Challenges and opportunities within simulation-driven functional product development and operation

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Abstract

The product development process at industrial companies has traditionally focused on hardware-oriented solutions. Business strategies strive towards more service-oriented solutions e.g., functional product business models. In this paper two case studies are developed and the objective is to highlight important challenges and opportunities by implementing a simulation-driven strategy in functional product development and operation. It can be concluded that challenges and opportunities within simulation-driven functional product development and operation are related to both quality and management of the simulations. With the proposed strategies for validation and coupling of the simulations, some of the challenges within functional product development can be overcome.

Keywords: simulation-driven design; functional product development; availability; risk; cost

1. Introduction

The product development process at industrial companies has traditionally focused on hardware-oriented solutions. However, a current trend is to extend business offers to include more service-oriented solutions. There are a number of definitions for service-oriented solutions. One such solution, where the supplier retains ownership of the hardware throughout the product lifecycle and instead provides and guarantees a function, is called a functional product (FP) business model [1, 2]. Functional products are typically constituted by hardware (HW), software (SW) together with a service support system (SSS) and a holistic approach by management of operation (MO). The functional product development process, including all the constituents, increases the complexity of the development process and implies a need to communicate and share information during the process [3]. A framework including the most important constituents has been derived for a functional product development process to manage the FP development [4]. This framework includes development of hardware, software, service support system and management of operation. Lindström et al. [5] further derived a framework defining the FP concept based on empirical studies combined with a literature review. The framework outlines how the four main FP constituents are integrated, including the sub-constituents, and how these constituents and sub-constituents relate to each other.

Providing a function requires a lifecycle perspective for the provider where all the constituents must be considered e.g., design and development, support and maintenance,
competence, risk management, finance, etc. Availability is one critical property in an FP business model that the customer and provider must agree upon; therefore, a framework has been derived for prediction of functional product availability to be used both during development and operation [6, 7]. Availability is a measure of the probability that the repairable system or subsystem is operating at a specified time. The repairable system must be maintained in order to operate and deliver the specified function over time i.e., system maintainability. Reliability is a measure of the probability of a hardware system or component to perform its intended functions under stated conditions for a specified period of time. The possibility of predicting the reliability of hardware for both components and systems is important in robust design engineering. Many failures are caused by variations, resulting in a substantial effect on safety or functional requirements; therefore a new method has been derived for predicting system reliability based on probabilistic Variation Mode and Effect Analysis (VMEA) i.e., how different sources of variation affect reliability [8]. Availability is a function of reliability and maintainability [9].

When buying a function it is important to know as much as possible about the process coupled to the function to be provided. From the provider perspective this might require a tailor-made function that demands close collaboration with the customer during the functional product development process. Well designed simulation tools are thus necessary in order to make correct decisions in both business agreements and in innovation processes.

Simulations can be used as a tool to verify proposed designs [10]. Hence, verifying simulation can be time consuming, a waste of time, resources and money, and a limitation for creativity. Simulation-driven design (SDD) is a simulation strategy that strives to use the simulation as a driver to guide the designers towards an optimal solution as early as possible i.e., design space is increased and some of the limitations are decreased [11]. Karlberg et al. [12] conducted a literature review to identify the state-of-the-art in SDD methodology and to show the research evolution in the field of SDD. The literature review includes definitions, criteria and effects of using an SDD strategy. Lideskog et al. [13] showed that a transition to function provision may create incitements for a more efficient value chain during functional product development. Combining simulation methods, including hardware, software, service support system and management of operation in an SDD approach improves the possibilities for sustainable functional product development [14]. Reliability prediction methods often use measured data or estimated data as input e.g., failure rates, hazard rates, etc. When designing new hardware system measured data or estimated data are often used as input to reliability prediction methods. However, if such measurement data do not exist, deterministic simulations can be used to derive the needed input data and concepts can be evaluated by means of reliability in early stages of the functional product development process [15]. During operation, the hardware system is controlled by a software system and it is therefore interesting to perform simulations of software systems. Simulation models of the control system, including signal and protocol processing units, and transferring information to the hardware and software have been performed [16, 17]. The repairable hardware system must be maintained in order to operate and deliver the specified function over time. Therefore, service support system simulation models (i.e. maintainability models) can be used to predict the maintenance procedures over a planned lifecycle within system reliability prediction for a functional product [18, 19]. Management of operation includes decision making and logistics; therefore, activities in such processes can be predicted by use of probabilistic simulations, i.e. discrete event simulations [20, 21] or by simulations that use the same strategy as a real-time processed business game. Business games describe the time-bound nature of business decisions and enable understanding of the supplier-producer-distributor-customer chain [22].

An example of an SDD approach that is frequently used to improve and secure the operation of industrial processes is Computational Fluid Dynamics (CFD). Simulations using CFD serve as a valuable tool to investigate complex designs and processes involving fluid flow, especially in milieus where testing is not possible or too expensive. Examples of applications are the design of a pelletizing plant [23], injection points of a NOx reducing substance [24] and spray nozzle position in a spray roaster [25]. CFD might thus involve several phenomena such as multiphase flow, combustion and heat and mass transfer. As the complexity increases, evaluation of the quality and trust in the simulations is of paramount importance. Mesh generation, turbulence modelling, validation, etc. must therefore be considered [26].

Although there are numerous simulation tools, few investigations have been done to determine how these tools should be utilized in functional product development processes.

Hence, the objective for this paper is to highlight important challenges and opportunities by implementing simulation-driven strategies in functional product development.

Challenges and opportunities within a simulation-driven functional product development and operation require a methodology to handle all aspects of functional product innovation enabling implementation. Hence, the provider is responsible for all the hardware, service support system, software and management of operation needed to provide the function with a certain agreed-upon availability. The focus in this paper is to highlight important challenges and opportunities industrial companies must take into account when a decision is established to implement a simulation-driven strategy for functional product development and operation.

2. Research approach

The research presented in this paper started with a state-of-the-art analysis of relevant research areas to clarify research gaps. Here, information regarding the possibility to use
simulations in different phases of product development processes and simulation of the four main constituents, and service-oriented solutions was of special interest. Data regarding the product development, simulation advantage, simulation usage and business strategies was further collected through interviews at two industrial partner companies. The interviews were performed with eleven company representatives at the two companies with varied positions in the company i.e., component level (bearing, gear, clutch shaft, etc.), assembled structures, control system, system testing, reliability and availability management, business, research and development. Based on the state-of-the-art analysis and the interviews, important challenges and opportunities were identified by implementation of simulation driven strategies in functional product development and operation. Finally, verification of case studies was carried out based on scenarios at two industrial companies.

3. Challenges and Opportunities

Implementation of simulation-driven strategy in functional product development and operation presents both challenges and opportunities. Due to the complexity of functional products where four constituents are involved concurrently, there is a need to share information between the simulations. Therefore, a simulation-driven strategy requires a greater degree of multidisciplinary interaction between the constituents.

Hardware simulations can be divided into deterministic simulations and probabilistic simulations. Deterministic simulations are used to predict diverse performance characteristic e.g., durability, fluid dynamics, etc. The probabilistic simulations of hardware use statistical information from a population of components or a system of components. From these populations distributions are derived based on components or systems of components to predict different probabilities, e.g. reliability, availability, etc. Software systems are used to control and manage the performance of the hardware system. Simulations of the software system can be coupled or uncoupled from the hardware system; the hardware system’s performance and wear are affected by the parameter setup for the software system. A service support system is used to conduct maintenance of the hardware system to establish agreed upon availability. Simulations of the service support system can be performed with maintainability models to predict, e.g. mean time to repair, which together with hardware reliability gives system availability. Availability is a function of reliability and maintainability and is one critical property in a functional product development and operation model that the customer and provider must agree upon. Management of operation constitutes handling planning and decision-making, where the core is collection of activities based on decisions.

Based on the interviews and the state-of-the-art analysis, the following challenges and opportunities implicit in the introduction of simulation-driven functional product development and operation strategies have been identified.

Challenges
- Management of simulation couplings between constituents (HW, SW, SSS and MO)
- Management of correct simulation information from input/output in different phases of the development process
- How to retrieve necessary information in different phases of the Functional Product Development process
- How to model and simulate SSS, MO, Performance, Availability (many parameters including combination of probabilistic and deterministic simulations, both time-continuous and discrete event)
- Simulation model validity maturity through FPD
- Organisational – who does what, and when are the activities performed?
- Time-efficient simulations

Opportunities
- Managing simulation coupled and in parallel between constituents (HW, SW, SSS and MO) increases the design space and hence the innovation capability.
- Increased possibilities for optimal total FP solutions (not only sub-optimal solutions)
- More and better information for decisions at gates (e.g., reliability instead of durability)
- Effective use of human capital
- Possibility to analyze new designs that are too costly to evaluate through testing i.e., less physical testing
- Reduced lead time

4. Case studies

Important challenges and opportunities implicit in the introduction of simulation-driven strategies in functional product development and operation were discovered in the state-of-the-art analysis and the interviews with representatives at the two industrial companies. To further highlight some of these challenges and opportunities two case studies were conducted.

4.1 Case study 1

The industrial partner company is the world’s leading manufacturer of climate-smart iron ore pellets. To maintain this position the industrial company needs to know as much as possible about their processes in order to buy the right functions. A well designed simulation tool is therefore valuable in order to make correct decisions in business deals and in innovation processes for improved pellets quality and reduced environmental impact.

The pelletingizing process, where the crude iron ore from the mine is upgraded to pellets, is a process that includes several stages involving complex fluid dynamics. In this case study,
focus is on the grate-kiln pelletizing process and especially on the rotary kiln. A kiln is a cylindrical, long, rotating oven with a burner in one end which can be characterized as an axi-symmetric enclosed turbulent jet diffusion flame, where most of the combustion air has to be entrained into the fuel jet. Only a small portion of the combustion air is channelled through the mechanical confines of the burner, while the remaining combustion air is introduced through the kiln hood in two separate inlets with a dividing wall in between, called the back plate, where the burner is located. The different air streams are termed primary and secondary air, respectively. Since the majority of the combustion (secondary) air enters through the kiln hood, the aerodynamics of the kiln is tightly linked to the combustion process and, primarily, the mixing between the primary fuel jet issuing from the burner and the secondary air. Generally, the combustion is largely controlled by turbulent diffusion mixing between the secondary air streams and the confined burner jet; hence, the combustion air supply system and the resulting air flow patterns have a huge effect on the overall performance of the burner. This motivates a systematic study of the kiln aerodynamics.

When buying a function, for example, a burner that should deliver a certain amount of heat with a specified maximum amount of emissions, it is important that the process is scrutinized. Without adequate knowledge about the process it is difficult to establish the right demands and specifications in a business agreement and modelling and simulations can provide valuable insight and knowledge. To derive a methodology for the prediction of the flow and combustion in a rotary kiln rather detailed numerical and experimental studies are needed. Here, simulations present an opportunity to avoid costly physical testing and to increase the design space during functional product development. They may also provide information in environments where experiments cannot be performed. Challenges are related to time efficiency and a high complexity in the physical models.

One of the most important research questions is; How simple can the set-up of the numerical simulation be while still describing the main features of the flow field? By starting as simple as possible, studying only the cold flow field without combustion and validating the simulations with experiments, a foundation for future geometrical optimizations can be achieved [23]. Later on more realistic geometries may be studied with the validated and verified simulations as a base. A schematic view of the procedure is shown in Fig. 1.

Research on kiln-aerodynamic simulations has shown that simplified models with a downscaled geometry can provide insightful information about the process [27]. One conclusion that can be drawn from the simulations is, for example, that the flow field in the kiln is strongly affected by the mass flow distribution between the secondary flow inlets as well as the geometry.

Fig. 1. Schematic view of simulation approach, here related to kiln aerodynamics

The results may thus be used to improve the combustion with regards to product quality, efficiency and environmental issues. Although seemingly straightforward, the models reveal unexpected difficulties in the simulation and experimental work. This justifies the strategy with a gradually increasing complexity of the model in the pursuit of a validated full-scale simulation model of the iron ore pelletizing rotary kiln.

4.2 Case study 2

Analysis of the interviews with the industrial partner company representatives and the state-of-the-art analysis from the literature review indicated that a typical product development process for industrial companies is to develop and provide hardware products i.e., the customer is responsible for operation, maintenance, repair, recycling, etc. However, to improve competitiveness, business strategies strive towards more service-oriented solutions i.e., functional product business models where the supplier retains ownership of the hardware throughout the product lifecycle and instead provides and guarantees a function. In this case study the main challenges and opportunities for functional product development and operation are highlighted. The provider is responsible for development and operation of the required service support system, software, hardware and management of operation. The complexity factor increases when four constituents share information between the simulations i.e., there is multidisciplinary interaction between simulations, see Fig. 2.
Iterative process

Provided function
at agreed upon availability

Hardware
simulations

Software
simulations

Service support
system simulations

Management of Operation
State the boundary
condition for the project

Fig. 2. Information sharing between constituents

In Fig. 3 (based on [14]), the four main constituents with the direct interaction between the constituents marked with arrows and the global interaction marked with circles. In the centre the provider manages a pool of hardware and software consisting of vehicles with software that can be updated to manage the performance of the hardware system to fulfill specific customer application, customer A and customer B. The service support system can operate both at the pool of hardware and software or at customer site, depending on the availability of required personnel, spare parts, etc. for maintenance or repair. The overall logistics and decision making are handled by management of operation i.e., decision regarding functional product development, business model, customer application, logistics due to maintenance schedule, etc.

The simulation models require different boundary conditions depending on provided functional product. Therefore, a simulation methodology is needed to manage simulation coupled and in parallel between the four main constituents. This leads to increased design space and innovative capability, increased possibilities for total FP – optimal solutions (not only sub-optimal solutions) and less physical testing already during the functional product development process i.e., in early phases of the development. A simulation methodology increases the possibility for more and detailed statistical data, based on distributions of products instead of one product e.g., reliability instead of durability and the information can be the basis for decisions (management of operation). It is crucial to access the necessary information in different phases of function development processes.

Some of this information is generated through simulations and, hence, it is critical to effectively manage the input and output data between different simulations. Modelling and simulation of performance, functionality, availability, etc. requires many parameters and may combine probabilistic and deterministic models, see Fig. 4 (based on [14]). The couplings between the constituents hardware, software, service support system and management of operation of the mobility function further need to be managed i.e., activities are structured both in time and compatibility. The relationships of simulations within the same constituent (intra-relationships) and relationships between the constituents (inter-relationships) derive information essential to fit in the timeframe for simulation models of affected constituents.
Another crucial challenge when developing mobility functions concerns validation of the simulation models to secure the outcome for confirmation of the agreed function. The simulation models need to be verified and validated continuously already during the early development stages. With valid simulation models in combination with more detailed mobility function layout, the simulation outcomes can finally be rated against different customer needs.

5. Conclusions

New business agreements continuously raise new demands on companies’ research and development processes. For example, industrial trends today are to buy functions rather than products. The project therefore focuses on how simulation tools shall be used, especially in the concept phase, to drive functional product development processes and to secure optimal operation. A primary concern in functional product development is availability and, hence, reliability. The complete system of hardware, software, service support system and management of operation should thus be considered in order to manage coupled and in-parallel simulation between the four constituents. The proposed simulation-driven methodology manages more related constituents than traditional hardware development i.e., to communicate and share correct information between simulations during the functional product development process. Further, the methodology requires an increased amount of multidisciplinary interaction to combine deterministic simulation and probabilistic simulation. The simulations may increase the design space and innovation capacity, but it is at the same time of paramount importance to ensure that the simulations are reliable. Validation of simulations is therefore a crucial issue to secure the quality and reliability of the results. Increasing the complexity will decrease the controllability of the simulations, and one possible strategy is therefore to decrease the complexity to facilitate validation. More realistic geometries may then be studied further on with the validated simulations as a base. Decreasing the complexity may also be an efficient way to reduce the computational cost.

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