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Capturing simulation intent in an ontology: CAD and CAE integration application

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ABSTRACT

Computational simulation is critical in the modern engineering design process. Currently, the use of simulation is limited by the time-consuming process of converting CAD assemblies into FEA models which are efficient to run and yet sufficiently accurate. In addition to the geometric representation of components, analysts require additional knowledge to describe the complete 3D simulation model. To speed up the generation of CAE models from CAD assemblies, we propose to capture high-level modelling and idealisation decisions, characterising the simulation intent, into a knowledge-based CAE model. In this framework, a simulation intent ontology formalises and structures the analysis parameters, the modelling and idealisation decisions. The ontological concepts and relations required to incorporate two of the key capabilities, cellular modelling and equivalencing, are described. Cellular modelling introduces the concept of cells, which subdivide the 3D space, and to which simulation attributes can be attached. Equivalencing maintains the link between different representations of the cells required for different analyses throughout the analysis lifecycle. Illustrative examples show how the knowledge-based CAE model is used to manage the idealisation decisions and to apply inference rules replicating current modelling practices.

KEYWORDS

Simulation intent; finite element modelling; cellular modelling; ontologies; CAD/CAE integration

1. Introduction

Computational simulation is a critical component in the modern engineering design process, where it is used to validate the design of large assembly structures. It is extensively used by aeronautical, automotive and other engineering industries to provide a full-scale digital representation of the design. However, it poses challenges in setting up increasingly complex numerical simulations for all the different physics which need to be considered in the development of new products. Currently, the cost and scalability of simulation technologies is bounded not only by the computation time but also (and often to a greater extent) by the time-consuming tasks of converting computer-aided design (CAD) assemblies (sometimes containing thousands of components) to computer-aided engineering (CAE) models (Boussuge et al. 2012; Vilmart, Léon, and Ulliana 2018). For example, a 3D thermo-mechanical simulation of a full jet engine (containing around 5000 components) requires man years of effort to construct.

Furthermore, different analysis models for different physics are created from the same design representations across all the simulation departments (see Figure 1). Because the simulation assumptions or solver requirements differ from one analysis to the other, analysts often tend to build their models from scratch rather than deriving them from existing CAD and simulation models. This practice is extremely time-consuming and keeps the modelling and idealisation decisions in silos, making it difficult to transfer and exploit the results and knowledge between simulation disciplines, or to propagate subsequent design changes to their associated analysis models. In engineering design, it is critical to support the interoperability of the different designs and associated simulation models in the product development process. The challenges are not only to create automatic tools to adapt the geometric models but also to facilitate and capture the reasoning of the idealisation decisions for automatic reuse across all aspects of the simulation lifecycle. In addition, the knowledge formalisation and representation should not be seen as an additional activity but should be an integrated part of the CAD to CAE process.

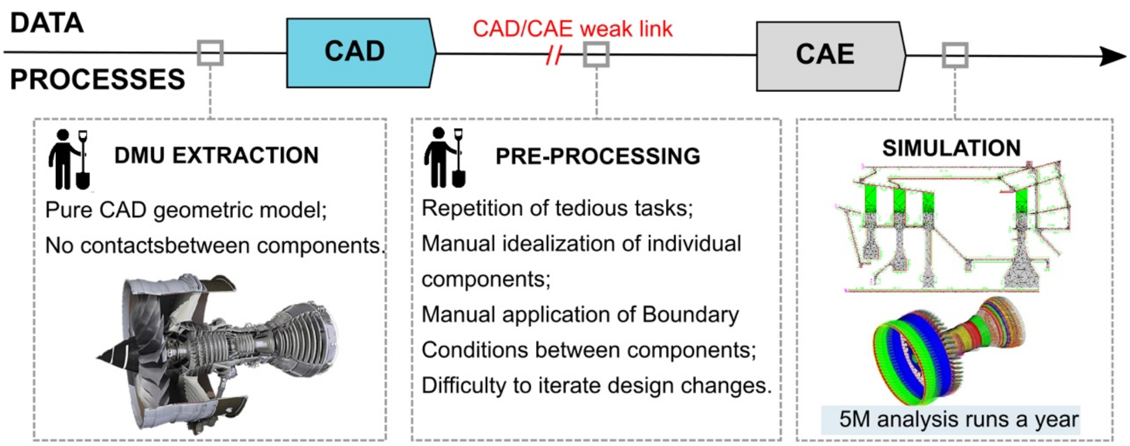

Figure 1. The pre-processing of CAD models to CAE models is a major bottleneck in the automation of simulation workflows, figure adapted from (Boussuge 2014). Repetitive and time-consuming pre-processing effort is required for all simulation disciplines.

1.1. The Simulation Intent concept:

CAD was initially developed and structured to design a product in view of manufacturing it. Since then, CAD models have become a common input for simulation. However, CAD geometry produced by the design department often includes details not necessary for analysis. To produce an efficient simulation, the analysts often need to idealise the CAD geometry (Armstrong 1994). Idealisation refers to: detail removal where geometric details considered not to influence the simulation results are removed; dimensional reduction where so-called thin-sheet volumes or long-slender regions are represented by specific lower dimension finite elements available in CAE software (see Section 2.2.1); and sub-division of regions for meshing or boundary conditions application. These idealisation steps reduce the complexity of FE models leading to a shorter computation time compared to highly-detailed volume models. However, they are mostly manual operations, which are time consuming, error prone and often break the link between the idealised FEM model and the original design geometry.

(Nolan et al. 2015) proposed the 'Simulation Intent' concept to help establish the link between design and simulation technologies that would facilitate the automation of, or eliminate the need for, many manual pre-processing operations. Simulation Intent can be defined as follows:

Definition 1. Defining Simulation Intent involves capturing the high level modelling and idealisation decisions required to create an efficient and fit-for-purpose analysis.

For example, defining the simulation intent of a FE mechanical analysis (with the objective of determining maximum stresses/displacements) requires the specification of load cases, boundary conditions, initial conditions (e.g. initial values of stresses, temperatures…), material properties and element types to be used. In addition, preparing the simulation will often operate on the initial CAD geometry to generate an idealised geometry (e.g. regions/components which been removed as unnecessary details, regions dimensionally reduced, topology adaptations). Models at different levels of fidelity will be required at different stages through the product life cycle (e.g. a simulation of a manufacturing process like welding or casting might provide insight into whether a given process is feasible, or what the allowable stresses should be in a subsequent performance simulation, a higher fidelity version of the same model may be used to refine the design further once the performance simulation is complete).

The objective of this paper is to demonstrate that the analyst's knowledge involved in generating the appropriate simulation models can be captured in an ontology-based simulation intent model which can be used to automate the definition of modelling decisions, managing the analysis data and driving the set-up of the resulting simulation assembly models. Once this knowledge is captured, as a first benefit, the analyst can focus on product development rather than simulation model setup, thus directly adding value to the end product. A secondary benefit is to increase the reusability of models, to make them more robust to design changes and to maintain the inherent links between multiple analysis models. It is shown in this work that once the Simulation Intent symbolic information is captured in an ontology the analyst can benefit from pre-defined inference rules, replicating modelling practices defined in their domain knowledge and generating new information which can be used to automatically generate fit-for-purpose analysis models. There is a drive to use simulation earlier in the product design process so that preliminary design decisions can be based on analysis results. To enable this an increasing amount of analysis is being carried out by designers (as opposed to specialist analysts). For non-specialists, setting-up analysis models is challenging. For example, meshing components or defining the correct set of boundary conditions requires user expertise based on knowledge of the discipline and analysis techniques being used. Another benefit of the ontology-based simulation proposed in this paper is to help non-specialists to understand the simulation knowledge formalized in the ontology (by highlighting for instance the relations between the simulation objectives and idealisation requirements). This also provides a standardisation of best-practices that can be used by both specialists and non-specialists.

In this paper, the application focus is on FE thermo-mechanical analysis, for example fully coupled thermal-stress analysis where the stress/displacement and the temperature fields are computed. The Simulation Intent data for this application covers:

- Geometry: a cellular model is the geometric framework (see Section 2.2.3) where the 3D space is partitioned into cells of analysis significance to which analysis attributes can be attached. The geometry can have different representations (detailed CAD, idealised CAD, meshed representation for FE simulation, etc.) depending on the phase of the simulation process;
- Simulation objectives: behaviour to be observed in the simulation such as maximal displacements in a particular cell, maximal stress or temperature under a prescribed mechanical behaviour, accuracy of the expected results, etc.;
- Analysis type: type of analysis run by the user (in this work mainly linear static structural analysis and thermo-mechanical analysis are used but the same proposed ontology concept can be utilised to cater for other analyses);
- Material: the physical parameters associated to a region of space (i.e. a cell in a cellular model). The material model associated with a given cell could be fluid or structural;
- Boundary conditions: the interaction between the regions of space describing the mechanical/thermal effects, such as the pressure from a fluid domain on a structure, or the temperature from a solid on the boundary of a fluid domain.

The description of the proposed contribution is organised as follows. Section 2 reviews the requirements for adapting CAD models to FE thermo-mechanical models. Section 3 reviews prior work on CAD/CAE integration related to data integration and ontology-based applications. Section 4 describes the main ontology vocabulary, i.e. the ontological concepts and the relations between these concepts. Section 5 shows use-cases where simulation intent inference rules are being used.

2. Requirements on recording the Simulation Intent for FE analysis

Large thermo-mechanical FE simulations, involving long pre-processing times, are mainly created in anticipation of a physical test. They allow engineers to predict the thermal and mechanical behaviour of a virtual structure without the existence of a real structure. As for a physical test, the analyst sets up an analysis model following a set of requirements and modelling practices using a specific CAE language. This section discusses the data and language involved in analysis model pre-processing conducted by FE specialists.

2.1. Current available information in the Digital Mock Ups as input

CAD assembly pre-processing mainly consists of: generating a finite element model (FEM) model based on appropriate assumptions about the physics, and transforming and meshing the resulting geometric model to produce solver input models, see Figure 1. To set up these simulation models, the analyst exploits the information available at a given stage of the product development process, which varies in fidelity as this process evolves. During the product development process, the main source of digital 3D models is available through the digital mock-up (DMU), which virtually represents the product being developed. The DMU, typically extracted from a product lifecycle management (PLM) system, provides full 3D detailed geometry (CAD) models as input. In practice however, the DMU is comprised of a set of components positioned in 3D space with respect to a global reference frame (Boussuge et al. 2012). Simulation requires not only the geometric shape of components but also the definition of the physical domains, the interfaces between components, and the most appropriate analysis representation to use, e.g. a thin sheet of material might be represented by a collection of 2D shell elements where the thickness is a property of the element. Consequently, analysts spend considerable amounts of time retrieving or creating additional information in order to idealise the CAD models into the desired simulation models.

2.1.1. **Boundary representation and non-manifold models**

CAD assembly models are composed of a set of CAD components usually defined as boundary representation models (B-Rep). The B-Rep contains the geometrical and topological information defining the shape of each CAD part. For example, for a B-Rep solid, the geometric information consists of a set of surfaces defining the boundary of the solid and locating it in 3D space. These surfaces are usually bounded and connected by trimming curves that are usually bounded by vertices. The topological data structure enables the expression of the mandatory topological properties, i.e. closure and relative orientation, that lead to the description of shells, faces, wires, edges, vertices, expressing the adjacency relationships between the topological entities. In this work, the input CAD assembly models are extracted from a DMU and defined as B-Rep representations.

To understand the different properties used in CAD volume modellers and CAE modellers, the notions of manifold solid and non-manifold objects have to be explained. Mainstream CAD packages (CATIA, NX, Solidworks) use a manifold modelling environment where a set of faces bounding a solid are defined to enclose a bounded partition of the 3D space that represents the physical object. Two adjacent solids have completely independent topological structures, and even if their boundary faces are coincident, a separate face will exist to bound each solid. Non-manifold representations extend the concept of manifold to represent the wider range of configurations needed for analysis. Consequently, an edge can be adjacent to more than two faces, a face can be shared by two solids. For example, a solid composed of two different materials, or a structural model with multiple shell bodies attached at an edge. A non-manifold geometric modelling kernel also incorporates the ability to describe and connect geometric regions of different manifold dimensions. Most of the commercial FEA packages contain manifold geometric modellers with extensions to be able to model non-manifold objects.

2.2. Requirements for pre-processing of FE thermo-mechanical analysis

The following section describes the main requirements affecting the set-up of a FE thermo-mechanical simulation covered later in the proposed ontology.

2.2.1. Multi-dimensional models

A CAD model usually contains 3D solids defining the nominal representation of the designed product. Currently, FEA software offers a large variety of finite elements of different dimensions. In Figure 2(a) for example, 1D elements are suitable to represent long-slender structures (such as beams) having two dimensions that are small compared to the third one; 2D elements together with a thickness attribute are adapted to represent thin-sheet bodies having one dimension which is small compared to the two others and 3D elements are used for a thick body, or when a fully detailed analysis is required.

Setting up an appropriate analysis requires the manipulation of different n-manifold geometries embedded into one multi-dimensional model. The choice of finite elements is a compromise between the geometry of the components, the desired accuracy of the simulation results as well as the computational resources available to reach this accuracy. For example, the analyst may use idealised 2D or 1D elements to reduce the number of unknowns in FE models, leading to a shorter computation time. However, this choice implies a time-consuming dimensional reduction process to generate an equivalent analysis model of an initial 3D CAD geometry. This process involves:

- The notion of 'morphology', where the analyst identifies in the initial CAD model the sub-regions having a morphology compatible for a certain type of finite element, for example thin morphological regions are adapted to 2D shells elements. This notion is detailed later in Section 4.2.9.
- The notion of 'equivalence', where an equivalent dimensionally reduced model is generated to represent an idealised representation of the same region of design space. Ideally, as proposed by (Nolan et al. 2015), the links between different analysis representations across multiple analysis models (see Figure 2(b)) should be maintained to automatically propagate loads, boundary conditions, physical properties, etc. This notion is detailed later in Section 4.3.2.

The equivalence between representations and morphology are key terminologies used in FE applications.

2.2.2. Model partition

FE analysis requires the ability to partition an object model into a set of joint volumes or surfaces. For example, an object made of different materials requires a partitioning of the initial solid. Partitioning operators can also be used during the meshing process to apply a particular meshing strategy over regions of interest. The region of interest can be meshed with a fine resolution compared to the rest of the model. For example, a solid can be divided into a set of hex-sweepable volumes in order to produce a full hex mesh (L. Sun et al. 2016; Armstrong et al. 2015). Particular regions of interest in a given simulation may be required, e.g. a crack at a given location.

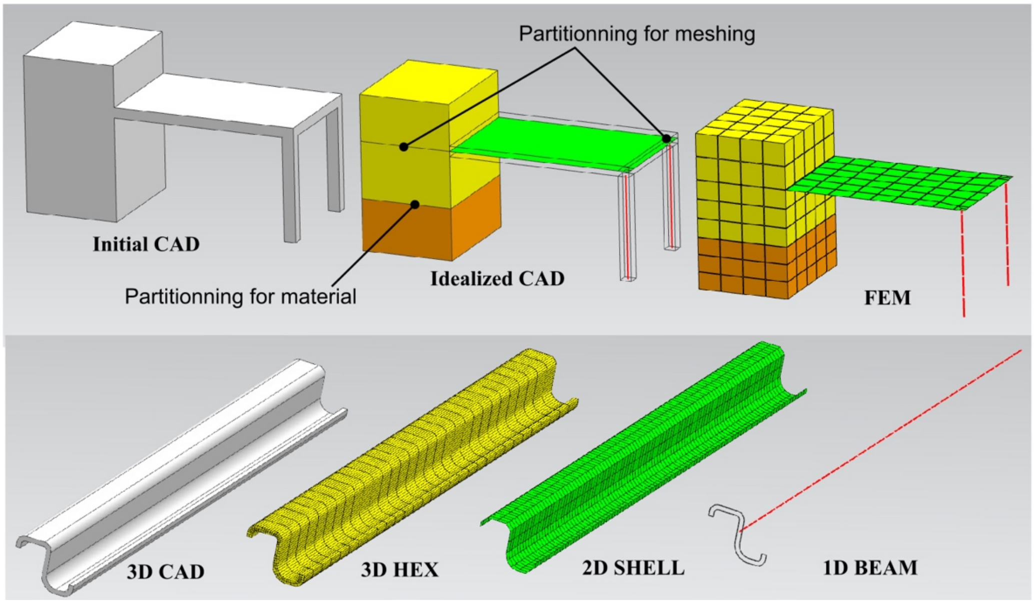

Figure 2 Generation of FE model from CAD model. (a) The intermediate idealised CAD is multi-dimensional (volume partitioned into three sub-volumes). (b) Equivalent representation of S-shaped beam for different simulation objectives.

Figure 2(a) represents a typical segmentation of a CAD solid which is divided into six sub-regions. One thin-sheet region is idealised with 2D shell elements. Two long-slender regions are idealised with 1D beam elements. The thick volume is divided twice; to separate regions with different materials (e.g. a composite structure), and to facilitate the meshing process (to ensure the node coupling and compatibility at the shell/hex interface).

2.2.3. Geometry simplification and design update

To reduce the computation time, CAD geometry may be simplified. For example, fillets and chamfers can be considered as shape details not influencing the global behaviour of a structure, provided they do not exist in areas of high stress. These regions may be removed from the CAD model, allowing a faster analysis. Similarly, tangency requirements can be relaxed to enable the use of finite elements with reasonable shapes (i.e. non-distorted elements within the limits defined by each FE solver). Most CAE software offers tools for partitioning and de-partitioning the model without disturbing the manufacturing-oriented design geometry. These operators are commonly named Virtual Topology operators (Sheffer et al. 2000; Sheffer 2001; Foucault et al. 2008; Tierney et al. 2017). An additional analysis topology is generated on top of the CAD topology which reflects the simplification operations that have been performed. For example, adjacent faces can be merged to facilitate the generation of a coarser mesh. Information to drive the virtual topology operations are not covered in this paper and is left for future work. The current focus is on partitioning, equivalencing and boundary condition application.

2.2.4. *Material Data, Loads and Boundary Conditions application*

In addition to the definition of the mesh geometry and its associated physical properties, e.g. sections, thickness, inertia, etc., the FE model requires the definition of the material models and boundary conditions. Material data is associated with each finite element to cover the mechanical and thermal properties of the components involved in the simulation. For example, a thermo-mechanical analysis requires the definition of heat transfer properties, such as conductivity of a material volume, or the heat transfer coefficient on a surface. Loads and Boundary Conditions are essential settings of the FE analysis, describing the current mechanical and thermal prescribed conditions of the solution variables: displacements and rotations in stress/displacement analysis, temperatures in coupled thermal-stress analysis, etc. External loadings can be applied in the form of concentrated or distributed loadings. For example, a load can be a point force applied at a finite element node, or a pressure distributed over the surface of a set of finite elements. Application of material, loads and boundary conditions is an essential part of the simulation pre-processing which requires a high level of analyst experience to correctly define the simulation models. These operations involve lots of repetitive manual tasks, such as the selection of the geometry, the selection of the boundary condition and the input parameters. On a large structure, such as a full aero engine, the definition of boundary conditions can take up to six months of work for a trained FE specialist. Each component-to-component interaction as well as fluid-to-component interaction should be defined. The automatic application of boundary conditions is described later in Sections 4.4 and 5 as a key application of the simulation intent ontology.

Better integration between the design and the simulation requires a new CAE level, independent of any solver, which can capture and structure the geometrical information and physical attributes required for the simulations. In this paper, the main requirement of this high-level CAE model is to maintain the links between different representations of the same product and to generate appropriate partitions of the initial geometry so that the material, loading and boundary condition attributes can be uniquely and accurately defined. In the next section we review the related work available in the literature concerning CAD/CAE integration models.

3. Related works

3.1. Existing CAD/CAE integration models

Regarding interoperability between CAD models and FEA/CFD models, different approaches have been proposed in the literature. A first type of integrated technology involved the development of algorithms and shape transformation operators to semi-automatically/automatically adapt a 3D CAD object (Zhu and Menq 2002; Lee et al. 2005) or an equivalent tessellated model (Léon and Fine 2005; Gao et al. 2010)) into an idealised model ready for meshing. The review by (Thakur, Banerjee, and Gupta 2009) presents a complete list of simplification techniques employed to simplify CAD models. We can add to this review the work of (Danglade, Pernot, and Véron 2014; Danglade et al. 2017) which uses artificial intelligence techniques to defeature CAD models for simulation and to estimate the impact of model simplification on the analysis results. AI technologies are promising but still face challenges in the number of available examples to learn from, in the number of different requirements posed by the various simulation domains and in the efficient processing of complex CAD shapes. As the target is to simplify CAD geometry, (Danglade et al. 2017) select input variables mainly based on geometric changes of the CAD components, e.g. distance between the original and simplified geometry, volume, curvatures, bounding boxes, … Such geometric criteria are a first step to remove small geometry regions; however, CAD/CAE idealisation should consider the physical behaviour of geometric regions as well as, at the assembly level, the function and purpose of the components (Boussuge, Shahwan, et al. 2014). The idealisation problem is not only a pure geometric issue, it also involves the analyst idealisation knowledge regarding a given simulation objective. Indeed, at the early phase of the model preparation, the expertise of an analyst drives the selection of components to include in the simulation, considering the component purpose and the physical phenomena to analyse. For example, an O-ring seal component may have a strong influence in fluid-related simulation but a much smaller one for stress/displacement analysis. Geometric criteria should also be extended to identify some specific volume sub-domains and interfaces between components, e.g. the identification of regions which can be dimensionally reduced into 2D shells or 1D beams (Chong, Kumar, and Lee 2004; L. Sun et al. 2017b) can help the analyst to apply efficient meshing and simulation strategies.

A complementary category of CAD/CAE integration focuses on the FEA methodologies and knowledge capitalisation in simulation data management. (Shephard et al. 2004) proposed a simulation environment for engineering design (SEED) to integrate tools between CAD and CAE disciplines. SEED includes two-way communication between a simulation model manager and an adaptive control tool to communicate information on design changes and simulation performance. The design model still needs to be defined upfront and linked to the abstract component model. An integrated framework has been proposed by (Gujarathi and Ma 2011) which uses a “common data model” containing the parametric information for both CAD modelling and CAE analysis. This framework builds the parametrisation of CAD and FE models simultaneously. Mapping parameters between CAD and FE is required for all applications, however, this mapping is still application dependent. (Badin et al. 2011) also proposed a knowledge management method to share parameters and expert rules between design and simulation. Yet, relationships between dimensional parameters of CAD and simulation models are not always available. (Pinfold and Chapman 2001) use Knowledge Based Engineering (KBE) techniques to help define a FE model, including its mesh generation. KBE aims at capturing the design intent as well as structural engineering knowledge. Rules can be defined to transform the input geometry into the targeted FE model. The limitation is the upfront investment required to gather knowledge and to implement the rules and constraints in the KBE system. In addition, this approach requires a strong investment at the early stage of the design to ensure that a CAD model is generated using the appropriate KBE design rules. (Xia et al. 2016) proposed a feature-based mechanism to automatically update the boundary conditions (BCs) when the CAD geometry is changed. Defining a BC as a feature in the geometric kernel allows the identification and retrieval of the topological entities affected by the model changes. The user, however, must define the initial BCs manually. In addition, this approach generates a dependency on the CAD application, complexifying the transfer of models to different CAE environments.

Our goal is to minimise the impact of the CAD/CAE integration processes used on the current Product Development Process. In large companies, CAD design protocols and CAE modelling processes are standardised. Modifying these in-house processes is difficult. Instead of relying on a strong CAD/CAE interaction where the design models must initially be developed using pre-defined modelling rules, we position our research on the extraction of knowledge from existing design models. The analysis decisions can be reasoned at the knowledge level and relayed back to the CAE systems. Such an approach provides a user with a platform able to disseminate CAE modelling methods in a generic way.

3.2. Cellular modelling

To allow the manipulation of non-manifold representations, Cellular Modelling has been proposed as alternative approach for feature modelling (Bidarra, De Kraker, and Bronsvoort 1998; Bidarra et al. 2005). In an FE analysis context, the 'cellular modelling' concept has been used by (Armstrong et al. 2000; Nolan et al. 2015). In this context, cellular modelling represents the 3D space as a collection of cells with specific analysis significance to which analysis attributes can be attached. Cells can be partitioned and de-partitioned to adapt their analysis significance for different applications. Hence, it natively incorporates non-manifold category of models allowing adjacent solids to be connected at their interfaces. For example, a shared face between two solids, called a 'Cell Interface', is able to directly propagate any modification of one solid to the other. Similarly, when the simulation requires compatible meshes at interfaces, this information can directly be associated to the corresponding Cell Interfaces. A particular physical property can then be associated to a region of space. Cellular modelling offers the capability to manipulate multi-dimensional models. FE models composed of different manifold geometry can be represented, e.g. surfaces representing thin-sheet domain can be connected to volume domains meshed with 3D Hex elements. This property ensures a direct connectivity during the meshing process. Finally, as showed by (Tierney et al. 2014), the cellular model provides the geometric framework to help maintain the equivalence between several representations of an initial volume.

3.3. Ontology in design and simulation

Ontology-based approaches offer an open framework where information can be explicitly defined, shared, reused or distributed (Martínez-Cruz, Blanco, and Vila 2011). Categories of objects, properties of objects and relations between objects can be defined in the ontology vocabulary to describe a specific domain of knowledge (Chandrasekaran, Josephson, and Benjamins 1999). To capture the design intent which aims at capturing the purpose of the design (J. Kim et al. 2008) (e.g. construction history, parameters, constraints, features, etc.), various ontology-based frameworks have been proposed. The authors in (El Kadiri and Kiritsis 2015) have analysed and classified several ontology-based product models addressing PLM research challenges. Among them, (K.-Y. Kim, Manley, and Yang 2006) reported a collaborative ontology-based assembly design framework for exchanging knowledge about design and product development process: specifications, constraints, design rules and design rationale (which refers to the reason why an artefact is designed). Standard queries are developed to interrogate the AsD ontology and hence access geometric information, material or intended functions. (Chang, Rai, and Terpenny 2010) extended the AsD ontology by adding manufacturing-oriented concepts to emphasise manufacturing issues and methods of the product development process. (Barbau et al. 2012) proposed OntoSTEP, a semantic model supporting both the product geometry concepts and additional information on function, behaviour and design rationale. (Zhang et al. 2013) developed the ISAA (integrated Issue, Solution, Artefact and Argument) ontology, a design rationale model to formalise the relations between the issue and the design structure of the product. To cover design change over time, (Demoly, Matsokis, and Kiritsis 2012; Gruhier et al. 2015) proposed the spatiotemporal PRONOIA2 ontology which is used for early-design phases in the product development. Currently, the implemented ontology-based models covers specific application domains: design, manufacturing, engineering (El Kadiri and Kiritsis 2015). Simulation processes, used to test/validate a physical behaviour of the product, are not covered by the design-oriented ontologies. Here, the CAD assembly is usually in an advanced phase. As explained in Section 2.1, information on adjacency between components, non-structural domains are often not available and should be generated upfront to benefit from an ontology model.

In the simulation domain, Sun et al. (W. Sun, Ma, and Chen 2009) developed an ontology-based framework to automate the definition of FE analysis models from CAD components. A shared ontology between design and simulation is used to map the design concepts (features, form, behaviour, geometry, material …) to the FEA concepts (analysis type, boundary conditions, geometry simplification …). The application system matches the semantic information input, looking for similar existing cases stored in a case library. Then, it generates a command file for the CAE software. The latter executes the pre-processing, solving and post-processing actions. The association of the function and behaviour of the structure to analysis scenarios allows the framework to reason at the knowledge level. Currently, the proposed framework does not address the partitioning and equivalencing capability of Section 2.3. In addition, another limitation of (W. Sun, Ma, and Chen 2009) resides in the initialisation of the semantic markup which uses CAD component features. The authors use the component feature tree and/or feature recognition. However, as acknowledged in (Boussuge, Léon, et al. 2014), the feature tree can be rather complex and non-unique for a given shape. Also, its specific format, layout and information it contains is CAD system dependent and is mainly oriented to design purpose. The direct exploitation of a design feature tree for simulation remains difficult for FE analysis. The difficulty also holds in the interpretation of features, which target a particular application with weak definitions, hence lacking geometric robustness as commonly recognised in the literature. Freitas at al. (Andre Freitas et al. 2013; André Freitas et al. 2014) proposed a conceptual model and framework focusing on automating the interpretation of FE bio-simulation data. Their framework uses semantic web technologies where the user can specify data validation rules on the model parameters and analysis rules to express the expected model. Although this framework shows the potential of an ontology approach to facilitate the interpretation of simulation results, the input model is already a fit-to-analyse model.

To benefit from a CAD/CAE ontology framework (W. Sun, Ma, and Chen 2009), it appears important to set up a link between the shape geometry and structure of the CAD components and the simulation modelling hypothesis. As mentioned in (Andre Freitas et al. 2013), the connection between the symbolic and geometry levels is still an area of research. Now, the main difficulty in FEA pre-processing not only holds in the generation of the FE mesh model (Foucault et al. 2008; L. Sun et al. 2017b; Tierney et al. 2017) but addresses also the generation of the boundary conditions (Boussuge et al. 2012; Nolan et al. 2015). When considering a standalone component analysis, the boundary conditions derive from the interaction between this component and its surrounding environment. For example, a bearing force applied on a cylindrical face informs the simulation that a non-represented bearing component interacts with the simulated one. In assembly FEA, the interactions between the meshed models should be defined explicitly. The extraction of geometric interfaces (Shahwan et al. 2013) between components is a first step to couple geometric regions, e.g. a planar contact between solids, with a specific modelling hypothesis, e.g. a mesh mating condition. Reasoning at the assembly level is essential to assembly simulation but can also contribute to more local simulations targeting standalone components, i.e. automatically applying the boundary conditions using its non-represented touching components.

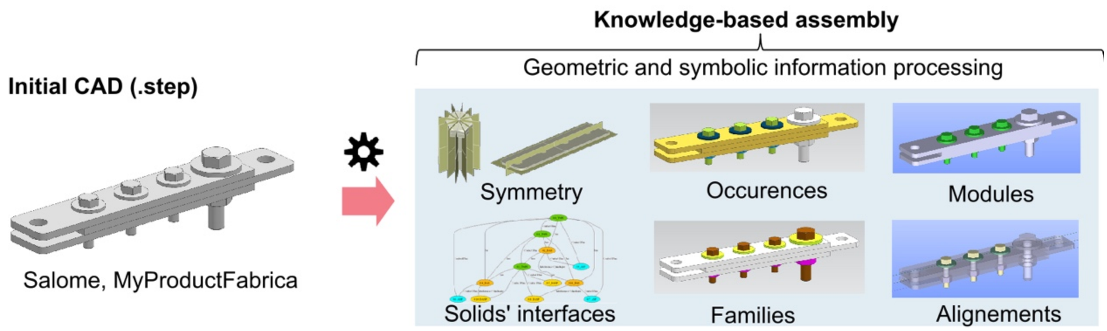

Figure 3 Geometry processing of a CAD assembly in the work of (Vilmart, Léon, and Ulliana 2018). New symbolic information is extracted from a B-Rep CAD model and stored in a knowledge-based assembly model. Examples of extracted information: orthogonal symmetry of components, interfaces between components, repetitions of components (occurrences), families of components, repetitions of sub-assembly (modules), alignments of components (rectilinear, circular).

In (Vilmart, Léon, and Ulliana 2018), the authors automatically identify intrinsic shape descriptor information, such as symmetries, occurrences of components and interfaces between components from a geometric analysis of the CAD assembly (see Figure 3). This information is then exported to a knowledge-based assembly model where inference rules are used to deduce further information, such as repetitions of sub-assemblies. The proposed assembly ontology adds new B-Rep shape information (not present at the design stage) directly available for FE pre-processing. However, CAE requires additional knowledge to describe the complete 3D model space. Often, high-level modelling and idealisation decisions must be applied not only to solid structural parts but also to adjacent void volumes containing air, gas, cooling fluids etc. Currently, the fluid domain, which is used in various simulations (CFD, thermal, acoustics, etc.), is not represented as a volume in the initial CAD assembly. The fluid boundary, as well as the fluid/structure coupling, should be included in the knowledge-based assembly model as they are important regions of the model. In addition, when setting up a simulation model, the components themselves might be subdivided into sub-regions with distinct analysis significance, e.g. long-slender regions to be represented as beams, thin-sheet regions to be represented as shell mid-surfaces, non-structural mass, etc. (see Section 2.2.2). This idealisation knowledge should also be added to the knowledge-based assembly model.

Based on prior work, it appears that an ontology-based approach is suited to capture the simulation intent in order to improve the automation of analysis model generation. Cellular Modelling is an appropriate representation to handle multi-dimensional geometry and to partition the 3D space. The following section details the proposed simulation intent ontology and shows how symbolic information about component physical domains, morphology and representations are extracted using two simulation intent capabilities: cellular modelling and equivalencing.

4. Semantic representation based on ontology for simulation intent

4.1. Evolving simulation intent toward ontology-based implementation

Simulation intent capabilities have been demonstrated in (Nolan et al. 2015) by using a relational database implementation where the CAD topology and key geometry information are stored using data relations (Tierney et al. 2014). Using this architecture, B-Rep geometry or topology can be accessed quickly through SQL queries. As explained in (Martínez-Cruz, Blanco, and Vila 2011), a database schema is designed to meet the requirements of a particular application. To share the knowledge across the design, simulation and manufacturing functions, ontology systems appeared as an alternative to a database, as the focus is not at the data level but at the knowledge level.

Hence, to allow the analyst to apply pre-defined inference rules independently of the data, we propose in this work to evolve the simulation intent concept toward an ontology-based implementation. Within our perspective, the advantages of an ontology are: (a) it allows us to define axioms, i.e. statements that say what is assumed to be true in the domain of knowledge (W3C Working Group 2012) describing a product as an existing object, an artefact, which may be geometrically represented using a B-Rep CAD or CAE model; shared concepts in the CAE domain and their relations can be formally and explicitly defined; (b) it is independent from a CAD software implementation since it operates at a higher level of abstraction. The simulation intent taxonomy is defined in the ontology and the inference rules can capture idealisation modelling guidelines.

As shown in Figure 4, the proposed pre-processing process uses an ontology-based framework to automate or support the tasks required in the simulation intent formulation. The initial input is a CAD assembly model. Following the generation of an equivalent B-Rep Cellular Model, the first phase automatically extracts the symbolic information of the Cellular model and stores it in a triplestore knowledge database. For example, information on cell adjacency, material, etc., is exported (see Section 4.2.4 for more details on the transfer of the cellular model information to the database). Then, the analyst can define/formalise the simulation objectives, select hypotheses and apply modelling practices as ontology rules on the extracted data (see Section 4.4 showing examples of inference rules). New facts are inferred from the inference rules selected by the user. As an example, regions to idealise will have a new specific idealisation simulation attribute attached following the application of an idealisation decision rule. Interfaces between solids and fluids can also support certain boundary condition simulation attributes. This automatic simulation attribute definition aims to reduce the pre-processing time and to avoid user manual selection errors. Different CAD/CAE packages can access the knowledge-base to query the simulation attributes associated with the cellular model. The geometric transformations can then be automated in the CAE environment by querying the idealisation decisions and by reading the analysis attributes attached to the cellular model. Section 5 shows applications of the proposed ontology. In this paper, the ontology is pre-defined with concepts, relationships and inference rules. In an industrial context, the ontology will evolve, be updated to correspond to the specific practices and knowledge used by the analyst. The following section introduces the main symbolic ontology concepts and relations initially proposed in the ontology.

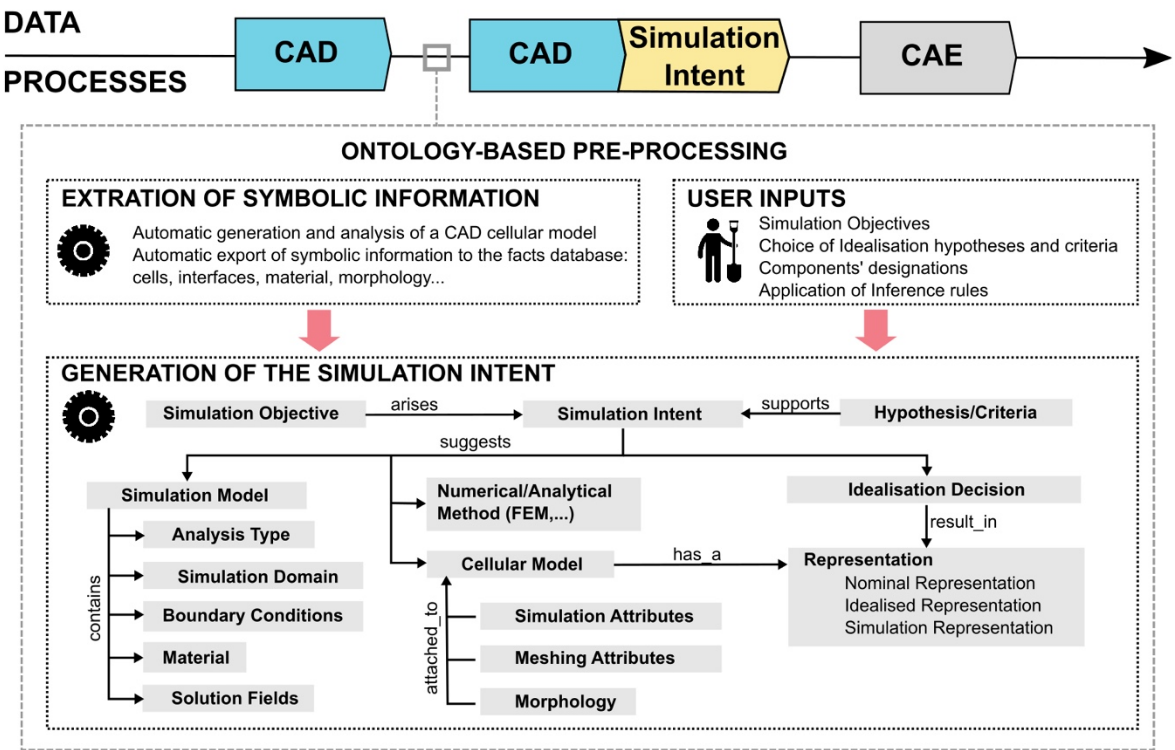

Figure 4 The concepts elements and relationships in the Simulation Intent ontology

4.2. The Simulation Intent ontology:

Based on the above requirements for a Simulation Intent framework, this paper proposes an ontology-based semantic representation. The Simulation Intent ontology is used to formally and explicitly represent the modelling information used during the preparation process transforming CAD assembly model into FE models. The ontology uses a set of shared concepts, relations and rules to describe the reasoning for defining the Simulation Intent in multiple CAE applications regardless of the CAD source. In the scope of this paper, it should be noted that the proposed examples and contents are not an exhaustive attempt to capture all the capabilities found in commercial packages. Rather, the intention is to demonstrate the capability of the proposed approach in the knowledge domain of a mechanical/thermo-mechanical analyst.

Definition 2. The Simulation Intent ontology is a conceptual knowledge base. The vocabulary defining the ontology is composed of a set of concepts (which represent the kinds of entities in the application domain) and a set of relations (which represent the kinds of relationships between these entities). The ontology also contains a set of rules, which represent the analysts' knowledge, generating new facts from inferred information.

In this paper, we define eight elements involved in the Simulation Intent knowledge using a conceptual graph knowledge-based language: **Simulation Objective** concept, **Simulation Model** concept, **Analysis Type** concept, **Cellular Modelling** concept, **Representation** concept, **Material** concept, **Analysis Attribute** concept, **Meshing Attribute** concept and **Morphology** concept.

The relations of the Simulation Intent ontology define the semantic relationships among the ontology, such as the inheritance relation ("IsA"), the association relation ("PartOf"), the equivalent relation ("IsEquivalent"), the holding relation ("HasX"), as well as specific Simulation Intent relations. As shown in Figure 4 , a simulation intent arises from a simulation objective, which can be defined as an "Arises" relation. A simulation intent suggests a simulation model, a resolution method, a cellular model and idealisation decisions, which can be defined as a "Suggests" relation. Figure 4 shows the principal concepts and relations defining the Simulation Intent ontology. The following sub-sections detail the main concepts and relationships of the SI ontology. This list of CAE-oriented concepts is not exhaustive (or prescriptive) and is given as an example to demonstrate the application of ontology rules in the following sub-sections.

4.2.1. Simulation Objective concept

Just as in a physical test, a FE virtual analysis has a specific objective: a simulation objective, e.g. the type of behaviour to be observed, such as maximal displacements in a particular area, maximal loads under a prescribed mechanical behaviour, accuracy of the expected results, etc. In a product development process, the simulation objectives represent questions that need to be answered to validate a given product design.

Definition 3. Simulation Objective concepts are abstract entities used to describe the motivation and objectives of a particular analysis of an artefact. It must be related to some parameters of the solution fields, i.e. maximum stress/displacement, pressure, etc.

4.2.2. Simulation Model concept

As described by (Szabo 1996), the first formulation of the model behaviour phase consists in building a theoretical model integrating the mechanical or thermo-mechanical behaviour laws representing the physical system. The analyst specifies and identifies the key attributes of the physical system and the characteristic values of the mechanical behaviour: the simulation hypotheses.

Definition 4. The simulation model concept formulates the model behaviour from the simulation objectives. It defines the boundary conditions, material behaviour law, shape domain, symmetries, set independently of any numerical or analytical method used to compute solutions fields.

4.2.3. *Analysis Type concept*

An analysis type reflects the physics to solve to answer the simulation objectives. The CAE model highly depends on the physical behaviour being analysed. For example, a static stress/displacement simulation will solve for the mechanical behaviour of structural components, while an acoustic analysis simulation requires solving for the sound wave propagation in the fluid domains. Then, the analysis type is the first driver in a CAE rule determining the regions to consider in the simulation and helping define the simulation model.

Definition 5. The analysis type concepts are abstract entities used to represent the physics to be solved in order to answer the simulation objectives.

Although, some methods may be specific to a particular numerical method or CAE solver, the analysis type can generally be classified regarding the physics and coupling involved. Figure 5 shows a partial hierarchical classification of CAE analysis types.

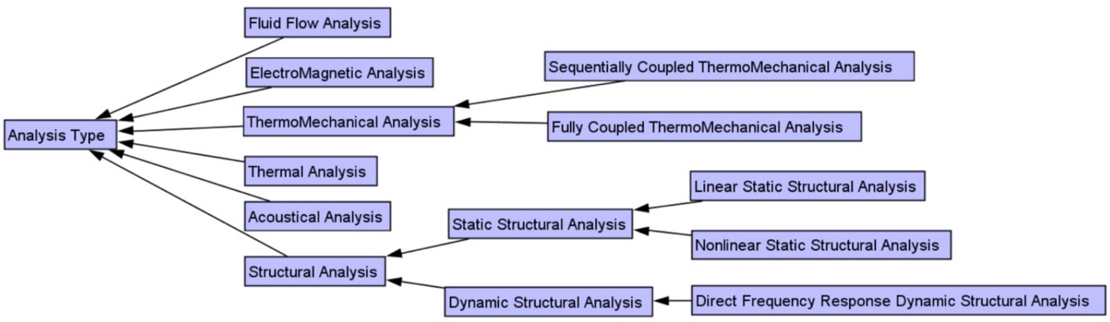

Figure 5 Analysis types.

4.2.4. *Cellular modelling concept*

Cellular modelling defined in (Armstrong et al. 2000; Nolan et al. 2015) is a division of the 3D design space into regions of significance, called cells, that simulation attributes can be associated to. In our context, the cellular model is used to set up a link between the CAD geometry and the simulation objectives of the analyst, defined as symbolic information in the ontology.

<u>*Concept of cell and simulation attribute*</u>
Cellular modelling introduces the concept of '*Cell'* to represent a specific region of the 3D space. A *Cell* is oriented and homogeneous with regard to its manifold dimension. It can be a volume, a face, an edge or a vertex. Table 1 lists the terminology regarding the dimensionality of the manifold the cell is representing.

Table 1 Terminology of Cells in the Djinn API (Armstrong et al. 2000)

Manifold Dimension	Cells with non-empty boudary	Cells with empty boundary	Cells forming the frontier of other cells
0		Point	Vertex

1	Arc	Curve	Edge
2	Patch	Surface	Face
3	Solid	Solid (the whole domain space)	

Definition 6. The cellular modelling concepts are an aggregate of concepts describing the partitioning of the 3D space into geometric domains which can be a volume, face, edge or vertex.

In this paper, we assume that a CAD model initially exists and is used to divide the whole space into solid cells with non-empty boundaries. Thus, volumes are bounded by faces, faces by edges and edges by vertices. As explained in section 2.2.3, a cellular model can be of any manifold dimension, e.g. a solid or fluid volume, a non-manifold T-section of three surfaces meeting at a common edge, a network of 1D wires representing a truss or even a 0D point representing a mass and inertia (Nolan et al. 2015).

To generate the cellular model, the Parasolid API (Siemens plm software 2018b) is used. A CAD file is imported into Parasolid and Boolean operations are applied on the set of 3D B-Rep solids to generate a non-manifold B-Rep model (Nolan et al. 2015; Tierney et al. 2014). Each volume region of the non-manifold model is associated with a *Cell* of type '*Solid'* named *CellSolid.* A solid region in a non-manifold model is bounded by faces. This is similar to a solid in manifold geometry except that a face can be shared by two adjacent solid regions and an edge can be shared by *n* solid regions ($n > 1$). Hence, each CAD component solid is associated with a set of *CellSolids* using specific attributes attached to them. A *CellSolid* represents a:

a. Structure, i.e. the regions initially defining the input B-Rep solids minus the interference between solids (if any);
b. Void, i.e. the regions generated by the Boolean subtraction of the structural cells from a bounding solid as box surrounding the assembly;
c. Interference, i.e. the regions generated by the Boolean intersection between the initial B-Rep solids.

The 'Material concept' (see section 4.2.6) can automatically be associated to the *CellSolid*s regarding the '*PhysicalDomain'* (structure, fluid and interference) they represent. For example, a casing component of an aero-engine product is defined as a *CellSolid* with a material attribute of type '*Structure'*.

Figure 6 illustrates the cellular modelling concepts utilised when transferring CAD manifold solids to a non-manifold cellular model geometry. Initially, the imported CAD solids are represented by 3D solid cells. New cells of type fluid and interference are generated. Contacts between solids are explicitly defined as interface cells, named *CellInterface,* of manifold dimension two. Then, this cellular model information is described as symbolic information and concepts in the CAE-oriented ontology.

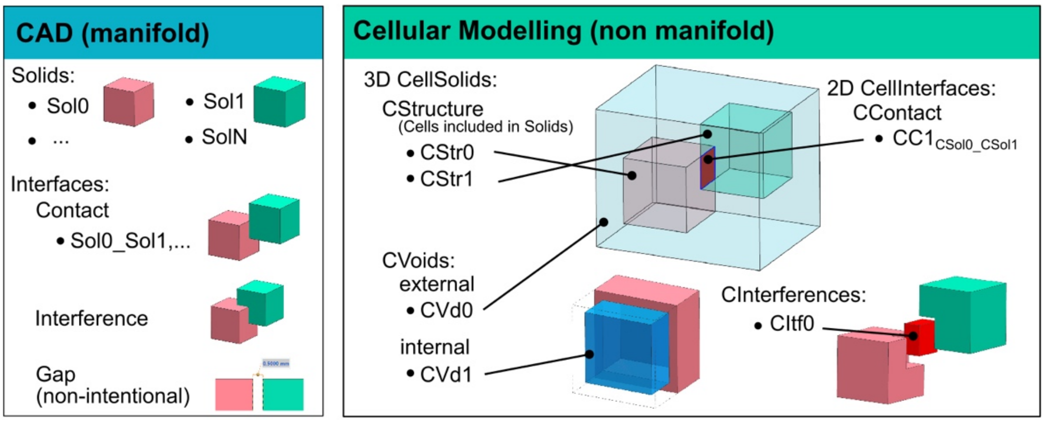

Figure 6 Transfer of CAD solids to a cellular model.

Interfaces between cells

Information about interfaces between CAD components is crucial for FEM analysis. Contact areas should be explicitly defined to model the interaction between components (Boussuge et al. 2012). When a FE analysis involves multiple physics, e.g. thermo-structural, aero-acoustic, vibro-acoustic, the geometric areas where the physical equations are coupled must be defined. Having a cellular model, where all the 3D domains are defined through cells, allows us to directly access the common boundary between cells. These common boundaries, e.g. shared faces, can be described as a *CellInterface*. A *CellInterface* can be classified depending on its manifold dimension:

- Dimension three: it corresponds to all the *CellSolid* having a physical domain '*Interference*'. This category associates the interference domains between structural components as *CellInterface;*
- Dimension two: it corresponds to all the common faces between *CellSolid*. This category represents most of the *CellInterface* found in a mechanical product, where a particular contact or interface condition can be applied later in the simulation model;
- Dimension one: it corresponds to common edges between *Cells*. This category includes the configuration where the intersection of two cell solids is a curve, e.g. a cylinder lying on a plane. It also includes the common boundary *CellInterface* between *Cells* of dimension two. *CellInterface* of dimension two can be reduced to a *CellInterface* of dimension one after the dimensional reduction of a 3D cell to its equivalent 2D mid-surface representation;
- Dimension zero: it corresponds to common vertices between *Cells*. This category includes the common boundary between *CellInterface* of dimension one. It can also refer to a contact point between *CellSolid*.

A *CellInterface* is of course also a cell. This classification of *CellInterface* is defined in the CAE-oriented ontology as a new concept. Figure 7 illustrates a simple model containing seven cells of the three physical domain types: structure, fluid and interference. For each interface between cells, two new RDF triples (see Section 5.1 for the proposed software architecture) are generated linking the *Cell* to its *CellInterface*. For example, the triples '$Cell_i$ – *HasCellInterface* – $CellInterface_k$' and '$Cell_j$ – *HasCellInterface* – $CellInterface_k$' expressed the fact that $Cell_i$ and $Cell_j$ are connected through the $CellInterface_k$. This adjacency information can directly benefit the automatic application of boundary conditions (see Section 4). For example, having the explicit representation of the fluid domain, the interface between fluid and structure can be accessed through a SPARQL query returning all the *CellInterface* in relation with a *Cell* having for physical domain '*Structure*' and a *Cell* having for physical domain '*Fluid*'.

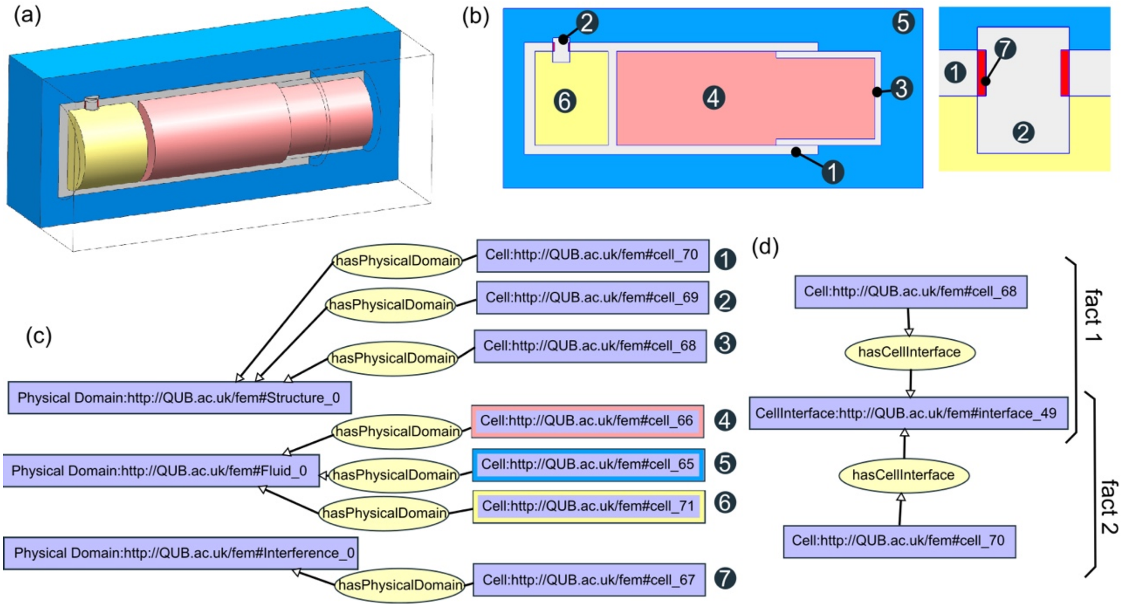

Figure 7 Insertion of cellular modelling facts: (a) initial cellular model containing three structural cells [1, 2, 3], three fluid cells [4, 5, 6] and one interference cell [7]; (b) section view of the cellular model; (c) graph of relations between cells and physical domain; (d) example of an interface expressed through two facts.

It should be noted that functional clearances between components, i.e. clearances larger than the CAD modeller tolerance, as described by Shahwan (Shahwan et al. 2013), are not defined at this stage as interface cells. Indeed, clearances are not explicitly defined at this stage of the cellular model. The initial fluid cell should be divided into sub-cells of type cavity and sub-cells of type gaps. Like the morphological analysis described in Section 4.2.9 on structural cells, further analysis of the geometry of the fluid domain should be developed to identify narrow regions considered as functional clearances. This analysis can particularly benefit from the symbolic information extracted in the work of Vilmart et al. (Vilmart, Léon, and Ulliana 2018) to help identify the regions to search for functional clearances, e.g. clearances in a fastener junction. This complementary processing of fluid domains is reserved for future work.

4.2.5. Representation concept

As explained in Section 2.2.1, CAD models use a B-Rep representation to define the nominal shape of a component. An FE simulation may use an intermediate idealised CAD geometry adapted to a given simulation objective. Then, FE simulations use a discrete meshed simulation representation of the structural or fluid domains. Additional representations of a given cell can be used for geometry pre-processing, e.g. a Medial Axis geometry, representing the skeleton of a 3D solid, can be used to identify specific sub-regions (Robinson, Armstrong, and Fairey 2011) considered as details. The concept of representation is then introduced to associate a given cell with an equivalent nominal, idealised or analysis representation, which can be either exact (CAD) or approximate (FE mesh, or tessellated model for visualisation).

Definition 7. The representation concepts are abstract entities used to describe the equivalence between different representations of a given cell. The representation concepts include the concept of nominal representation (usually represented as a CAD B-Rep model), the concept of idealised representation to represent an intermediate cell simplified for a given FE analysis and the concept of simulation representation describing the model used as input geometry (usually represented as a FE discrete mesh for FEA).

It should be noticed that the shape of a component can vary during the lifecycle of a product. For example, an engine casing component will have a cold and a hot shape depending on the thermal loading applied at a given phase of the engine cycle. Deformable components, e.g. seals or elastic rings can be represented in their undeformed or deformed (mounted) shape. This variation in the nominal representation of a component refers to the notion of lifecycle of a product. A temporal dimension, as defined in spaciotemporal ontologies (Demoly, Matsokis, and Kiritsis 2012), is required to consider representation changes due to operating conditions. In this paper, the concept of lifecycle is left for future consideration. All the components of a given CAD assembly are considered to have a unique in-use nominal representation.

4.2.6. *Material concept*

Material properties of components or fluid domains are expressed as parameters that are shared across simulation, design and manufacturing functions. Often, a material library is available for each individual CAD/CAE software. With the ontology approach, there is an opportunity to link a Cell to a shared material database, e.g. MatWeb (MatWeb 2018) or even to merge with a material ontology as defined in literature (Zhang and Luo 2014).

Definition 8. The material concepts form a hierarchical structure according to the physical, chemical and mechanical properties of a domain.

Fluid regions, e.g. air, water, oil, etc., surrounding the structure must be defined and discretised for FE or CFD analyses. Here, where the starting point is a CAD assembly, the fluid regions don't exist, i.e. they are not modelled explicitly and are only implied by the assembly components. Our proposition is to generate the fluid regions using a cellular model where the fluid domains are modelled and represented in the same way as the structural components. Within the non-manifold model, the void cells are generated as the subtraction of the structural components from their surrounding bounding box. In this paper, the void cells are initially considered to represent fluid domains. Hence, for every cell, a symbolic information '*Material'* is associated to it, e.g. '$CellSolid_i$ *– HasMaterial – FluidMaterial*$_j$'.

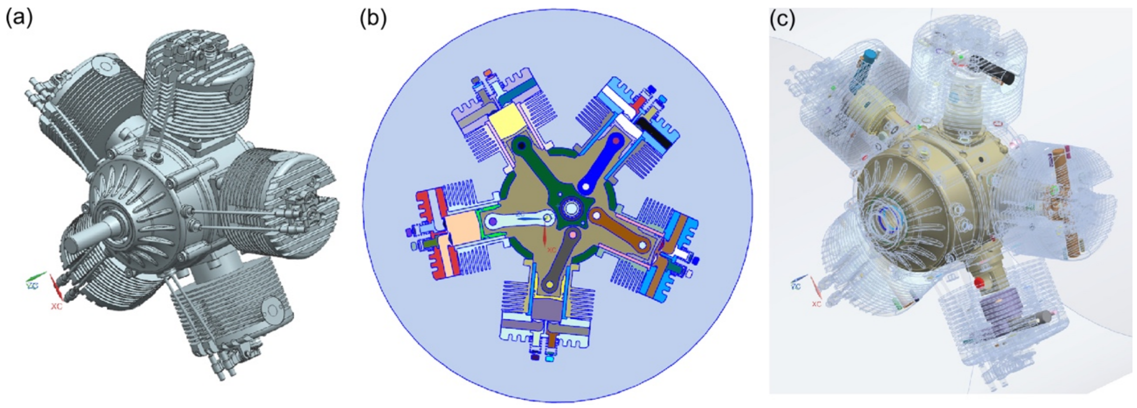

Figure 8 Example of fluid domains in a cellular model: (a) the initial CAD assembly (model from the GrabCad community (Stratasys 2018)), (b) 2D section view of the cellular model, (c) internal fluid domains exported as B-Rep solid models in a CAD environment.

Figure 8 represents a cellular model of a radial engine. This model contains 380 *CellSolid* of type '*SolidMaterial*, 150 *CellSolid* of type '*FluidMaterial*' and 36 *CellSolid* of type '*Interference*'. Currently, all fluid domains are associated with a unique material type. No distinctions are made at this stage between interior or exterior fluid domains or between the physical properties of the fluid, e.g. air, oil, gas-air mix, which are sub-concepts of the fluid material (e.g. compressible or incompressible fluid). As mentioned in Section 7, in future work, a better description of the material could be derived using inference rules looking at the connection between the fluid *CellSolid* and the surrounding components, e.g. a piston component. With additional partitions or *CellInterface* the separate cells to represent air, oil or gas-air mix can be defined.

4.2.7. Analysis Attribute concept

Analysis solvers require physical properties, e.g. a thickness of a 2D shell finite element, to be applied to each element. The type of contact between meshes should also be specified. The simulation also requires the definition of boundary conditions (loads, displacement constraints). This concept is introduced into the ontology to be able to express the relationship between CAE attributes and *CellInterface*. These associations will be the results of the user's inference rules. After defining a specific analysis context (e.g. selection of the analysis type, hypotheses, idealisation decisions) the user can select pre-defined inference rules which will automatically infer the analysis attributes that need to be applied. For example, a shell to solid constraint can be automatically attached when a *CellInterface* linking a 2D-shell *Cell* and a 3D-Tet *Cell* is found. This automatic process aims at saving time and avoiding selection errors in the simulation attributes definition.

Definition 9. Analysis attribute concepts are properties used to describe the physical behaviour of a region of space described by a cell of a cellular model. It includes the subconcepts of Boundary Conditions and Physical property.

Specific FE boundary conditions can then be attached to a Cell, for example to impose a specific pressure field to a set of FE nodes. It can also be used to describe the interaction between components of an assembly. For example, a thermal contact condition to apply between two mechanical components becomes an analysis attribute associated to the *CellInterface* shared by the *CellSolids* of the two components.

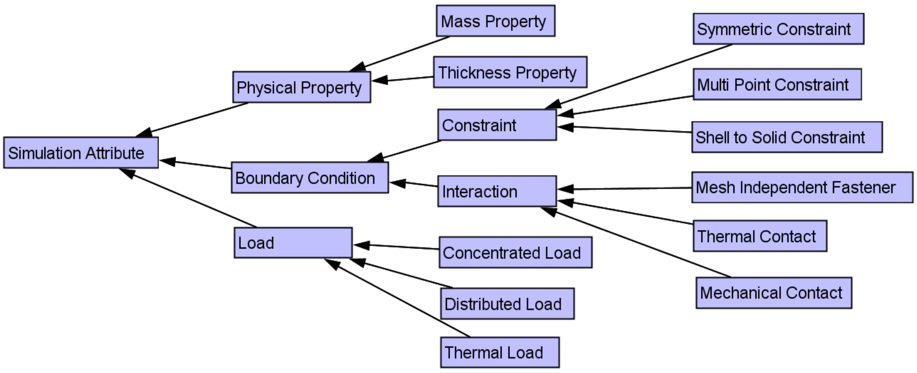

Figure 9 A subset of *Simulation Attribute* sub-concepts

4.2.8. Meshing Attribute concept

Similarly, meshing attributes can be attached to *Cell* to drive the meshing process. Usually, choosing the appropriate finite element for an analysis type is one of the first questions an analyst should answer. Meshing attributes, for example element type and mesh mating conditions are introduced into the ontology to appear into the conclusions of some inferences. The meshing attributes derive from the analysis type and the geometry of a cell, where for example tetrahedral or hexahedral elements may be more desirable depending on analysis and geometric characteristics. An advantage of the ontology-based approach is to automatically infer the meshing attributes once the analysis type, simulation hypotheses, etc., have been selected by the user. Finally, the simulation intent is suggesting a certain element type corresponding to a given simulation objective; the ontology reasoner is used to infer this information.

Definition 10. Meshing attribute concepts are properties used to describe the specific finite element to be used in the FE mesh for each region of space. This attribute is associated to a cell of a cellular model in conjunction with the prescribed simulation objectives. It includes the subconcepts of element type, element size and interaction element model.

Usually, a component corresponds to one *CellSolid* which is discretised by finite elements which could be volume hexahedral or tetrahedral elements, dimensionally-reduced surface elements, such as 2D shell, or 1D beam elements. When a component is divided into several regions modelled by different element types, the corresponding cellular model may contain several cells where a specific meshing attribute is associated to each of them. Often, to represent standard connections, such as a bolted junction, the analyst applies a simplified representation of the connection linking the degrees of freedom of the nodes in contact with others belonging to different components of the junction. Figure 11 illustrates a spider connection used to model a bolted junction. As an example, this specific connection model is added in the ontology as a sub-concept of the meshing attribute concept.

4.2.9. Morphology concept

As described in Section 2, a segmentation of CAD components might be required to apply a particular meshing strategy over regions of interest. In this paper, we show the capability to store embedded partitions of component cells by segmenting thin walled CAD models for hex-dominant meshing using the tools of Sun et al. (L. Sun et al. 2017a, 2017b). The tool subdivides a B-Rep solid model into regions producing appropriate sub-solids for hex-meshing or dimensional reduction operations. The automatic operators analyse the initial shape and identify:

- Thin-sheet regions: regions with large lateral dimensions relative to the thickness (see the green regions in Figure 10)
- Long-slender regions: regions where the characteristic dimension in one direction is much larger than that in the other two (see blue regions in Figure 10)

This segmentation allows us to define the concept of morphology which can be associated with a solid cell, e.g. '*CellSolid$_i$ – HasMorphology – ThinSheet*'. This morphology characterises the shape of a cell independently from a discretisation parameter like FE size.

Definition 11. Morphology concepts are used to describe the shape of a particular region of space which contains proportions representing a predefined mechanical behaviour.

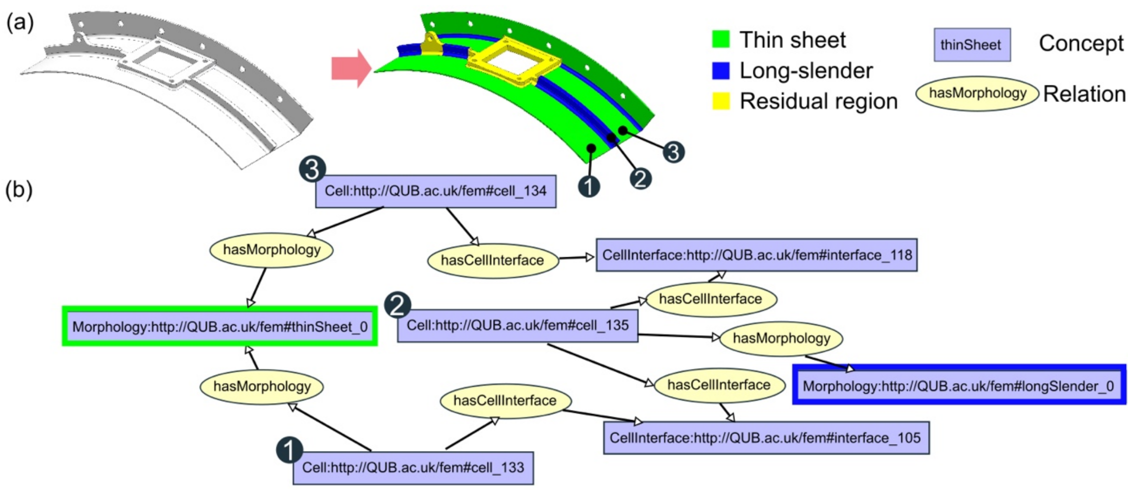

Figure 10 Morphological analysis of solid cells: (a) identification of thin-sheet, long-slender regions in CAD components (L. Sun et al. 2017a, 2017b) (b) graph representation in CoGui of the inserted facts.

Figure 10 (a) illustrates the segmentation of an initial *CellSolid* corresponding to a CAD component, into thin-sheet, long-slender and residual regions. For example, for a global stress/displacement mechanical analysis, an inference rule can be defined by the analyst to automatically associate a thin-sheet cell with a 2D shell mesh element type. The CAE software, when querying the cell morphology, will automatically know that the thin-sheet cells must be transformed into a 2D mid-surface model meshed with 2D shell elements and a thickness simulation attribute representing the missing dimension. The interface in the idealised representation is then captured through the equivalence of the 3D representation.

Additional information on simulation-oriented morphology types can benefit from feature recognition techniques which identifies specific geometric configurations (e.g. identification of fillets (Zhu and Menq 2002; Venkataraman, Sohoni, and Rajadhyaksha 2002), or ribs (Lai et al. 2018)).Similarly to (L. Sun et al. 2017a, 2017b), additional segmentation techniques can divide the B-Rep into simpler volumes adapted for a particular FE analysis (Lu, Gadh, and Tautges 2001; Chong, Kumar, and Lee 2004; Boussuge, Léon, et al. 2014; Liu and Gadh 1997; L. Sun et al. 2017b, 2017a). These techniques can also be used to generate local information on the component shape.

However, the extracted regions should still be linked to the component's purpose and behaviour. For example, a fillet feature should be linked to its mechanical purpose, e.g. avoiding stress concentration.

4.3. Relation rules and logic in the SI ontology

The concepts of the Simulation Intent ontology defined previously are linked to semantic hierarchical relationships. The main relations used are the inheritance relation ("IsA"), the association relation ("PartOf") and the holding relation ("HasX"). For example, a particular analysis attribute is associated to a cell using a holding relation (e.g. '$CellInterface_i$ – *HasBoundaryCondition* – *DistributedLoad*). Two specific relations of the Simulation Intent ontology are additionally described in the following sub-sections.

4.3.1. Parthood cell relationship

As mentioned in Section 2, CAE applications require the ability to partition the components into a set of cells. For example, components of different materials require a partitioning of the solid into cells of unique material. To allow the analyst to apply their simulation intent to a particular region of interest, we use the parthood relationship into the simulation intent ontology to describe the relations between cells. Hence, when a *Cell* is subdivided into sub-cells, a new relation is introduced to help define the link between original cells and their downstream sub-divided analysis representations. An example of fact expressed with a triple would be: '$CellSolid_i$ – *PartOf* – $CellSolid_j$'.

4.3.2. Equivalencing relationship

Depending on the CAE application, the representation of cells may differ. For example, a global structural analysis of thin components may use shell elements. A local contact analysis may use detailed 3D models. As the fidelity of a cell changes so does its interaction within surrounding cells. The notion of equivalence relationship is used to capture this link. Element types can also vary: 3D Hex, 3D Tet depending on the solver capabilities or the accuracy required. The representation of fluid regions also varies. For example, in CAE software, fluid domains are often extracted as an approximate object representation: a tessellated mesh which is then transformed into a FE/CFD mesh. The implicit true geometry (which could be represented as a CAD B-rep model) does not exist. The CAE software directly creates a mesh model adapted to the simulation requirements.

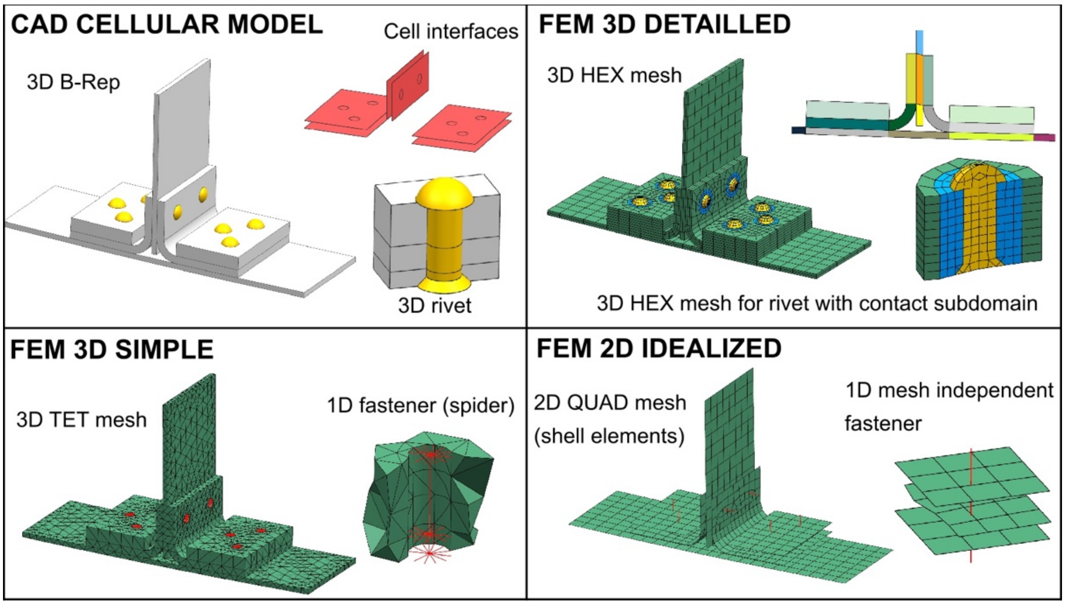

Figure 11 Equivalencing a cellular CAD model at different FE models dimension and idealisation.

As defined in (Nolan et al. 2015), 'Equivalencing' establishes the link between entities in different design and analysis models which represent the same region of space. Figure 11 illustrates four representations of the same assembly structure: a CAD cellular model contains B-Rep components as initially defined in design; a FE 3D detailed model where the solid components are meshed with structured Hex-dominant elements; a FE 3D simple model using Tet elements and a FE 2D idealised model with 2D shell elements. While these models are geometrically different, they represent the same product adapted to a particular type of simulation. Essentially, since these models are representations of the same domain they are considered equivalent to that domain, and by extension to each other.

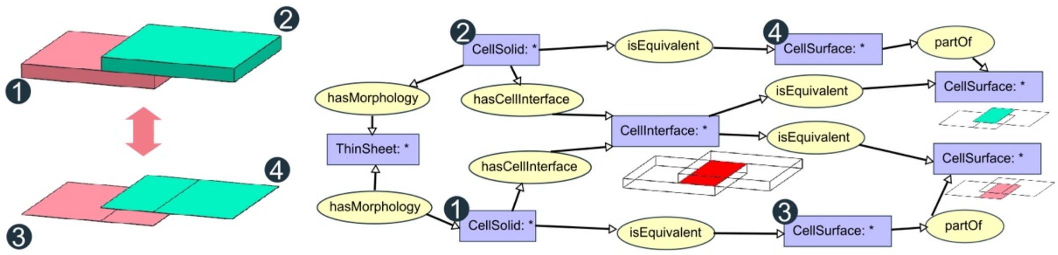

Figure 12 Deriving equivalence between 3D solid models and dimensionally reduced 2D model.

To form the equivalence between multiple representations of the same cell, a new relation type is introduced in the ontology: '*IsEquivalent'*. This relation links the cells of the initial cellular model to the equivalent cells of the simplified/idealised CAE models. For example, in Figure 12, the *CellSolid*$_1$ and *CellSolid*$_2$ have a thin-sheet morphology type. Within a global mechanical analysis context, these particular thin-sheet cells can be represented by mid-surfaces and have equivalent cells *CellSurface*$_3$ and *CellSurface*$_4$. Similarly, the equivalence of interfaces can be captured by utilising the link between the *CellSolids,* which are explicitly defined in the cellular model as *CellInterface.* In Figure 12 the dimensional reduction operation leaves no explicit interface between the mid-surface representations. However, this implicit interface is automatically derived from the equivalence relationships. After idealisation the interface is mapped to its equivalent faces using the same '*IsEquivalent'* relation. In this equivalence instance, the non-manifold interface is equivalent to two distinct manifold faces in the idealised analysis representation. These two manifold faces are part of *CellSurfaces* of their parents' mid-surfaces. Hence, in this dimensionally reduced scenario, the interfaces between mid-surfaces can be automatically derived from their equivalent cells linking the initial solid interface.

4.4. Inference rules in SI ontology

When setting-up a FEM or CFD simulation model, the analyst sequentially applies a series of operations on a CAD model in order to transform it into a simulation model suited for a particular analysis. The choice of geometric transformation, element types, and any simulation parameter is guided through modelling practices. These practices can be formalised in documentation guidelines, however, they are applied informally by the analyst, and are often based on their own modelling experience or company best-practices. With the ontology-based approach, this modelling knowledge can be formalised as inference rules. A set of pre-defined rules can be expressed using the Simulation Intent concepts and relationships described previously. Then these rules can be applied automatically to assist the user in generating the idealisation of an input CAD model. The deductive reasoning is made by an inference engine, here CoGUI(CoGui 2018), which applies a set of rules selected by the user on the set of symbolic information (generation of facts) automatically extracted from the CAD model. The inference rules are based on the '*Hypothesis/Conclusion'* logic form. The '*Hypothesis'* and '*Conclusion*' are defined interactively in the CoGUI software (see Figure 13). By defining a graph pattern to search for in the symbolic information extracted from the cellular model, the reasoner can generate new symbolic information to be read by the CAD/CAE software.

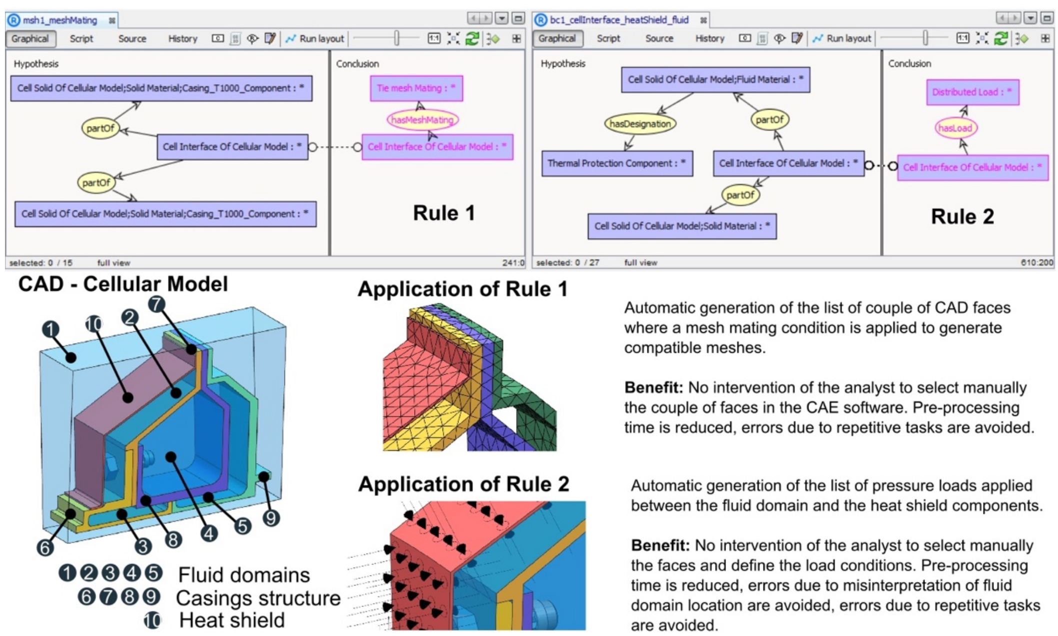

Figure 13 Examples of ontology rules defined to capture and apply modelling practices. Rule 1 infers a mesh mating condition between structural cells. Rule 2 infers a boundary condition at the interface between a heat shield cell and fluid domains.

Figure 13 illustrates two examples of pre-defined inference rules. These rules can be selected by an analyst to automatically generate simulation and meshing attributes attached to the cells (satisfying the rule conditions). In these examples, the components' designations, e.g. casing and heat shield, are given by the user using a name tag in the CAD software. This assumption is made in this work to focus on the benefit of using ontology rules to automate certain pre-processing tasks. For example, Rule 1 is associating a tie meshing attribute to all *CellInterfaces* between casing components. A CAE software, here NX CAE (Siemens plm software 2018a), can query all the interface cells having a mesh mating attribute and automatically apply the condition at the associated pairs of faces. Hence, in a scenario where the solver requires compatible meshes at the components' interfaces, the tedious pre-processing task to manually select all the mating face pairs in the model is avoided, reducing the time to generate the simulation model and avoiding user errors in the selection of faces.

Similarly, Rule 2 associates a pressure boundary condition as a simulation attribute attached to the *CellInterfaces* between a heat-shield protection component and a fluid domain. Such inference allows the robust location and selection of all the faces of the heat shield component in contact with the fluid domain. In addition, as the cellular model generates the imprints of one object onto another, the tedious task to delimit the fluid domain is also avoided. Currently, the rule does not distinguish between the interior and exterior fluid domains. Future work will develop a geometry processing and partitioning algorithm to distinguish the cavities from the exterior fluid domain in order to enrich the knowledge base allowing the user to specify an even more precise simulation intent. Additional rules are provided in Appendix (see section 9).

5. Application of the Simulation Intent ontology to speed up FE pre-processing

5.1. Software architecture for concept evaluation

Here, to maintain the compatibility of the proposed ontology with the one developed by (Vilmart, Léon, and Ulliana 2018), the same software architecture is used. In (Vilmart, Léon, and Ulliana 2018), the Salome (Salome 2018) plugin: myProductFabrica is coupled to the Cogui reasoner (CoGui 2018), developed by the GraphiK Inria team. The ontology concepts and relations are defined in Cogui and exported as an RDF (W3C Working Group 2014) file to a JENA (JENA 2018) server. Although the Salome modeller offers non-manifold geometric capabilities, pre-existing development using the Parasolid geometric modeller (Siemens plm software 2018b) is used to generate the cellular model (see Section 3.2).

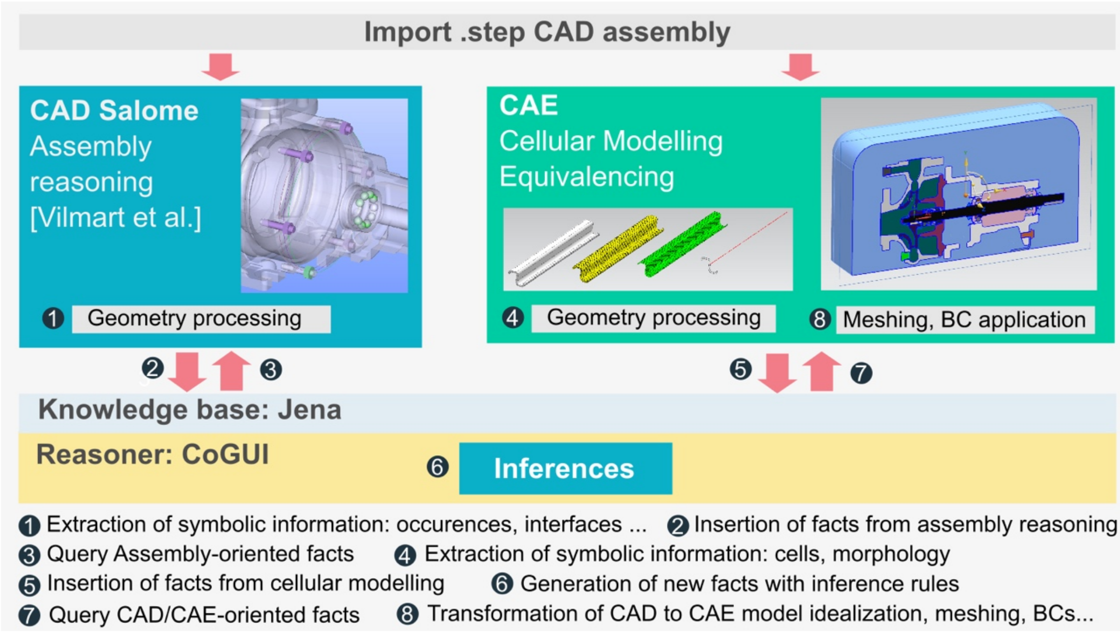

Figure 14 Research scope. The software architecture is derived from (Vilmart, Léon, and Ulliana 2018). The cellular modelling and equivalencing is developed in the CAD software NX (Siemens plm software 2018a) and Parasolid (Siemens plm software 2018b).(Siemens plm software 2018a) and Parasolid .

As an input of the simulation preparation process, we use a STEP file containing the geometrical and topological information about the CAD assembly model. This file is read by the Parasolid CAD modeller to generate the corresponding cellular model (see Section 4.2.4). The symbolic information is automatically extracted from the cellular model, then stored and processed in a JENA knowledge base describing the CAE-oriented ontology as RDF triples. For example, each *CellSolid* generates an individual, a material is attached to this individual using a relation '*HasMaterial*'.

Then, the CoGUI reasoner infers the new RDF triples from the set of pre-defined rules (modelling practices). The new symbolic information automatically generated by the reasoner is then used to drive the automatic geometric transformation operators in the CAD/CAE software (see Section 4). In addition to the CoGUI reasoner capability, a conceptual graph editing tool is available to design the inference rules replicating the CAD to CAE pre-processing practices (see Appendix Section 9). Changing these rules allows the user to quickly test and iterate different modelling practices. Figure 14 summarises the software architecture used in this paper.

5.2. Processing CAE symbolic information

In Section 3, the simulation intent capabilities have been captured as symbolic information (concepts and relationships) and inserted in the Simulation Intent ontology while maintaining the connected to the initial CAD geometry through the cellular model. The purpose of this section is to illustrate with some common examples how this ontology approach can benefit the analyst. In these scenarios, the inference rules are used to set up a ready-to-solve simulation model from a CAD model.

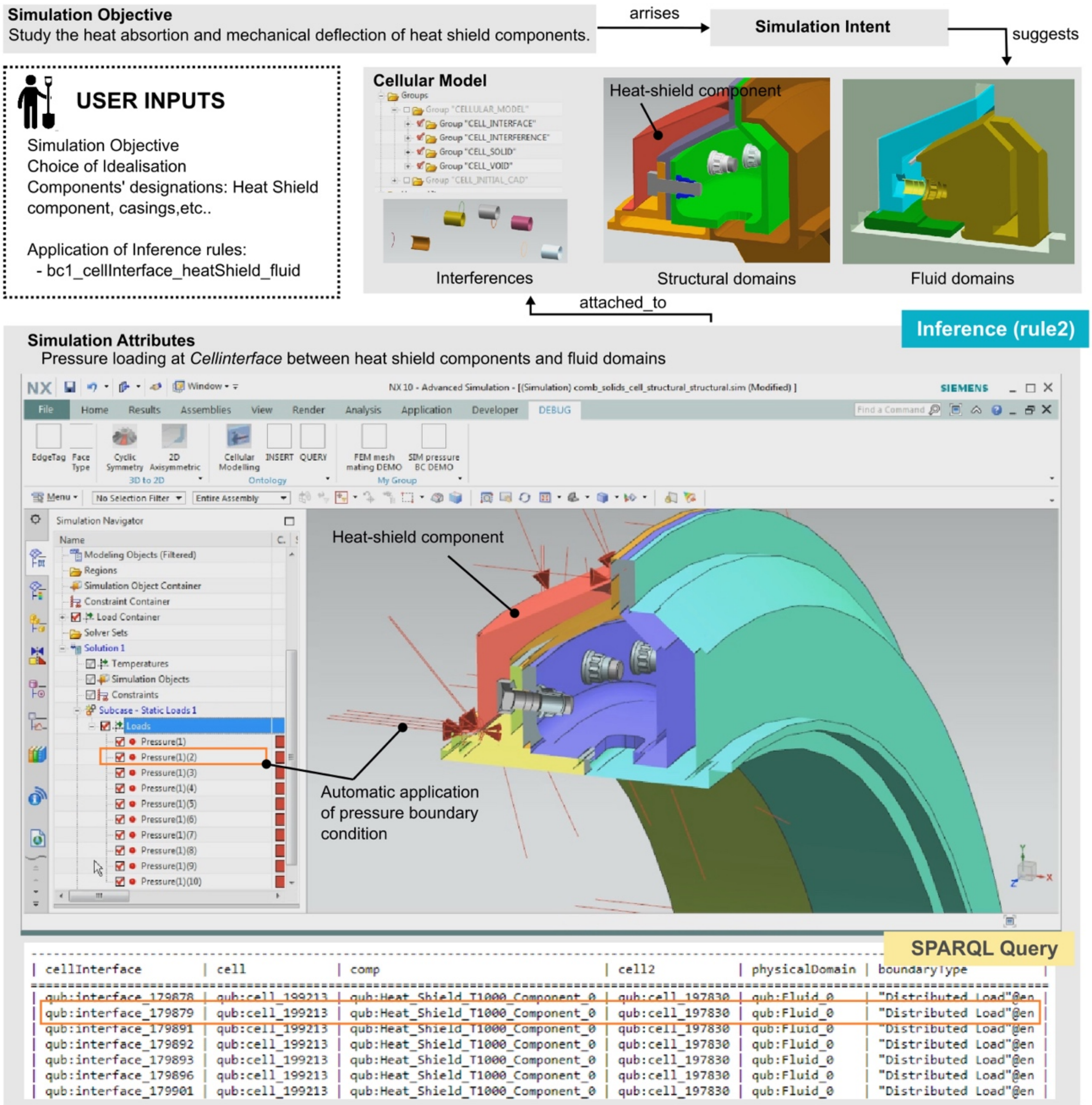

Figure 15 Example of a partial thermo-mechanical analysis simulation intent. The user selects the "bc1_cellInterface_heatShield_fluid" inference rule associating automatically a pressure loading conditions at the interface between the heat shield components and the fluid, the inference rule2 of Section 4.4 is used.

Figure 15 shows an application example of the simulation intent ontology on an assembly replicating a combustion case section. This model replicates an industrial tedious pre-processing task where the analyst has to manually define a boundary condition at each CAD face in contact with a fluid domain. In a first place, a cellular model is generated using Parasolid (see Section 4.2.3). Then, the cellular model information, the material as well as the components' designation (initially entered manually by the user) are extracted and sent as symbolic information to the JENA server. Finally, by selecting pre-defined inference rules (see Section 4.4) the database of facts is enriched with the new facts resulting from the rules. For example, using Rule 2 of Section 4.4, all the *CellInterfaces* between a heat shield component and the fluid domain have a new pressure loading attribute. Using a SPARQL query from the NX CAD environment, this information can be used to apply automatically the loading condition to the corresponding CAD faces. If one of the component solids is replaced by a different design, then the SPARQL query can be re-run giving the updated fluid volumes and the new set of faces to which the pressure loading is applied. Interferences are also captured in the cellular model of the assembly, though additional idealisation transformation are necessary before meshing the assembly. In this first example, the pressure loads have been generated automatically. In addition to the time saved by the user to manually define the loadings, the ontology-based reasoning robustly locates the entities (here the CAD faces) where these boundary conditions are to be applied.

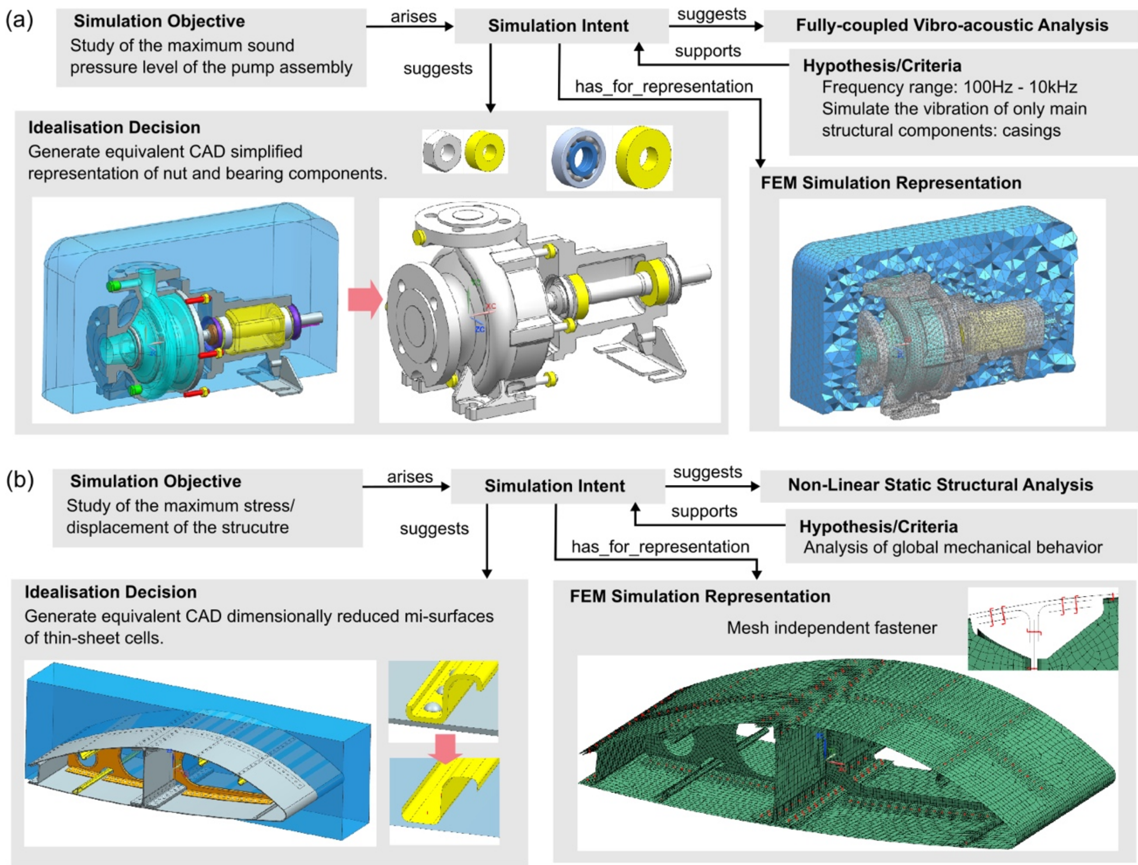

Figure 16 Two examples of FEM models derived from CAD assemblies with their main simulation intent concepts. (a) A vibro-acoustic model: the geometric cells associated to bearings and nuts are simplified; the fluid and structure are meshed with 3D tetrahedral elements. (b) A static stress/displacement model with 2D shell elements and mesh-independent fasteners (model from the GrabCAD community (Stratasys 2018)).

In Figure 16(a), the standard components, e.g. families of bolts, washers, etc., are of low interest to the analyst. For this analysis type, the user can specify a rule to use a CAD simplified representation for the *CellSolid* associated with the nut and bearing components (see Appendix in Section 9). A python script read by the NX software is used to query the components to transform and to automatically generate an equivalent simplified CAD representation. Then, the cellular model is updated to generate the simplified fluid domain to be meshed with tetrahedral elements. This scenario is an example showing how the ontology can be used to robustly define components to idealise based on a pre-defined modelling rule. Figure 16(b), the idealisation decision concerns the dimensional reduction of thin structural components and the use of mesh independent fastener FE model to define the rivet junctions. A script has also been developed to automatically generate a 1D model from a given 3D rivet and its associated *CellInterfaces*. In Figure 16(b), the analyst still benefits from a reduced pre-processing time (especially in the transformation of the 361 rivets). The manual transformation of Figure 16(b) can be estimated to be two hours compared to several minutes for the automatic process (b)).

These three assembly models are examples of particular simulation intent. The selection and choice of simulation parameters (e.g. element type or fastener junctions) to be part of inference rules will depend on the company's approved method and may be defined by the methods engineers. The CAE-oriented ontology approach offers a framework for method engineers to define their preferred formulation through ontology concepts and rules.

6. Discussion

As mentioned in Section 1, the current challenge in industry is to evolve from carrying out analyses using small or medium simulation models of one or two components to full-scale technology validation on models of the complete product, in a useful timeframe. Alongside the improvement of solver capabilities to reduce the computation time, progress in the pre-processing phase of the analysis process is needed to reach the simulation of an entire mechanical structure. CAE is still very fragmented in terms of proposed solutions. Often, each simulation department may use a specific specialised solver. In large companies, analysts have access to solvers from different vendors to cover all the physics involved in the product definition. For example, an aero-engine will involve the study of fluid dynamics, structural resistance to stress, thermal expansion of components, acoustic transmission, etc. The variety of pre-processing requirements coming from different FEM or CFD technologies, alongside the numerous software packages that may be utilised, makes it difficult to share the geometric models across all the simulation departments.

Ontology-based approaches appear the ideal candidate to manage the exchange of information between disciplines, through a unified framework linking the geometrical and functional information across simulation domains. Using this approach, the analyst can capture the modelling methods and link them to the product being designed. Rather than imposing a specific workflow and unique CAD-CAE environment, the simulation intent ontology proposes to capture the analysis decisions which are being made at a higher level than independently in each software package. By reducing the number of pre-processing manual tasks with low added value, the user can concentrate on analysing the trade-off between the chosen simulation hypothesis (which may involve idealisation decisions), the available resources and the expected accuracy of the analysis results. Currently, the inference rules are predefined in CoGUI. Depending on the simulation objectives, the user selects the rules which automatically set the idealisation requirements to the cellular models. With its link to the knowledge database, the idealisations requirements can be directly queried by the engineer from within the CAD system (see Figure 15). Ideally, to enhance the acceptance of the ontology-based approach, the selection of rules should also be implemented in the CAD system directly. As the link with CAD has already been developed this extension requires only the development of a suitable graphical user interface. For analysts or designers, this integration should allow them to focus on the simulation objectives and analysis results. Generating and testing the inferences rules still requires an understanding of the reasoning techniques, concepts and relations. This task is seen more for advanced users (e.g. methods engineers in large companies).

7. Future Work

The assembly processing and cellular modelling is currently used as the first phase to extract the knowledge-based assembly model. In the future, there is an exciting opportunity to extend the reasoning mechanisms to identify the functional designation of components. Even though the representation of simulation models differs from one analysis to another, the physical behaviour related to the connection between components can be uniquely described through their functions. As shown in Section 5, accessing components by their functional designations, e.g. a bearing, seal, fastener, etc., allows idealisation algorithms to robustly identify the set of cellular volumes to transform. Future work will focus on the development of methods and tools to analyse the morphology of fluid domains. In the cellular model, the fluid boundary and its interfaces with the structural components are automatically determined. Depending on the accuracy required, analysis involving fluid domains may use a simplified version of the fluid domain and may need to identify specific regions of this fluid domain, e.g. cavities, air passage, clearance seals etc. Similarly to the work of Sun et al. (L. Sun et al. 2017a, 2017b) on structural components, a morphology analysis of a fluid domain is required for a better integration of multi-physics models. Currently, the proposed framework is compatible with the ontology developed by (Vilmart, Léon, and Ulliana 2018). There is also an opportunity to connect the simulation intent ontology to other efforts in knowledge management in engineering (see Section 3.1) through the Basic Formal Ontology(Arp, Smith, and Spear 2015).

8. Conclusions

A new approach to capture "simulation intent" as an ontology-based application is proposed. The two simulation intent capabilities, cellular modelling and equivalencing, are connected to a knowledge base reasoner. The cellular model provides a spatial framework to which attributes describing any required analysis can be attached, whilst equivalencing tracks how the different cells are represented in any given simulation.

Information on cell geometry is linked to simulation attributes and meshing strategies through the ontology concepts and relations. The analyst can then use pre-defined ontology rules to capture the high-level of modelling and idealisation decisions required to set up a fit-for-purpose analysis model. The simulation hypothesis, idealisation decisions relative to the physical scales, space partitioning, detail removal, etc., can be recorded and linked to the cell geometry and morphology. Applying the ontology rules with the reasoner enriches the CAE-oriented knowledge model and makes it available for the various CAD/CAE packages across the simulation departments. Examples have shown querying symbolic information on the cells' simulation attributes allows the automatic application of specialised geometric operators. Using an ontology approach as the simulation intent framework makes it independent of CAD/CAE packages and allows the generated models to be shared by multiple simulation domains. This provides a critical technology for CAD/CAE integration and simulation-based design where reasoning from analysts within multi-disciplinary domains is combined within one framework. This provides a mechanism to maintain multiple models at different levels of detail and fidelity and exploit the links between them.

Acknowledgments

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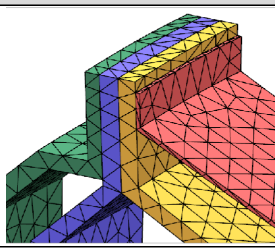
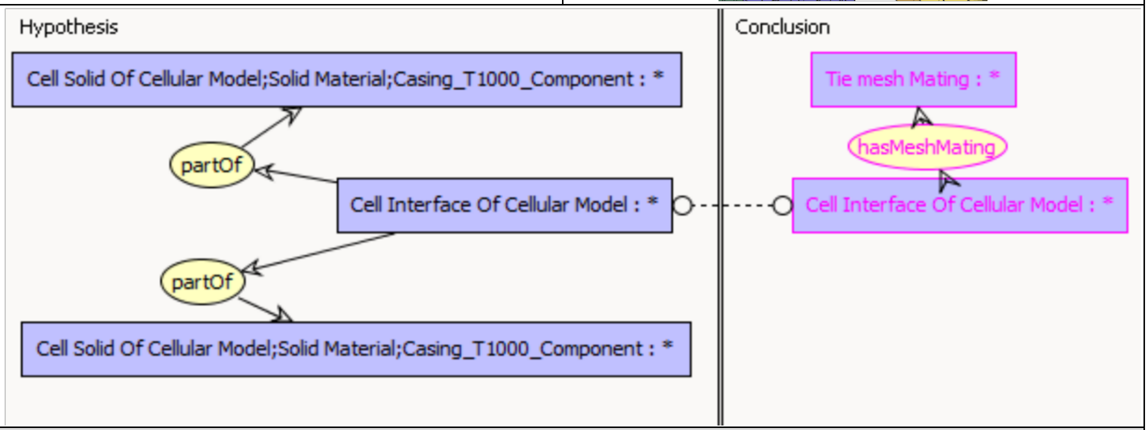
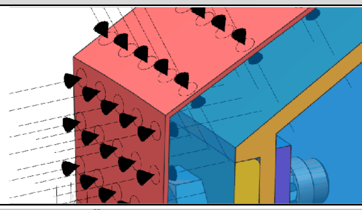
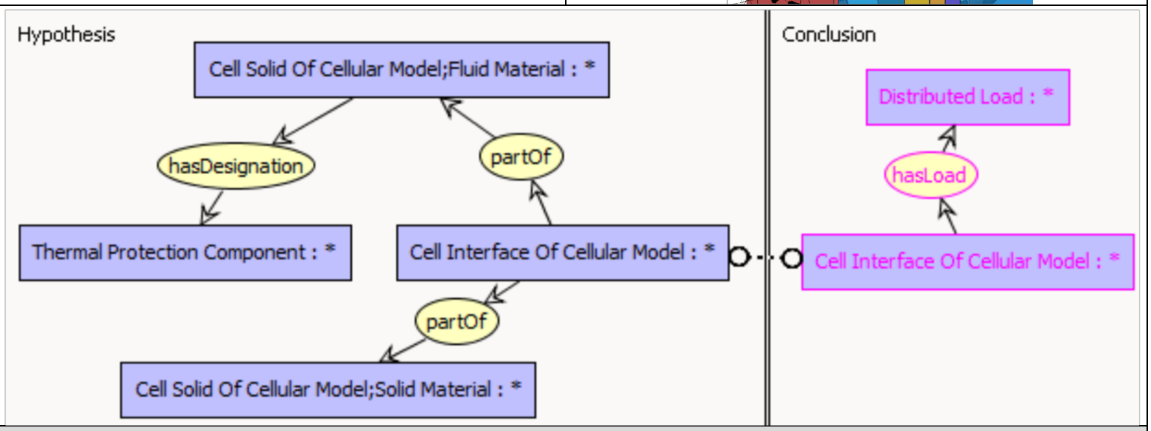
9. Appendix

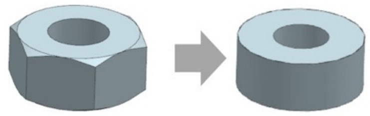
The following table illustrates examples of pre-defined rules using the concepts and relations developed in the ontology. After the extraction of symbolic information from the CAD models, an analyst can apply these rules to produce new facts, for example to associate simulation attributes to specific components or geometric regions (e.g. faces, edges...).

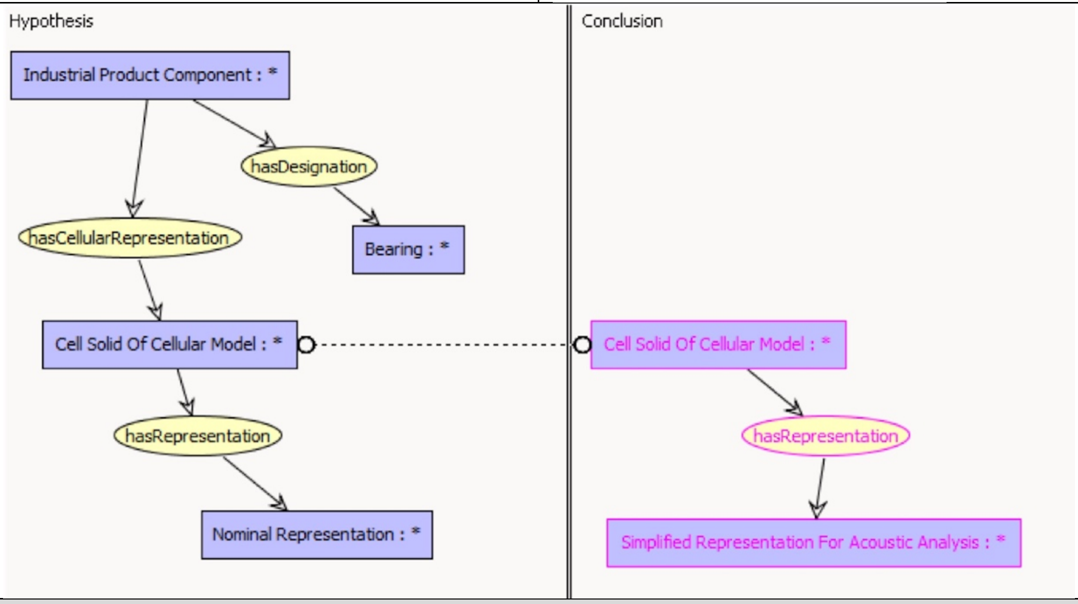
Table 2 Examples of pre-defined inference rules replicating current modelling practices. The rules are defined in the COGUI software (CoGui 2018).

msh1_meshMating Associate mesh mating conditions to ensure compatible meshes between casing components.	
	
Bc1_cellInterface_heatShield_fluid Associate pressure loads at the interface between heat shield components and fluid domains.	
	

sp1_nut_acoustic

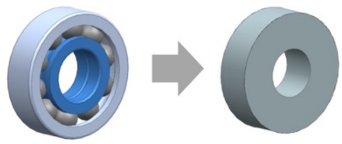
Simplify the 3D representation of nut components for acoustic simulation.

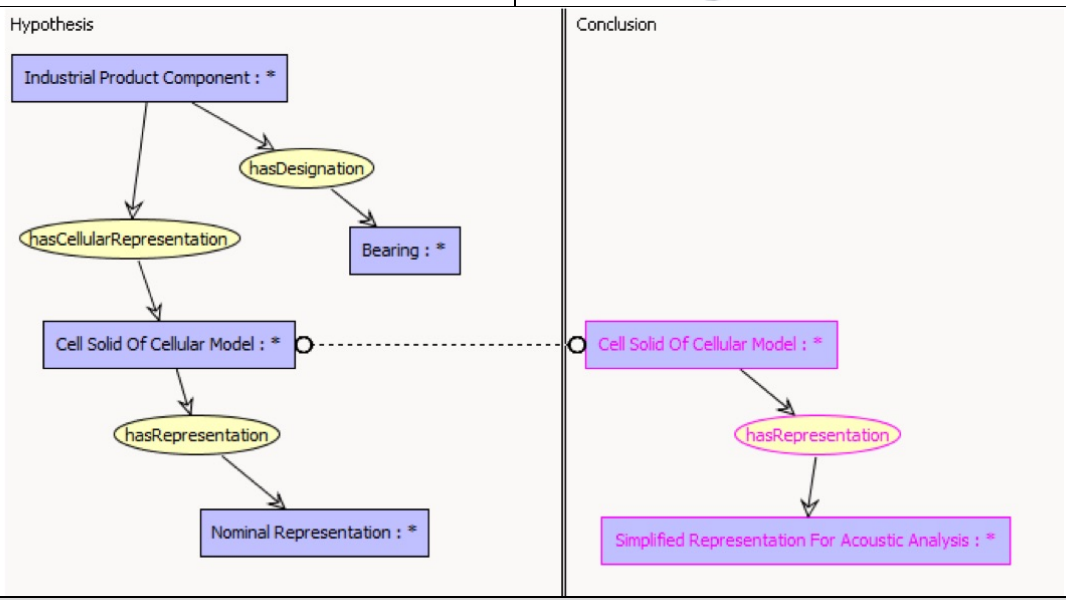




sp2_bearing_acoustic

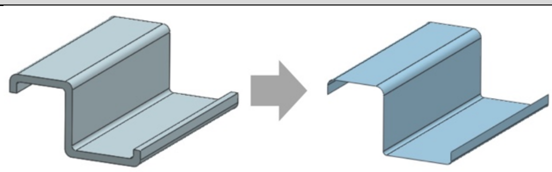
Simplify the 3D representation of bearing components for acoustic simulations

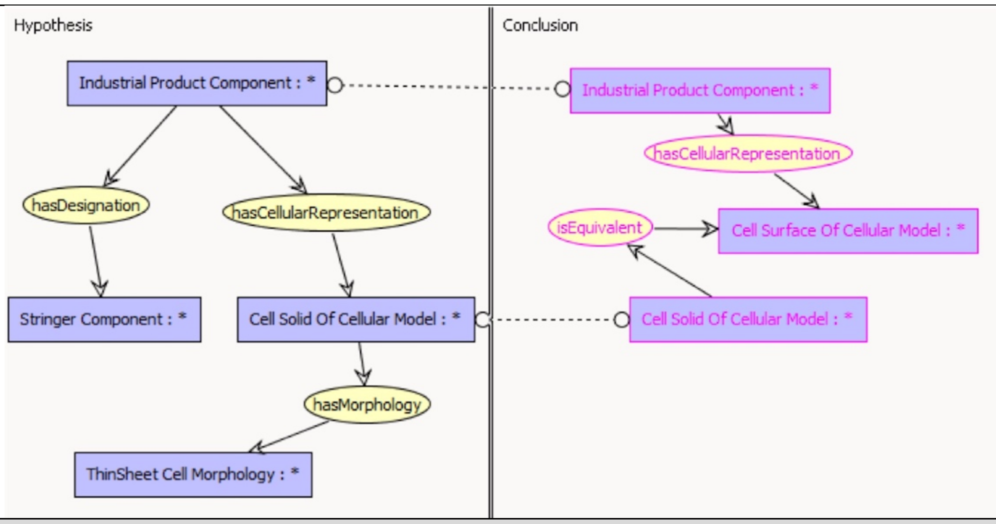




dr1_midsurface_stringer

Generate equivalent midsurface models for thin-sheet stringer components.





Dr2_meshIndependentFastener_rivet
Generate an equivalent 1D mesh independent fastener model for rivet component.