Abstract

The multi-disciplinary nature of complex system, such as aero engines, requires a data structure that considers the behavioural interactions within the system. This paper focuses on the management of simulations models and data, with respect to complex system structure. It is proposed to use model based system engineering (MBSE) methodology to support modelling activities and improve the integration of simulation activities in the design process. Current studies on MBSE address the issue of representing and integrating design models with diverse analysis / simulation / behavioural models. However, some limitations can be identified, especially regarding the federation of system presentation for addressing the overall behavioural aspects of the product (multi-physic, local and global behaviours) and thus considering the several system levels. Our proposal is to provide a software framework based on a data model that manages complex system structure. This data model structures behavioural information considering three major interactions:

- Interactions between components simulation models,
- Interactions considering multi-level behaviours (e.g. use of components simulation for a module simulation) and
- Interactions between domain behaviours (e.g. Thermal impact on mechanical).

A demonstration of this software framework is proposed, based on the set-up of a mechanical simulation of an aero engine using CATIA / SIMULIA V6.

1. Introduction

The current context of aero-engine product development is highly challenged as well by new norms (Noise, NOx emission...) as by more exigent expectations from customers. Then, the integration of new technologies to satisfy these demands is increasing the complexity of the product. This complexity is characterized through an increasing number of elements (e.g. component or assembly of component) in interaction. Moreover, the complexity is also incoming from the several behaviours that have to be studied through individual or combined engineering studies (e.g. mechanical, fluid mechanical, electronic...). In order to support the behavioural analysis, computer-based simulation is widely used during the design process. To perform a simulation of a complex system, engineers have then to gather numerous data about the element they have to analyse, such as:
• the solution enables the management in a uniform way of the design information. The design data of the element (e.g. geometry - CAD data, design parameters - mass, materials).
• The context of the simulation (e.g. parameters that describes the state of the element in its context of use and the environment of experiment as boundary conditions of the system or element studied).
• The data related to sub-systems adjacent to the sub-system studied (e.g.: simulation results, models).

In current scientific researches [1],[2],[3], CAD - CAE integration is challenged to ensure the handling of these design data and parameters. However, this integration is limited to the scope of individual simulation of component or assembly of components. Considering complex systems, it then remains challenges regarding the methods and support to properly structure and use these information in a coherent and consistent way. It means how to consider:
• Interactions between components simulation models,
• Interactions between sub-systems and system behaviour
• Interactions between domain behaviours (e.g. Thermal impact on mechanical simulation).

This paper proposes an innovative method based on Model Based System Engineering (MBSE) concepts to support complex systems characterisation for design and simulations. This method is explained through the description of a system formalism including new components (e.g. interfaces) that will ensure the management of the above listed interactions. It is also proposed an improvement of classical simulation data management data model integrating these new components and proposing new rules and functioning principles.

In order to illustrate these concepts a demonstration, made in collaboration with Dassault Systèmes, during the CRESCENDO project (Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation) will be presented. This demonstration has been adapted for the paper and use only simple subsystems interaction and physical behaviour.

2. Industrial challenges in simulation management for the design of complex system

Today, industries develop complex product characterised by a numerous number of component in interaction, and that require the integration of engineering discipline know-how (e.g. mechanical aerodynamics, acoustic, thermal...). Due to this increased complexity, the design of product becomes a set of collaborative tasks shared among multidisciplinary and distributed design teams [4]. In this context, each design team is responsible of design and analysis of a subset of the product. This analysis is performed through CAE tools dedicated to study a specific behaviour, by creating models and providing results. Due to the distributed design context, the analysis of the overall product is performed iteratively, by the integration of simulation data (e.g. models and results) provided by design teams. The models and results integrated have different representation and fidelity with regards to the discipline and the subset of the product studied. Despite the benefits of the use of simulation tools to improve the design process regarding the traditional performance criterion (quality, cost and time), some limits occurs with regards to the integration activities for the simulation of complex product. These limits occur in the management of the product complexity and with the exploitation of the CAD and CAE tools in coherency with design activities. Consequently the next challenges for industry are to better support and integrate simulation activities within the overall design process. This challenge can be accomplished through:

• An improvement of current industrial practices with regards to the management of complex systems information. Indeed, industry is missing robust information system to ensure the management of the product as a system enabling:
  - multi-view characterisation (from the entire system down to elementary component and vice versa)
  - multi-fidelity representation enabling to get adequate representation for a considered simulation (e.g. rough models are enough for the simulation of an assembly whereas detailed models are required for fine simulation),
  - and finally multi-physics representation ensuring that the complexity of the behaviour of the system is preserved and can be analysed
• An improvement of current practices related to the processes. Using new information systems is always an opportunity for improving rules and functioning principles. By subsequently improving information classification and ensuring its robustness for use, it can also be targeted to improve its exploitation.
  - A first improvement can be envisaged regarding the use of already existing information. For example starting from long experience of the enterprise, it is easy to imagine the potential gain of integrating the already existing knowledge related to practices.
- A second improvement can be offered thanks to the dynamic aspect of information capitalization inside these systems. As engineers are working for a specific purpose in a dedicated context, these tools could capture the knowledge and record all information generated inside the system.

- Lastly, an improvement regarding resources use and application. As most of the time, engineers activities are gravitating around the use of several tools for their studies, such a system must also manage their integration in the information system environment. This is a sine qua non condition for ensuring a high performance in use of such a system.

3. Review of scientific practices to manage product complexity for simulation.

As introduced in previous sections, simulation provides solutions to save cost, time and to improve the quality of product along the development process. However, this is demanding new efforts, and according to Mocko et al [1], the design-analysis integration for complex system requires:

- An understandable structure of design data to ensure appropriate data for simulation activities that represent the characteristics of complex system (multi-level – multi physics),
- A link between the different product representation used in design and simulation,
- A design and simulation data model to manage different aspects of product data regarding the design process and the different engineering tasks related to a specific domain.

From these recommendations, it is then necessary to consider two majors objectives. The first one should be dedicated to the management of the complexity and the integration of design information, whereas the second should consider the simulation set-up and execution of complex product.

3.1. Management of the product complexity

The management of the complexity for behavioural studies requires to handle the product representation and the interaction between each of its elements in a scalable structure. So as to perform their activities, engineers must be in a position to handle the product characterisation (description and structure) from multiple perspectives (i.e. different scale and different discipline). To manage the design of such a complex product it is then required to get methodologies so as to reduce its complexity. According to Andersson et al [5] this reduction is made possible by using the “modularisation” [5] of the product. The modularization is a method considering the product as composed of sub-systems to which are attached specific functions. These sub-systems are then assimilated as building blocks containing their own characteristics and supporting the design information such as its function and behaviour. To ensure physical, functional and technological links, these given “module blocks” are then interaction through element called interfaces. This methodology of modularisation is a pillar for managing complexity and it has been also managed in other methods as model based system engineering (MBSE). The MBSE is an approach addressing different system modelling methodologies and framework in order to support complex system design [6]. System engineering is a wide broad methodology that manages the several activities of engineering design as requirements, functions, process, behaviour and structure of the product, by the use of models. Despite the wide broad aspect of MBSE, this study considers the use of MBSE to model the structure of complex product in a generic representation for different discipline. This generic representation has been implemented through a system modelling language: SysML. This modelling language permits to model the product, based on the modularization methods, with a set of building blocks that represent the system or its sub-systems and port providing information about the boundaries of the considered building block (system or sub-system). Through these building blocks, SysML supports the design information materialized through engineering data such as CAD and CAE data. This capability has been demonstrated by Peak et al [8] and Vosgien et al [7]. Peak et al proposed a solution based an environment called Multi-representation Architecture (MRA) [8], based on a SysML modelling language to define computable simulation model [8]. Vosgien et al. [7], extend the MBSE approach by proposing a method to enrich and structure the design data to be used in simulation activities. Based on a system representation, the structure of the product can be adapted to a specific simulation domain activity by providing an appropriate organisation of the product components and their relationships. These contributions have shown an appropriate use of the MBSE methodology so as to provide a federated formalism for the product representation which is suitable for simulation. However, an extended use of this model in simulation activities seems to be limited. Indeed, the links between the considered breakdown levels of the product and the appropriate model to use are not ensured. Therefore, it seems that these
proposals cannot really handle the product complexity regarding the management of design analysis integration for different breakdown level. Moreover, a simulation without its context has very few meaning, and in these studies, it has never been mentioned how to manage product characterisation with regards to the simulation context.

3.2. Simulation of complex system

To manage the design and analysis data within the design process, Shephard and al [9] and Sellgren [10] proposed a methodology: Simulation-based design. Simulation-based design is based on the design analysis integration concept, and defines the simulation as the core activity to validate the design studies at each step of the design process [9]. To handle such a method, Shephard et al [9] have proposed an environment called Simulation Environment for Engineering Design to ensure the management of simulation data in coherency with design activities. This environment targets at managing all the engineering data related to a type of simulation. Despite a description of this environment, no data model has been proposed. Also, the context of complex system has not been taken into account. In his work, Sellgren [10] have proposed to manage the design analysis links, by using a layered data model composed of: a design layer, an analysis layer and an applicative layer. Based on what he called “Question – driven Modelling”, the objective of such method is to ensure the derivation of all the relevant data and parameters for modelling activities from the design layer to the simulation layer so as to create the simulation context. From this context creation in the simulation layer, the design data can be exploited properly for simulation activities (modelled and integrated in a simulation model). Finally, the applicative layer is in charge to transmit (through format translation) this simulation model to authoring tools in order to be computed. Sellgren defined a data model that ensures the creation of a context for simulation activity and has also proposed its integration within the design process to gather appropriate data. However, in his paper, Sellgren has not mentioned how it was intended to manage the multi-level aspect of the product and how the link between them could be ensured. On their side, Peak et al. [6] proposed a data model to manage different aspects of the complexity. They proposed a data model ensuring the management of the simulation activities in coherency with the design data available. The objective of this data model is to associate the relevant data regarding the type of simulation to perform, and generate the appropriate models in a formalism that enables its computation in authoring tools. Based on this defined data model, the authors have provided information about their implemented environment in SysML.

3.3. Perspective of using MBSE approach for managing simulation in complex product design

From the studies presented in previously section, interesting researches have started to tackle design-analysis integration problems. They offer the conclusion that developing approaches based on MBSE methodology can be powerful enough to strengthen the link between design and simulation world. Indeed, it offers methodologies to make a step forward regarding current limitations observed in many authoring tools. However, these approaches are not yet complete due to the fact they are only dealing with subset issues of design analysis integration for complex system. So as to ensure a better design analysis integration, some improvement can be foreseen regarding the management of the interaction between the different studies made on the sub-systems of the product. Moreover, progresses have also to be performed while attempting to build the integrated model made of the aggregation of sub-systems results. In this context, the contribution of this paper is to propose an extension of current researches based on the use of MBSE so as to manage design and analysis activities links with the purpose of finally creating an appropriate simulation models. In this paper, the final objective is to propose a method managing:

- The context of simulation regarding the type of analysis to perform and the considered breakdown level of the product,
- The definition of an appropriate product structure that gathers all the relevant design data,
- The synthesis of design information to generate a computable simulation model.
4. A MBSE framework for setting-up an integrated simulation model

The integration of simulation model is an activity that required specific data from various sources. The MBSE is mainly used to define appropriate product structure for simulation activities. The proposition made in this paper is to contextualize the design activity in order to retrieve the appropriate product structure and related design information to perform an analysis study. The proposition is represented through a data model shows in figure 1, that supports:

- The Management of the product complexity by using the MBSE approach to define the structure with breakdown element which contains the description of the components, their interaction and the design information.
- An extension of the MBSE approach by a contextualisation of the information regarding the design context. This design contains is describes through the design activities and the resources used to perform simulation analysis
- The dedicated objects that ensure the use the design information to perform analysis. These objects able to describe the models and the situation of the product analysed.

4.1. The MBSE approach to describe the appropriate structure and the organisation of the design information

According to Gero et al [11], design information gathers all data that describe a system in terms of:

- **Function** variables: describe the purpose, the role of the product or subset of it i.e. what it is for and what are the related technical targets (i.e. design requirements),
- **Behaviour** variables: describe how the considered system behaves in a given operational state and permit to assess if the system fulfils the design requirements corresponding to the function in this operational state,
- **Structure** variables: describe the components of the considered system and their relationships (hierarchical and functional relationships i.e. their interactions).

The use of this organization, based on Gero et al concept [11], ensures the definition of all design data that provide the product information which correspond to a specific breakdown level. Therefore, in our approach a **Product** is described by various **System Breakdowns**. A **System Breakdown** (composed of **Breakdown Elements**) can be a structural, functional or behavioural breakdown respectively composed of:

- **Structural Breakdown Elements** correspond to the description of the component and its organisation. The structure is managed by **elements**, **ports** and **interface**. This description of the structure of breakdown is made with the same approach than the SysML language. The **element** ensures the description of the component. The **interface** provides the description of how the **elements** are in interaction. The **ports** are particular objects, that are associated to an **element** and which define, on the component or assembly of a component, the location of the interaction. These objects are all linked to a representation to gather the associated models (**CAD model** and **CAE model**) that constitute the design information. These models are relating each other to ensure the CAD CAE integration.
- **Functional breakdown Elements** is described by the object **function**. It provides information about the role of the breakdown element of the product structure. Also, it is the object that is needed to validate for the simulation and assess the technical definition of the product designed,
- **Behavioural Breakdown Elements** provide information related to the simulation activity. It ensures the management of the behavioural studies, performed in **Simulations**. The class simulation gathers information about the obtained **Simulation Results** and the **Simulation objectives**.

These three main objects, ensure to gathers all the design and analysis information about the product. These classes are interrelated. The structural breakdown element supports the design information materialized through the class **representation**. Specifically for the behaviour of the product, the simulation uses dedicated models that are based on the aggregation of CAE model. This part of the data model ensures to reduce the complexity of the product and organize the design information through elements that are interconnected. With this approach, engineers can reach the design information that suits to the part of the product they have to study.

4.2. Contextualized product information for simulation activity

In the design of complex product, the structure of the product is not view in the same manner for each design activity. That is the case for simulation, where simulation model must represents the product view that matches with the design discipline that it belongs to. Through this contextualised information, it ensures engineers to retrieve the
correct and adequate information in regards of the analysis context. The description of the context is ensured by the class `design context`. This class described the context of the activity by the `product`, the `resources` and the `discipline`. The class `product` ensures to define the correct product definition regarding its version and its configuration and the breakdown level studied. The `discipline` is linked to the characterization of the design activity performed. For simulation, it defines the type of behaviour studied (e.g. Mechanical, Thermal...). Finally the `resources` class defines the tools and methodologies used to perform the activity. In regards of the simulation activity, the design context is associated to a class `study` that enables to collect the context definition. This part of the data model is the extension of the MBSE approach that ensures to relate the analysis activity within the design development. It provides the appropriate structure and associated information in order to perform a simulation. Consequently, when the engineer wants to initiate a simulation, the `study` provides the `tools` to use, the `methods` such as the modelling requirements and the `operational state` (i.e. the condition of use of the `product`) that describes the boundary condition of the system studied for the simulation.

The MBSE approach and the relation with the context enable the management of the information related to the design process and the product for a dedicated activity.

4.3. A data model to ensure simulation based design.

The information model defined previously enables the management of design information in coherency with the simulation activity. The design and analysis information are supported by data such as CAD and CAE models within PDM systems. The objective of this data model is to ensure the exploitation of CAD and CAE models coherent with design and analysis information. Some objects of the MBSE methodology have been included within the information model to be linked with the appropriate design and simulation structural information; as well as the corresponding CAX features ensuring a model-based characterisation of the studied system. This approach enables set-up of the simulation in order to be computed. To a given simulation performed within a specific context, are associated a set of appropriate `Tools` permitting to set-up and run the simulation (i.e. pre/post treatment tools and solvers). A FE Model, has a specific breakdown structure and a configuration (set of `FE_Models` with the appropriate modelling features and physical properties, and their `interfaces`) that is already fully specified within the MBSE framework. However this structure and configuration need to be understood by the solver that will simulate the `Simulation Model`. Associated to a given `Tools`, the data model permits to define the appropriate solver used to compute the simulation model. In this section the data model and the concept to support design and analysis integration for complex product simulation has been defined. The next section is dedicated to the implementation of these concept through an environment based on CATIA / SIMULIA V6 from Dassault Systèmes, and its validation through an industrial test case which is the generation of an aero-engine mechanical simulation model and its computation.
5. Illustration on the set-up of a simulation model for a mechanical simulation of an aero engine

5.1. MBSE framework implementation in CATIA / SIMULIA V6.

CATIA V6 is the last CAD and CAE software from Dassault Systèmes that integrates system modelling tools that ensure a representation based on blocks, port connector as it defined in the previous section. CATIA V6 is associated to simulation data management environment able to manage the different CAE models and simulation studies. In this application, a tool called Dymola provides a system representation language that includes the elements of blocks ports and interfaces. This tool has been customized in order to support CAD and CAE models as described in figure 2. The management of the design information are performed through the solution SIMULIA. Therefore CATIA V6 has been customized through dedicated applications that enable to define the design context of the simulation studies and to retrieve the correct system representation and associated CAD and CAE from the SIMULIA system.

5.2. Use Case Description

In aeronautical industry, a typical activity is the integration of the whole power plant system. The power plant system is composed of a nacelle, a pylon and an engine. These elements of the system are different simulation model regarding the domain. Moreover, these models are created by different suppliers. The objective of integration is to verify and assess the behaviour of the integrated product. So the verification is performed by gathering models from other supplier and assembles them so as it can be computed. In this use case, the creation of individuals’ models is already performed by the suppliers. The integrator has to define the context of the simulation through the process development.

5.3. Definition of the simulation context and product representation using the MBSE framework

In the system, the analyst who will perform the simulation defines all characteristics of the simulation by a template illustrated on figure 2. This template, ensure the definition of the simulation context and collects data about the status of the product he want to perform (its simulation, its operational state, the version and the configuration). It also provides the definition of simulation analysis. This approach enables the retrial of all data related to the simulation to perform. Henceforth, the analyst can define a dedicated product representation based on MBSE methodology illustrated on figure 4, by defining ports and components organization.
5.4. Association of CAD and CAE models

Starting from the generic global power-plant system view, the analyst can derive his own view, dedicated to the simulation he intends to perform. In this specific view, he will define the way to set-up the simulation model by defining interaction area on port element of the MBSE framework as shown on figure 3 below. Through the MBSE environment, as well as the association of MBSE element and CAE model, the analyst can define the convenient CAE models and features relative to the block and ports of the MBSE framework. He can also specify the physical interaction occurring at the interface and describing the behaviour of the product.

5.5. Set-up the simulation model

The proposed MBSE approach allows the analyst to gather all the required data enabling to set-up the assembly of the simulation model. Based on the identification of the correct product definition, the appropriate system breakdown level and the specific type and purpose of the simulation, the analyst can easily gather, integrate and structure the relevant data sets used to set-up the simulation model and perform its computation.

Once the simulation model well-structured and configured within the MBSE framework, the model is exported automatically to a pre-processor tool where the user has to define the boundary conditions and load cases to create the appropriate “analysis – card” of the simulation. This analysis card is sent to the solver in order to be computed as illustrated on figure 4.
5.6. Results and limitation

Through this test case, we demonstrate the potential of use of MBSE to manage complex system simulation. The environment provided by CATIA V6 demonstrates a new way of managing design integration in the context of complex system. However, in the context of this research project, we realized that a number of performance and scalability issues would still need to be addressed before being ready for large scale deployments:

- The management/automation of a high number of interfaces instantiations both in the system and in the 3D assemblies,
- The automatic linking (“implementation relations”) of system ports with the corresponding publications on the 3D models.

Currently, in our prototype these actions were done manually and are not automated. One possibility is to manage the implementation of CAE element with the MBSE framework using instance objects. However some limitation occurs related to the different ways to define a CAE model. Instance cannot be generic and applied to the entire model, due to various simulation model of the product (e.g. 1D, 2D, 3D mesh for instance). In addition, the sharing of parameters between system and 3D finite element models levels could be improved, especially in the case of multiple instantiations of a similar interface, but with different parameters. This is a challenge from data-management perspective and it implies new features in managing/sharing parameters in the PLM with knowledge-ware parameters inside 3D and system authoring tools.

6. Conclusion

Design-simulation links represent critical points in decreasing design loop time and increasing the confidence in system behaviour. In this work, we propose a MBSE framework to define design-analysis links addressing the context of simulation models, integrating different data related to several system levels and with the aim of providing specialized environments for different engineering domains adapted to their needs. This approach is developed in order to ensure the coherency of data in view to cross-domain system design. The approach is illustrated on a real case-study in aero-engine development. The test-case showed also the integration of this approach into commercial tools. Through this approach and its use in the test-case, the design integration has been extended in the way to integrate the simulation activity inside the design process. In respect of the challenge evoked, the solution provides a better support of the simulation activity for complex system design. Regarding the traditional approach, the study demonstrates how integrates MBSE approach in the management of simulation activities and a required extension to integrate it inside the design process. Moreover the solution enables the management in a uniform way of the design information. In a collaborative environment, simulations are not integrated only by the association of the models but also by its association with design context. Through a contextualisation of the design activities, design teams are able to integrate information from various sources and ensure the traceability of the studies. The benefits are the ease of the preparation of simulation model by providing the appropriate structure and data suitable for a specific simulation and decreased the lead time of the design process. The test-case provided can be considered as simple and needs to be done on more components and also on the interaction of different physics. Also, this solution has to been extended on other simulation methodologies, such as optimisation, multi-physics simulation. The perspective of this approach is to improve its use with the integration of knowledge based system to manage the methods, the automatic definition of simulation models so as to speed-up the simulation activity. Additionally, some study has to be provided in the use of its methodology in an extended enterprise context with interoperability issue.

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