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INTEGRATED DESIGN FRAMEWORK: TOWARDS AN APPROACH FOR EARLY DESIGN

François CHRISTOPHE[1], Raivo SELL[3], Eric COATANEA [1], Jean-Pierre MICAËLLI[2]

[1]Helsinki University of Technology, Machine Design, Finland

[2] University of Technology of Belfort-Montbelliard, RECITS laboratory, France

[3]Tallinn University of Technology, Mechatronic Laboratory, Estonia

ABSTRACT

Making the mechatronics product development process more efficient is a key point for companies, researchers in the field of Design Theory and Methodology or teachers in Mechanical Engineering. In the early design stages, this sort of products requires an integrated framework that helps designers of each domain to have a clear view of the functions, behaviors or structures of the entire system. It also helps them to be early informed of the choices about the different conceptual or architectural solutions that affect their future performance. In the literature and in most curricula, presentations of design methodologies or models are still based on specific viewpoints. In that way, there is still a lack of a global or integrated framework. Consequently, the development of such a framework is important. The joint engineering curriculum with novel learning aids presented in this paper tries to satisfy these needs. The design approach proposed will be applied in a real joint engineering study process. This development is the result of cooperation between five European universities of technology. In this paper, we present our initial attempt to combine coherently SysML for modeling purpose and Dimensional Analysis Theory for early comparison, simulation and evaluation of the proposed design solutions. The introduction to the context of mechatronics product development process naturally leads us to summarizing the fundamental aspects of SysML and Dimensional Analysis. We then articulate coherently these two approaches. As a conclusion we underline the necessity of future development of the SysML language to include tools dedicated to evaluation, comparison and simulation.

Keywords: Mechatronics, Early design, Systems Engineering, System Modelling, SysML, Dimensional Analysis Theory.

1 INTRODUCTION

The key question for companies, researchers in the field of Design Theory and Methodology or teachers in Mechanical Engineering is: “How to make the mechatronic products development process effective and more efficient?” A global approach is required in order to tackle this issue. The functions, behavior or structure of the system have to be described and correctly “managed” by the designers involved in a common product development process. Nevertheless, in the literature, as well as in most curricula, presentations of design methodologies or models are still based on specific viewpoints. In that way, there is a lack of a global and integrated framework.

Consequently, its use is really important, especially during the early stage of the design process.

The present paper is an initial attempt to combine coherently SysML for modeling purpose and Dimensional Analysis for early comparison, simulation and evaluation of the proposed design solution. Section 2 introduces the context of the mechatronic product development process. Section 3 summarizes the fundamental aspects of SysML. Section 4 presents Dimensional Analysis Theory and a possible way to integrate this formal approach into SysML. Section 5 concludes by underlining the necessity of future development of the SysML language to include tools dedicated to evaluation, comparison and simulation. Nevertheless, this is not yet sufficient to claim having obtained a unified design approach for the conceptual stage. In this perspective, our paper is very limited and it should be seen as an initial approach proposing extension of the initial SysML model to evaluation and comparison of solutions.

2 FROM INTEGRATED SYSTEMS TO INTEGRATED DESIGN FRAMEWORK

According to Otto and Wood [1], Product Development is the entire set of activities required to bring a new concept to a state of market readiness. This set includes several activities, from the original idea, to the user or business analysis, engineering design, development of production plan, validation of the product design. In that way, a design process is the organization in space and time of this set of activities. Its core is the refinement of the system vision into functional specifications, embodiment design, and detailed design. Neither the product development process nor the design process includes the production system. Nevertheless, its design is a part of the product development process. For example, product embodiment design and detailed design of the production process are usually integrated in the concurrent engineering approach.

The place of Research and Development (R&D) in the "product development landscape" is not clear. R&D refers to the development of new technologies for incorporation into launched products or effective production systems. Usually, R&D is seen as a specific and separate process from design: it is closer to research than development. This way of thinking is not convenient, as underlines the Kline and Rosenberg's "chain-linked" model [2]. An effective innovative product development process requires close links and loops between marketing, technological watch, invention, research, product design, and production system design. The map of all the activities involved in product development process is shown Figure 1.

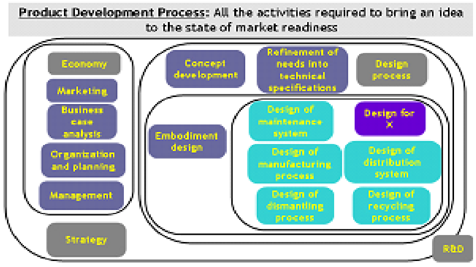

Figure 1 Product development process and design process

According to the International Council on Systems Engineering (INCOSE) [4], Systems Engineering is an interdisciplinary approach and means to enable the realization of successful complex systems. It has both managerial and technical purposes. The first one organizes technical, support and managerial processes which combines the set of activities shown Figure 1. The second one consists on a set of tools related to the early stage of System development.

The ways of linking the Systems Engineering processes differ from a type of product development to another. Three types of development projects can be roughly established: *original design*, which requires elaborating a new or novel solution for a given problem, *adaptative design*, which requires adapting a known system to a changed mission or modifying an existent system, and *variant design*, which requires modifying the parameters of an existing design (e.g. size, geometry, material, control parameters). The first one is a kind of “concept-push” project; despite the last one is a “solution-pull” one. In that way, the conceptual stage of the product development process is critical in original design. During this stage, usual CAD systems are of no use. The geometry of the product is not defined, thus its components. New tools are required, to model in an abstract way the entire product. This requirement is especially important in the case of mechatronic products development, because they integrate in a common architecture several multi-physical components (mechanical, electrical and electronics hardware, embedded software…). Tools of the development process can be joined with new system modeling approach such as SysML [3]. This language is both an extension and a specialization of the Unified Modeling Language 2 (UML) created at mid-1990s.

3 SYSML TOOLBOX FOR MODELING CONCEPTUAL DESIGN

In the software design world Unified Modeling Language (UML) is de facto the standard for object-oriented software design. Started with UML 1.1 and UML 1.6 the most recent official version is now UML 2.1. The essence of software modeling, as in all modeling, is abstraction: the removal of fickle and distracting detail of implementation technologies as well as the use of concepts that allow more direct expression of phenomena in the problem domain [4].

One of the recent trends is the software-intensification in everyday products, mechanical devices included. According to this, there is growing need for close communication and integration of techniques and tools between software design and conventional hardware design (e.g. mechanical, electrical).

There are several attempts to apply UML for non-software design. Serious improvement has been reached in recent years. The important outcome is OMG SysML specification finalized in 2008, which is initially derived from UML RFP: UML for System Engineers Request for Proposal [6] in 2005.

For mechatronic product design, SysML specification is a useful language for describing a system. SysML reuses a subset of UML 2 diagrams. It also augments them with some new diagrams and modeling constructs appropriate for systems modeling. SysML is designed to complement UML 2, so systems engineers who are specifying a system with SysML can collaborate efficiently with software engineers who are defining a system by using UML 2 [14]. Four pillars of SysML are shown Figure 2.

In mechatronics and Systems Engineering, a very wide range of SysML applications can be considered. Different products and domains have there own specifics language and tools therefore it is necessary to customize general system modeling tools to meet the specificities of particular application domain (specialization). At the same time the connection and compatibility have to remain. UML and SysML contain the mechanism to extend and/or restrict the initial language, ensuring the required compatibility. In this paper we summarize briefly using Figures 3 and 4, the SysML profiling mechanism which consist of a SysML profile for mobile robotic platform development in the conceptual stage and one example of using profile specific stereotypes in *Use Case* diagram.

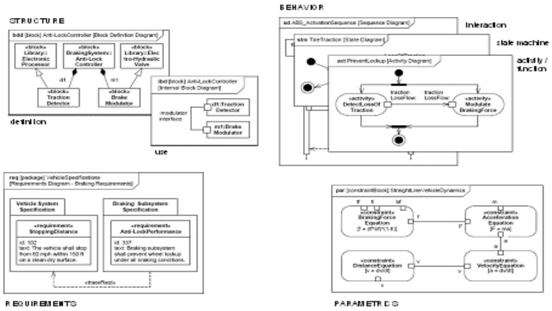

Figure 2 SysML pillars [12]

The general structure of the SysML toolkit is shown in Figure 3. The toolkit is defined as a SysML profile and external simulation package. The profile itself consists of template libraries, diagram extensions and model libraries. Standard model libraries are *Principle*, *Terrain* and *ContactType*.

The Mobile Platform Toolkit (MPT) Principle library consists of the working principles and subsystems formulated in SysML and extended profile. This means that similar subsystems can be found in different libraries although the abstraction level is different. The subsystem is defined in semi-formal language rather than physical component.

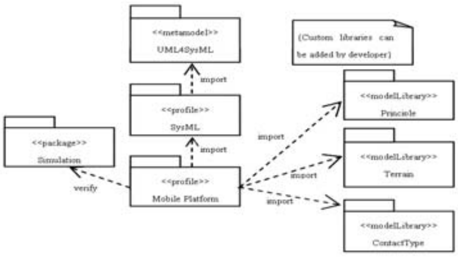

Figure 3 Mobile Platform Toolkit structure

In Figure 4 the system main services are modelled in a Use Case diagram where MPT specific stereotypes are used. For the structure and behaviour similar diagram types are specified. The toolkit specification has been further studied in the following work [4].

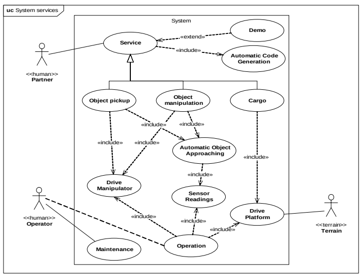

Figure 4 System services

Simulation is usually exploited for validation of the design solutions. Thus, simulation is used in the later stage of the design process when the model of the product is already well defined. In order to get the maximum benefits, the proposed design framework includes the simulation into the conceptual design stage. The model (structure and behaviour) consists of special block element stereotyped as *simu*. It is not possible for space reason to present and example here. Some works [14] have shown the possibility to apply the multi-agent system, genetic programming combination to automate the generation of initial concepts of solution. SysML toolkit can be combined with a theoretical approach dedicated to early evaluation and comparison. The idea here is to integrate a formal model into a semi-formal language: Dimensional Analysis Theory (DAT) into SysML.

4 INTEGRATION OF DIMENSIONAL ANALYSIS THEORY IN SYSML

DAT is a field of Qualitative Physics which concerns units and magnitudes. Similarities between scales are major area of contribution [16]. The fields of application are numerous; we can quote electromagnetic theory, aerodynamics, aeronautic. DAT mostly relies on the Vashy-Buckingham’s theorem, published in 1914. It states that the study of a physical problem expressed with n dimensional quantities can be reduced by a factor k if expressed in a dimensionless form. As an example of DAT results, we can consider an electrical battery and simulate is charging phase. The following variables are considered: *U* potential of the battery, *I* its charging intensity, *E* the energy stored, *Ω* its internal resistance, ρ_V the volumic electrical density of the battery and ρ_M its massic electrical density. For that device, the variables of interest are *U* and *I*, the other ones being internal variables. DAT gives us two dimensionless numbers:

$$\pi_U = U.E^{-1}.\Omega^{-1/2}.\rho_V^{1/2}.\rho_M^{-1/4} \qquad (1)$$

$$\pi_I = I.E^{1/3}.\Omega^{1/2}.\rho_V^{-5/6}.\rho_M^{-1/4} \qquad (2)$$

From this dimensionless group, we can simulate the behaviour of a certain types of battery during the charging phase, considering *Ω*, ρ_V and ρ_M as known. DAT provides also a way to compare solutions using the similarity principle. The leads to similarity condition between different concepts of solutions. Those similarities conditions can be used for comparison purpose [16]. DAT has proved to be very powerful approach to formalize a set of solutions either effective or potential. This approach allows the simulation, evaluation and comparison of these solutions at this early stage of product design. We propose to integrate DAT in SysML via its structure pillar [4]. Indeed in the structure pillar, a simulation block exists, which allows implementation of the Vashy-Buckingham algorithm as shown Figure 5. This analysis made in this article is very limited but nevertheless in our viewpoint the initial research results are promising.

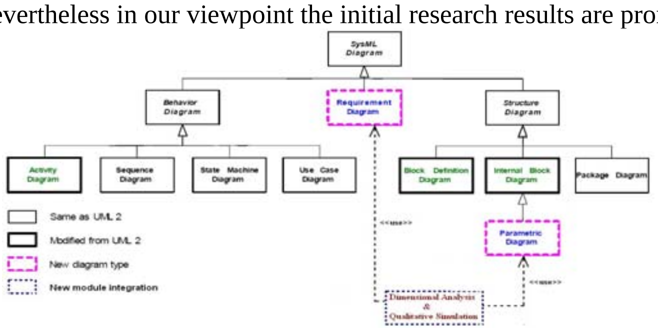

Figure 5 Coherent Integration of DA module into SysML

5 CONCLUSION

This short article proposed the basis of an integrated design framework meant for the early stage of Mechatronics product development process. Our key results are the following ones: first, this process requires close links between Research and Design; second, it requires a high level language of description, SysML; and finally, it requires the integration of formal models from Physics to SysML.

As conclusion, we would like to underline the necessity of future development of the SysML language to include formal tools dedicated to the generation, simulation, evaluation and comparison of early-design solutions. Nevertheless, this is not yet sufficient to claim having obtained a unified design approach for the conceptual stage. In this perspective, our paper is very limited and it should be seen just as an initial approach.

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[1]François CHRISTOPHE
Helsinki University of Technology
PO Box 4100 FIN-02015 TKK
Finland
francois.christophe@tkk.fi
+35894516272

[2] Associated Professor Raivo SELL
Tallinn University of Technology
Ehitajate tee 5, 19086 Tallinn
Estonia
raivo@staff.ttu.ee
+3726203203