between idealized components can no longer be subjected to other hypotheses, e.g. contact and/or friction. Again, this observation highlights the prominence of idealization transformations over interfaces ones.

5.1.3 Processing interfaces

Interfaces between components are the location of specific hypotheses (see Table 1) since they characterize junctions between components. Naturally, they interact with hypotheses and shape transformations applied to the components they connect. Let us consider the example of Figure 9.

In a first place, a simulation objective can be stated as: modeling the deformation of the assembly with relative movements of plates A, B, C under friction. Under this objective, hypotheses are derived that require modeling interfaces (A,C) and (B,C) with contact and friction. Then, even if A, B and C, as standalone components, can

be candidate to idealization transformations, these idealizations cannot be idealized further because the interfaces would need to be removed, which is incompatible with the hypotheses.
In a second place, another simulation objective can be stated as: modeling the deformation of the assembly where the junctions between plates A, B, C are perfect, i.e. they behave like a continuous medium. There, plates A, B, C can still be idealized as standalone components but the hypothesis on interfaces enables merging the three domains (see Figure 9 b) and idealizing further to obtain an even simpler model with variable thickness (see Figure 9 c).

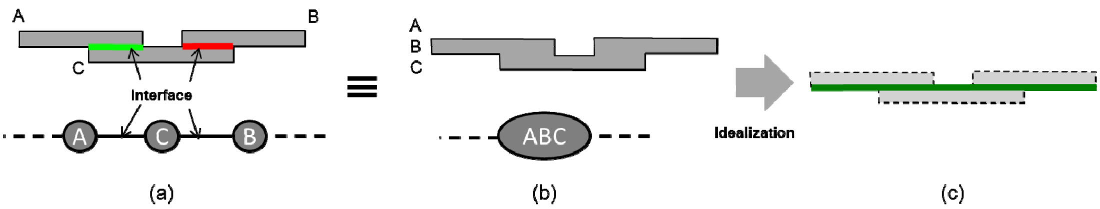

Figure 9: Influence of interfaces over shape transformations of components.

Thus there are priorities between shape transformations deriving from the hypotheses applied to interfaces. Indeed, this indicates that hypotheses and shape transformations addressing the interfaces should take place before those addressing components as standalone objects. Effectively, interfaces are part of component boundaries; hence their transformations modify these boundaries. It is more efficient to evolve the shape of interfaces alone first and to process component shapes, as isolated domains, afterwards.

5.1.4 Evolving the concept of details in the context of assemblies

Section 2 has shown that the relationship between detail removal and idealization has not been investigated. The definition of details stated in this section [20, 21] addresses essentially volume domains and refer to the concept of discretization error that can be evaluated with a posterior error estimators [33-35].

When considering idealizations, there is currently no estimator to evaluate the influence of the dimensional reduction achieved through this transformation. When possible, a comparison with simulation results over the initial volume model can be an indicator though it is hardly usable in an industrial context with the constraint of a PDP.
Processing assembly models adds even more idealized sub-domains because the simulation model complexity increases with the number of components. Evaluating the influence of idealizations compared to initial volume models becomes even more complex.
Assemblies add another complexity to the evaluation of details. It is related to the existence of interfaces between components. As illustrated in section 5.1, interfaces

are subjected to hypotheses to define their simulation model and Table 1 illustrates the diversity of mechanical models that can be expressed with simulation entities. Recently, Bellec [36] addressed some aspect of this problem but comparison between the influence of rigid and contact interface models is comparable to the evaluation of idealization transformation. It is also a complex issue.
This short review of major concepts (idealization, interfaces) specific to assemblies shows that the concept of detail, apart from referring to the real physical behaviour of a product, is difficult to characterize. The structural engineer's know-how is prominent, which means that interactive shape transformations are a strong constraint of an assembly simulation preparation process.

5.2 From dependencies between shape transformations to a methodology of assembly preparation

Section 5.1 has analysed the relationship between simulation objectives, hypotheses and shape transformations of assemblies. One outcome of this section is dependencies between hypotheses and shape transformations that address an assembly at different levels. The purpose is now to exploit these dependencies to structure an assembly simulation preparation process so that it appears as sequential as possible compared to the various loops appearing on Figure 6, thus improving its efficiency.

5.2.1 Dependencies of geometric transformations of component and interfaces upon hypotheses

Section 5.1.1 has shown the dependency of observation areas upon the simulation objectives. Defining observation areas acts as a partitioning operation an assembly, independently of its components boundaries. Section 5.1.2 introduced the concept of entire idealization of components and pre-defined solutions fields. Indeed, the shape transformations derived from section 5.1.2 cover also sub domains over the assembly that can be designated as *areas of weak interest*. Indeed, the interfaces contained in these areas are superseded by the transformations of section 5.1.2. From a complementary point of view, areas of interest, once defined, contain sub-domains that can still be subjected to idealizations, especially transformations of volumes sub-domains into shells and/or plates.
Consequently, areas of weak interest are regarded as primary sub-domains to be defined. Then, entire idealization of components and pre-defined solutions fields will take place inside these areas. These areas are necessarily disjoint from the areas of interest.

Sections 4.1.2 and 5.1.3 have shown that hypotheses about interfaces influence the transformations of components' boundaries, hence they are outside of areas of weak interest and are known once the latter are specified. Consequently, they come as a second task after the definition of the areas of weak interest and the corresponding shape transformations should be applied at that stage.

As highlighted at sections 4.1.1, 4.1.2 and 5.1.3 idealizations are shape transformations having an important impact on component shapes. As mentioned at section 2, the order of detail removal operations and idealizations has not been studied precisely yet. However, once idealizations have been assigned to sub-domains, these transformations produce new interfaces between sub-domains (see Figure 3 c) in addition to the interfaces originated from the interactions between components. Independently of skin and topological details, idealizations can be regarded as a third task in the preparation process.
Anyhow, these new interfaces are the consequences of idealizations of sub-domains; they cannot be processed during the second task. These new interfaces should be processed in a first place after the idealizations contained in the third task. The corresponding shape transformations form a fourth task.

Now, as pointed out at section 5.1.3, idealizations can interact between themselves because sub-domains can be extended/merged in accordance to their geometric configurations. This new set of shape transformations can be regarded as a fifth task that could indeed appear as part of an iterative process spanning tasks three and four. This has not yet been deeply addressed to characterize further these stages and conclude about a really iterative process or not. Even though task two addresses hypotheses attached to interfaces and corresponding shape transformations, it cannot be swapped with task three to contribute to iterative process discussed before. Indeed, task two is connected to component interfaces that could be influenced by component idealizations, e.g. idealizing the shaft in Figure 4 influences its contact area with the bearing.

Figure 10 summarizes the structure of the preparation process after the previous analysis.

Hypotheses and shape transformations enable the definition of a mechanical model over each sub-domain but this model must be available among the entities of CAE software. Consequently, if an analyst defines interface transformations consistent with hypotheses, there may be further restrictions to ensure that the shapes and mechanical models are effectively compatible with CAE software capabilities. For sake of conciseness, this aspect is not addressed here.

5.2.2 Toward a methodology of assembly model preparation

The previous section has identified dependencies among shape transformations connected to simulation objectives and hypotheses. Detail removals are not investigated further and are part of future research. Currently, they can take place after task two but they can be prior or posterior to idealizations. The definition of areas of interest has connection with the mesh generation process to monitor the level of discretization of sub-domains. This definition acts as a partitioning process that can take place at any time during the process flow of Figure 10.

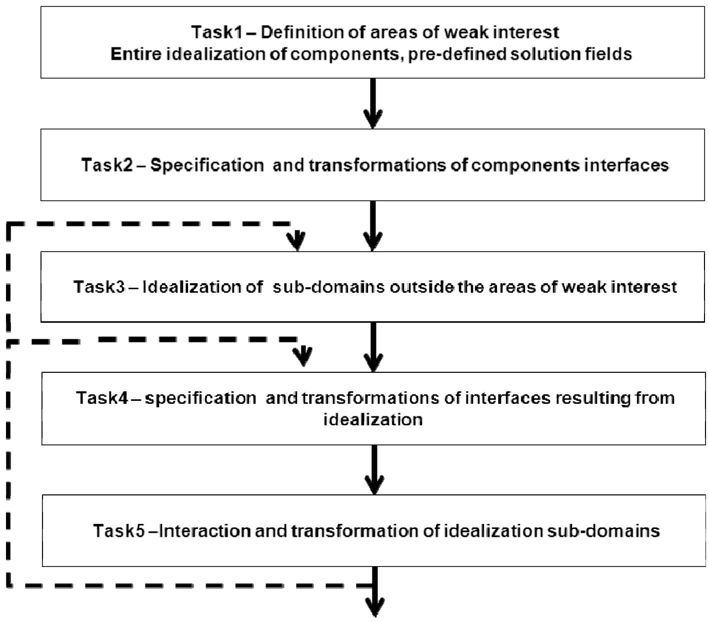

Figure 10: Synthesis of the structure of an assembly simulation preparation process.

5.3 Synthesis

The difference between a simulation model of a standalone component and an assembly relates to:

- The interactions between components. The analyst formulates a hypothesis for each interface between components. These hypotheses derive from assembly simulation objectives,
- The ordering of shape transformations. The entire idealization of components and the specification of pre-defined solution fields, then shape transformations of component interfaces, are prioritized,
- The interactions between idealizations and interface transformations. To be able to model large assemblies, not only component but groups of components must be idealized, which can significantly increase the amount of interactions between idealizations and interface transformations.

The simulation objectives are expressed through hypotheses on shape transformations. With the identification of functional features of the assembly through the interfaces between components, it becomes possible to locate groups of components related to similar assembly functions and therefore it can set a connection with the simulation objectives. The multiple idealizations and interfaces between sub-domains can generate repetitive patterns too. Identifying and processing these patterns is a means to speed up significantly preparation processes.
The constraints related to mesh generation, through mesh size constraints have not been incorporated into the current analysis of preparation processes even though the respective locations of interfaces between sub-domains may need to be modified when the FE size gets larger than the distance between interfaces with an orthogonal

setting of sub-domains (see Figure 3 c). These constraints will be addressed in future work.

6 Conclusion and future work

6.1 Conclusion

Assemblies, as set of components, have been addressed in the context of structural simulation to analyse and structure the shape transformations required to evolve from a DMU to a finite element simulation model. Currently, engineers are limited to simulate small models due to the large amount of interactive operations to prepare complex assemblies. Preparing each component is already a tedious task, especially when idealizations are necessary, that increases significantly with the number of components and the interfaces between them, which form new entities to be processed. It has been observed that repetitive configurations and their processing is also a critical issue of assembly preparation, justifying the need to automate the preparation of large assembly models. Functional information can be an efficient enrichment of a DMU to identify and process repetitive configurations.

The analysis of shape transformations has revealed specific categories of transformations. Studying the interactions between simulation objectives, hypotheses and shape transformations has revealed dependencies between categories of shape transformations. These dependencies have been organized to structure the assembly simulation model preparation process in terms of methodology and scope of shape transformation operators. Also, it has been observed that the concept of shape detail, in the context of assembly simulations, becomes more difficult to set up, showing that the engineer's know-how and the interactivity and parameterization of assembly simulation models are an important challenge to be able to insert these simulations in PDPs.

6.2 Future work

Component decomposition for idealization: a CAD component derived from a DMU contains only geometric and topological information. Future work will set a link between geometry and simulation objectives, hypotheses through functional features to decompose assembly components into several sub-domains connected by interfaces.

Monitoring geometric transformations: an assembly is not anymore regarded as a set of components positioned in space. The next task is to set up an analysis method of this structure when it is enriched with functional information to set up criteria assisting the structural engineer during the decomposition of an assembly into sub-domains. This analysis will lead to a simulation model preparation process and incorporate the mesh generation constraints. This process will drive the geometric operators to simplify, idealize, insert, modify, areas specifically identified by the geometric and functional information.

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