Knowledge structuring and simulation modeling for product development

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Abstract

This paper proposes a new approach based on knowledge structures for building simulation models. The target are products to be redesigned integrating new technologies. The main idea of the approach is to limit the development of an analysis model to that of the new technology and merge it into the existing prototype using the connection parameters determined at the hand of the knowledge models. This approach was implemented for the design of a next-generation system iron. The approach enabled easy collection of data and automatic model verification, demonstrating its capability to reduce complexity in product development.

Keywords: Simulation; engineering modeling; knowledge structures

1. Introduction

Modern products encompass more and more multidisciplinary features. This makes the design and manufacturing of these products also more complex. Multi-domain criteria need to be analyzed and evaluated, and quite often – in the interest of a rapid time-to-market – the design team settles for a working solution rather than an optimized solution.

To improve the product development process and shorten design times, there is a clear need to structure knowledge of the design process. By having a comprehensive overview (i.e. a knowledge structure) of the design artifact in question, designers and engineers are aided in the processes of organizing, modeling and solving design tasks.

In this paper, the task of knowledge structuring is based on the Design Process Unit (DPU). In essence, the DPU is a basic representation of the design process and describes the information flow between the 4 individual sub-processes involved: synthesis, analysis, evaluation and adjustment. To demonstrate the advantage of using a DPU-based knowledge structure, it is used for the product development of the next-generation system iron.

The design of this system iron is a complex process. For the product to be successful it must continuously meet revised consumer needs. For the design engineers, in general, this means designing a smaller product with new features and better technical performances.

The outline of this paper is as follows. Section 2 will elaborate on the theory of DPU modeling. Section 3 describes the details of the approach from a design theory point of view. In Section 4 the case study example of the system iron is presented. The DPU of the system iron’s design process will be illustrated. Finally, in Section 5 the conclusions of this research paper are presented and some recommendations for future research are given.

2. Design process and knowledge structure

A well accepted generic model of the design process is shown in Figure 1 [1]. According to this, a candidate solution is first generated in a synthesis process. Then it is analyzed to calculate its performance and evaluated to assess whether the design is to be adjusted (path 1), rejected (path 2) or accepted (path 3).

The knowledge used to support each of these phases can be classified into two categories, namely, declarative...
and procedural. Declarative knowledge describes static entities, like for example types of components, parameters and relations. Procedural knowledge describes dynamic processes, like for example design strategies and algorithms.

On the one hand, procedural knowledge in design depends on the specific requirements of the problem being solved. As a consequence, it cannot be used for describing the essence of a design process. On the other hand, declarative knowledge remains independent on the requirement settings. This property makes declarative design knowledge convenient for producing models of design artifacts in a generic fashion.

![Figure 1: Generic model of the design process [1]](image)

There are three basic types of declarative knowledge present in a design process: embodiment, scenario and performance [2-4]. Embodiment regards knowledge describing the object being designed, like its topology and its properties. Scenario is related to the set of entities describing the flow of energy, mass or information the embodiment is exposed to. Performance determines how the embodiment behaves under a certain (group of) scenario, and can be both energy quantities or physical object properties.

The relation between these three types of knowledge varies according to the design phase (Figure 1) they are applied to. In the synthesis phase, embodiment knowledge is specified such that it meets certain performance values for a given scenario, as shown in Figure 2(a). In an analysis phase, performances are quantified or qualified for an embodiment that is undergoing a given scenario by using analysis equations, as shown in Figure 2(b). The evaluation phase uses performances to determine the following action to undertake with an already generated candidate solution. Finally, the adjustment phase applies small changes to some embodiment variables to improve the performance of the solution.

![Figure 2: Knowledge structure in the analysis and synthesis process](image)

2.1. The Analysis model

Relations used during the synthesis, analysis, evaluation and adjustment phases are also considered to be declarative knowledge. This is because these relations do not determine design procedures as such and hold for the design process independently of the specific characteristic of the requirements. For example, the equations used for calculating the deformation and stress of a spring are independent of the specific process order in which the spring is designed. Similarly, rules of thumb to be used in the synthesis process for determining the diameter of a spring are also independent on the specific procedure that might be used to design it.

Yet, only analysis relations are required to be known when completing a design process, as they represent the way in which the quality of a design solution is determined [2]. The group of analysis relations used for quantifying the performances of an embodiment is here regarded as the analysis model. An analysis model relates all relevant embodiment and scenario variables to performances, and therefore, it determines the level of detail and specification of the design process. This also means that embodiment and scenario variables that are not regarded in the analysis model have no role in the design process as they do not affect the qualification of the solution.

Additionally, depending on the type of design process (innovative, creative or routine) and its the level of detail (conceptual, embodiment detail), analysis relations range from qualitative descriptions to numeric ones, and from simple *if-then* rules down to analytic relations, numerical
simulation analysis and test bed based experimental analysis [5].

2.2. Design Process Unit

According to the previous, there is a triplet of declarative knowledge that is required to be known for a design process to occur, namely, embodiment, scenario and performance. In this paper we define this triplet as Design Process Unit (DPU), as it accounts for the core knowledge that is either gathered or available when designing. Figure 3 shows an example of a DPU for the design of a mass spring system. As the figure shows, the mass and the stiffness are regarded as the embodiment (design) parameters. Force and frequency are regarded as scenario. Finally, the performance parameter displacement specifies the behavior of the system for a given scenario. The analysis equation shows the relation between these parameters. In this paper, DPUs are graphically displayed as in Figure 3: embodiment parameters on top of the analysis model, scenario parameters on either the right or left hand side of the analysis model and finally performance parameters on the bottom of the analysis model.

Figure 3: DPU of a mass-spring system

2.3. DPUs based knowledge structures

DPUs can be seen as design knowledge building blocks, and as such, a design artifact can be modeled as a web of different DPUs representing knowledge at different levels of detail and for different components and assemblies. Either embodiment, scenario or performance serves as starting point to join artifact’s constituent DPUs. This is schematically shown in Figure 4. By making DPU maps of an artifact’s components, one can get an overview of the level of multidisciplinary and interconnectedness between the different knowledge chunks. Knowledge structure maps can be used to determine product development strategies, knowledge fields interfaces and build-up analysis models of the artifacts being designed. When embodiment, scenario and performance parameters are known, but the analysis equations are unknown, an analysis model has to be assembled prior to starting the design process. When developing a simulation or analytic model is not possible because of time constraints or complexity of the principles, an experimental set-up can be used as analysis model. This is addressed in the next chapter.

Figure 4. Knowledge structure: each color represents a different DPU.

3. DPU based simulation modeling

3.1. The challenge

A common practice at industry is to redesign existing products to either improve their performance, increase their market value, add more functionality or a combination of all of these. When the redesign consists of integrating new technologies into an existing product, we are dealing with innovative design. Adding new technologies requires the development of new analysis models and their experimental verification. Such models are either analytic or simulation based models. When dealing with dynamic behavior, simulation models are preferred as they are better suited for modeling the time dependencies of the system. Making such models requires a great effort as both the existing parts as well as the new technologies have to be integrated into one analysis model. Furthermore, models errors are difficult to track as the space of possible mistakes encompasses the whole product analysis model.

3.2. Approach rationales

In order to minimize the efforts of building simulation models for redesigned products integrating new technologies, this paper proposes a new approach based on DPU knowledge structures. The main idea of this approach is to only develop an analysis model of the new technology and merge it into the existing prototype using the scenario and performance parameters of its corresponding DPU. This is achieved by sending real variable values obtained by measurements on the prototype to the simulation model. The advantages of doing so are:
- Reduced model making efforts
- Models errors are easier to track as modeling is kept within the boundaries of the new technology.
- The effect of the system’s real inputs in the new technology implementation can be directly assessed.
As modeling is always related to some level of simplifications, the behavior of the new technologies can be assessed without the noise that would be brought by the models of other components. Generally speaking, this approach enables a goal directed identification of relevant integration variables and technology behavior.

3.3. Steps in the method

The approach consists of three general steps, as shown in Figure 5. First, each of the relevant components are modeled as a DPU and combined into one general knowledge structure, as shown in Figure (a) and Figure 5(b), respectively. In this case, the pink DPU is the new technology (NT) to be integrated. The knowledge structure allows determining the variables where the simulation model and the experimental set-up must be connected.

Finally, the simulation model is merged with the physical prototype to obtain a coupled simulation-experimental analysis model, as shown in Figure 5(c). Here, the scenario parameters of simulation model C3 are directly obtained from the experimental set-up by means of sensor measurements.

4. System Iron Case Study

The core task of the system iron is wrinkle removal. With the help of ironing appliances, people want to efficiently remove wrinkles fast and effortlessly. The idea behind the system iron is that high quality steam (i.e. vapor at a minimum of 2 bar) is generated in a separate unit and transported to a handheld iron. The advantage of such a system is that the iron itself can be very lightweight and slim, since the stream is generated elsewhere.

The interior of the system iron is shown in Figure 6(a). It comprises 4 main building blocks necessary to create the required pressurized steam, namely a pump, heater, boiler house and valve. The latter is an electronic trigger operated by the user. When the user triggers (opens) the valve, pressurized stream should be ejected immediately. The steam is transported through the tubing to the handheld iron. To guarantee sufficient steam (vaporized water), the pump pumps (cold) new water from the reservoir into the boiler when the water level drops beneath a threshold value. The heater is attached to the bottom of the boiler, as shown in Figure 6(b). Also, a thermal sensor is attached here. Finally, the pump, heater and sensors are controlled by the electrical control board.

The user requirements demand perfect ironing during normal operation. This is captured in a number of trigger activity user scenarios. Whatever the design of the system, following any scenario the iron should always deliver high quality steam. To make things worse, over time the system will react differently to the heat input, due to foaming and scaling of the water inside the boiler, and unwanted solid particles adding-up inside the boiler.

The system iron is a good example of a modern, complex multidisciplinary product. Key target of this research was to improve the design of the system iron. Originally the system also contained a pressure sensor to monitor the pressure of the steam and indirectly the water level inside the boiler. Improvement of the system is sought by removing the pressure sensor and controlling the water level using only the temperature sensor. Additionally, with a better control algorithm the size of the boiler should be made smaller. Altogether, this would enable both a smaller product and a lower cost price.

Due to the multidisciplinary nature, redesigning the system iron in a time-efficient manner is complex. Therefore, the entire system was put into a knowledge structure and modeled according to the DPU theory. The
knowledge structure consists of 3 main process units. The first describing the boiler properties, the second describing the quality of the steam and the third describing the control system.

Figure 7 shows the integrated knowledge structure of the main DPUs of the newly implemented technology for the iron system. The new iron uses the same boiler container and control system, but replaces the heating element, the pump and the valve to increase ironing performance and decrease energy consumption. DPU-A (boiler material and geometry) and DPU-D (control system) are representing the existing parts of the iron, DPU-B (heater) and DPU-C (pump and valve system) represent the new technologies. Power dissipation \( P_{\text{dissipation}} \) is the performance of DPU-B, while at the same time it is the embodiment of DPU-C. Temperature \( T_{\text{sn}} \) and pressure \( P_{\text{sn}} \) of the steam are the performance of DPU-C and elements of the scenario of DPU-D as well. In DPU-B, analysis is determined by a model of natural convection. For DPU-C, mass and energy conservation rules are the core of this analysis model. Steam tables representing water and steam equilibrium properties are referred to for the analysis in DPU-C.

Figure 8 shows the analysis model of DPU-B and DPU-C as well as their interconnection with the prototype experimental set-up depicted in Figure 9 by DPU-D. Figure 8 shows the main idea of the coupled simulation-prototype analysis model.

This model has been implemented in Simulink. As Figure 8 shows, the analysis model concerning energy dissipation from hot boiler to the cooler environment has been divided into three parts, namely part B, part C and part D representing DPU-B, DPU-C and DPU-D respectively. Part B describes the calculation of the two performances of DPU-B, which are the temperature and pressure in the equilibrium state. This is done by applying the theory of mass and energy conservation and by using as input values the total input energy and total initial mass of water. Part C of Figure 8 concerns the energy dissipation calculation, where thermal theory of natural convection is used. By knowing the material type of the boiler shell, the geometry properties of the boiler and the temperature difference between the boiler surface and the environment, the instantaneous dissipated energy can be calculated for a certain state. In part D of Figure 8 the control methods influence is assessed, which allows determining the gain or loss of the mass of water and the loss of energy.
Figure 9. Overview of the heating system analysis method

By using real-time results from the experimental setup representing DPU-B and DPU-C, these quantities are calculated accurately, as the noise coming from modeling errors of the simulation model are omitted. Furthermore, results also enable real-time verification of the simulation model made for the new technologies represented by DPU-B and DPU-C.

Fig. 8 Schematic view of components and their interfaces built in the Simulink model

Conclusion

The implementation of knowledge structures for building simulation models to the design of the new system iron system has delivered 3 advantages in comparison to orthodox modeling approaches. Firstly, by processing the real experiments, data requested for building the simulation model can be collected easily. Secondly, by using the simulation model, design tests can be done much faster than former experiments. Thirdly, by combing the simulation model with experimental setup, automatic experimentation can be reached and performance data can be compared easily. Hence, iteration work on performance comparison and solution revision can be done more efficiently. This enables a synthesis approach to optimize the design of products with fluctuating consumer requirements and reduce the complexity of the overall design process.

References