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Life cycle simulation to support cross-disciplinary decision making in early PSS design

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Abstract

The development of early-stage simulation capabilities is a critical step in the quest for 'frontloading' early stage PSS design activities, so to reduce the cost and risk for rework associated with sub-optimal decisions. This paper describes how life cycle simulations, based on a Discrete Event approach, can be applied to support cross-disciplinary decision making in PSS design, facilitating the identification of the most valuable hardware configuration for a given business model. The proposed approach is exemplified in a case study related to the design of a zero-emission asphalt compactor, which is part of a product-oriented and use-oriented PSS offer. Co-located physical meetings and interviews with industrial practitioners highlight the role played by DES as an enabler for leveraging tacit knowledge sharing across roles and disciplines in the organization, making possible to explore the design space with more rigor. They further reveal the need to exploit data mining techniques and to develop new constructs so to inform decision makers of maturity and impact of models used in a specific decision scenario.

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Keywords: Product Service System, Discrete Event Simulation, decision making, Value Driven Design, value model.

1. Introduction

Increasingly saturated and commoditized global markets drive manufacturing companies towards shifting their business focus from "being owners of competencies and resources to become integrators of a set of skills, resources and technologies able to realize complex value creation processes" [1]. This "servitization" [2] or "service transformation" [3] trend challenges traditional product-based business models, stressing the need for selling 'utility' and 'performance' associated with the use of a product, rather than the product itself.

The main business benefit of servitized business models - often referred to as Product-Service Systems (PSS) - lies in the opportunity to leverage 'value generation' for customers and stakeholders [4]. Understanding and measuring 'value' along the entire PSS development process is a widely debated topic in PSS literature [5-7]. Particular emphasis is given to early concept generation and selection tasks [8,9], which are often advocated to be the most critical decision-making points for ensuring the success of PSS offerings. For this reason, simulation techniques have become popular in recent years [10,11] to 'frontload' [12] the PSS design process, reducing costs and risks for rework associated with sub-optimal decisions. The development of early-stage modeling and simulation capabilities has become a priority for many organizations, so to generate all the necessary information to assess (in a virtual environment) the value creation opportunity linked to alternative PSS concepts.

The guiding research question for this work can be described as: "*How to support decision-makers in assessing the value of early stage PSS concepts through the use of simulation techniques, so to increase awareness of unspoken needs, estimated performances, and impact of contextual conditions on product operations?*"

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The main objective of this paper is then to describe how Discrete Event Simulation (DES) is applied as part of a Value-Driven Design (VDD) execution loop [13] to support the identification of the most valuable hardware configuration for a given PSS business model.

1.1. Research approach

The research is conducted in collaboration with a Swedish multinational engineering manufacturer of mobile compactors for road surfaces. The empirical data gathering stage - which featured semi-structured interviews with engineers, managers, and technology experts - aimed at understanding the role 'value' has in PSS design decision making. Data were triangulated by means of regular co-creation workshops and through the analysis of internal company documents. In the prescriptive study phase, the researchers made use of visual demonstrators – exemplified in a case study related to the design of an electrical asphalt compactor - to identify critical topics for modeling and simulation. Interview and co-located workshops sessions with practitioners, stakeholders and process owner aimed at verifying feasibility and applicability of the proposed process and technological enablers.

2. PSS simulations in design: a literature review

Product and production development feature a long and successful history with regards to the application of simulation techniques for design verification. More recently, simulation has become increasingly popular in the service domain too, as a means to compare the behavior of different processes, evaluating their impact on customers and company needs [14].

A recent review from Musa et al. [15] reveals a broad range of applications for simulation technologies in PSS research: from capacity assessment [16] to cost estimation [17] to technology evaluation [18]. The main reason for simulations to be so widespread is that PSS development stresses the need to embrace a life-cycle-oriented approach in decision making [19]. This, in turn, suggests the design team to create multidisciplinary simulations able to inform decision-makers about 'value creation' along the entire lifecycle of a system.

Discrete Event Simulation (DES), System Dynamics (SD) and Agent-Based Modelling (ABM) have been extensively applied to address variability, uncertainty, and risk in the design of PSS [20,21], with DES being the most popular approach [15]. These techniques entail different advantages and characteristics, which make them more or less suitable for PSS design decision making, depending on the task at hand. SD, for instance, is acknowledged to provide an effective means to represent flows and cause-effect relations in a system at a strategic level, mainly because the behavior of a system is strongly dependent on its structure. DES, on the other hand, is often applied to verify qualitative and quantitative feasibilities and performances among different options regarding life cycle strategies, as well as to evaluate design configurations [22].

The main reason for prioritizing DES application for early stage PSS decision making is that this technique is process-centric and focuses more on a tactical/operational dimension, when compared to other simulation techniques, such as SD and ABM [21]. An additional advantage of DES is that it considers the stochastic nature of the usage scenario parameters, so to provide realistic predictions along the all life/usage-cycle of the PSS hardware. Furthermore, since the simulation verifies a limited number of moments during the simulation time, the run results compressed and more efficient. Furthermore, the focus of DES, which is on resource sharing and sequences of activities, is found to be more intuitive for decision makers than SD and ABM. This 'intuitiveness' makes DES model a preferred 'boundary objects' for the PSS cross-functional design team [23]. DES models facilitate negotiations and knowledge sharing within the team, with beneficial effects for decision-making during the early stages of the design process.

3. A life cycle simulation approach for early PSS design

The research work brought to the development of a life cycle simulation approach for PSS design (Figure 1), which was further applied to verify the suitability of given hardware concepts for the selected PSS business cases.

3.1. Generate the experimental plan

The findings of the empirical study conducted in collaboration with the industrial partner, as well as previous contribution from the literature [24], reveal that new products, sub-systems, and components are seldom radically new designs. Rather, the necessity to comply with a number of requirements related, for instance, to manufacturing commonality, logistics and supply chain management, limits design freedom to incremental improvements of a given product platform. Hence, early in the design process the assessment of a PSS hardware kicks-off from the identification and further development of such a platform. From this, a number of platform 'variants' (i.e., design configurations) are tested for 'suitability' for the targeted PSS business models.

The value-driven design loop kicks-off by creating a parametric 3D CAD representation of the PSS hardware platform, from which to derive a number of alternative design configurations by means of a Design of Experiment (DoE) approach (see [25] for details). The generation of PSS hardware configurations from this generic representation is controlled from the MS Excel® environment. After importing design data from the 3D CAD model in MS Excel®, a list containing all selectable design variables - both continuous (such as geometrical dimensions or capacities) or discrete (e.g., technological options) - is automatically generated in the provided interface. Here, the team can select a subset of these variables to be varied in the study, together with their upper and lower bounds (i.e., minim and maximum admissible values in the experiment). After selecting the number of design configurations to be generated, the design team can choose a suitable statistical method for generating the experimental plan. Most commonly, the team chooses a Latin hypercube sampling, through the *lhsdesign* function in the MATLAB®' software, to generate a near- random sample of parameter values from the multidimensional distribution.

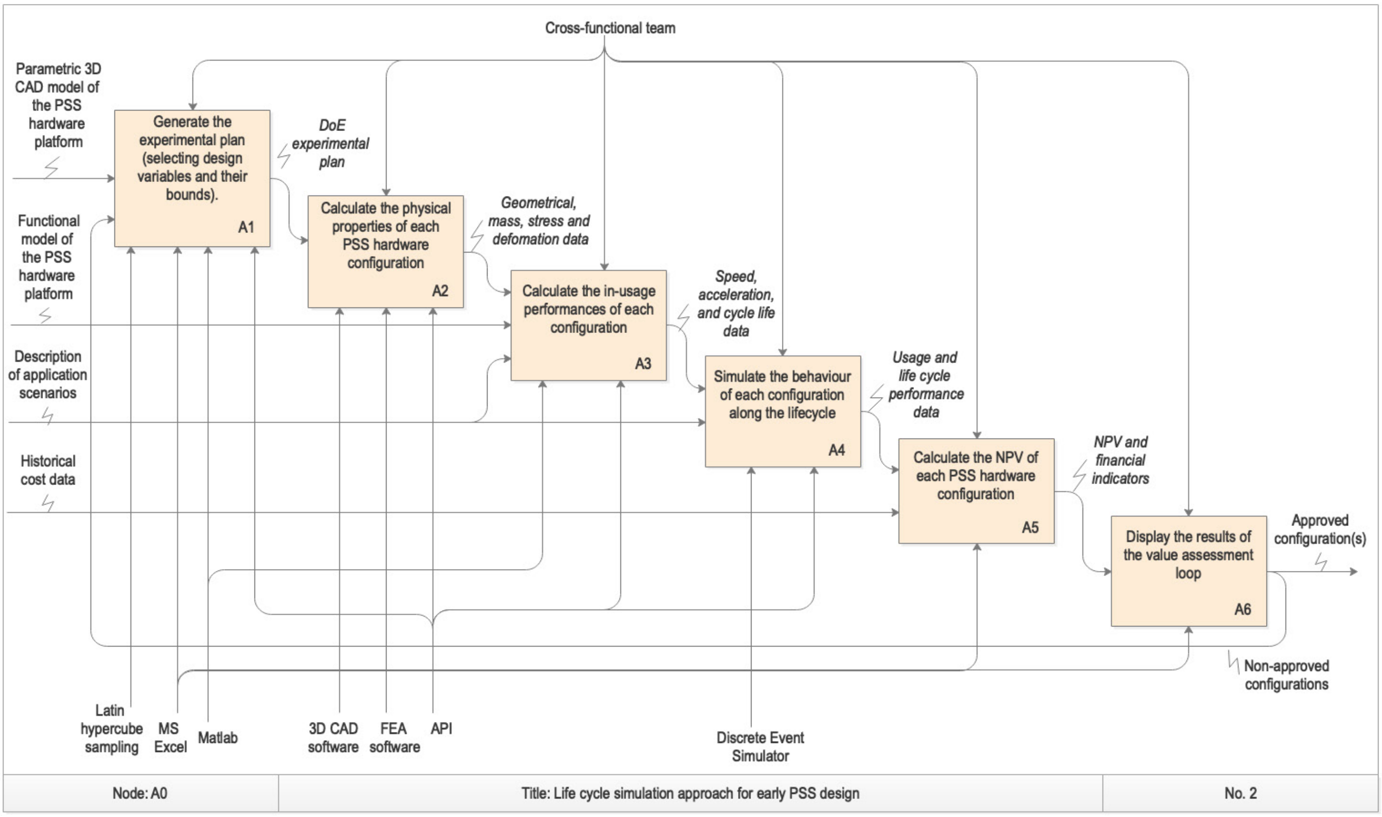

Fig. 1. Life cycle simulation approach for early PSS design (IDEF0).

3.2. Calculate the physical properties of each PSS hardware configuration

Each instance in the newly generated experimental plan is inputted in the 3D CAD environment to automatically generate a geometrical model of the PSS hardware. The data exchange between the MS Excel environment® and the CAD application is enabled by establishing generic communication protocols/functions that exploits the application programming interface (API) of each software. The model embeds design automation rules that allow adding or removing components/sub-systems in the assembly, to automate the generation of topologically (not only dimensionally) different configurations. When the experiment is executed, associated attributes for all concept variants in the generated experimental plan are predicted from the newly generated geometry, and further stored in a database. Each generated configuration renders a number of physical properties for the PSS hardware, such as dimensions for all modeled parts, weight data, centers of gravity and more. These are calculated in the CAD environment considering the actual displacements, loads and interface requirements introduced by the above inputs. This information further is used as input in a finite element analysis (FEA) software to obtain information about stresses and deformations for critical components in the system.

3.3. Calculate the in-usage performances of each design configuration

The derived geometrical and physical characteristics of each design configuration are further imported in the MATLAB® Simulink environment to calculate the in-usage performances of each generated option. This activity takes as input the description of typical application scenarios for the PSS hardware (including environmental conditions, expected loads, the frequency of use). The hardware is described here by means of a functional model, describing the functions of the system, the relationships between them, their input/output elements and their sequence. The main output of this activity is a set of specific system and sub-system performances (e.g., accelerations, speeds, deformations or cycle life) characterizing the operation of the machine in the specified application.

3.4. Simulate the behavior of each configuration along the lifecycle

Once generated, geometrical-, physical- and performance-related data are further imported in a Discrete Event Simulation Environment (DES) environment, by exploiting existing API. This activity aims at simulating the system-level behavior of each design configuration. The characteristics of the PSS hardware are first imported in simulation models that replicates typical usage scenarios, to predict how each design will behave in the customer operational process. This stage features the creation of several usage simulation models, that are iteratively refined during the development process. These models take a more ‘system-level’ view compared with those deployed in the previous step and consider the interaction of the proposed hardware with both humans and other machines. Additional DES models are developed to provide better understanding of the hardware performances along the entire life cycle, estimating serviceability, maintainability, upgradeability performances and more.

3.5. Calculate the NPV of each design configuration

The results of the above simulations and experimentations are later used to populate cost and revenue modes in the following value analysis phase. This phase exploits a Net Present Value (NPV) function, similarly to what proposed in VDD literature for the evaluation of complex systems [26]. The function compares cash inflows and outflows over a period of time considered relevant by the cross-functional team. The definition of the cost items follows the model for the Total Cost of Ownership proposed by the PROTEUS Tool book [27]. From here, cost areas are shortlisted, distinguishing between items considered to be priorities, negligible or not assessable when developing the cost engineering approach. These prioritized items are cascaded down to a series of models able to generate the necessary data for the NPV function to be populated. Importantly, separate value models are developed to account for alternative PSS business model types. In doing so, revenue data are calculated by considering, for instance, the effective utilization of the PSS hardware, its availability in the different PSS types, its flexibility in operation and more. The NPV model results are used then to identify the most valuable combination of features for the hardware given alternative business models.

3.6. Display the results of the value assessment loop

The last step concerns the visualization of the value analysis results. Value-related data are displayed maintaining the link with specific features of each hardware sub-system, to enable trade-off studies to be conducted. The main goal of this phase is to identify areas of improvement in the current configurations, so to refine the design in the next iteration with an outlook towards optimizing the value of the solution from a system perspective. In order to facilitate the discussion and negotiation of design trade-offs among the cross-functional team members, the value analysis results are displayed in an ad-hoc environment at one of the authors home institutions, named Model-Driven Decision Arena (MDDA) [25]. The MDDA is inspired by the concept of Decision Theatre (DT) [28] and consists of a high-speed server with large fixed screens on which to display complex data, models and simulation results (Figure 8). It also features a touch screen in the center of the room to control and manipulate the models and interact with the results. The MDDA relies on an MS Excel® server that controls interaction, data transfer and execution of all modules in the environment, connecting one design model (e.g., CAD) to the next (e.g., DES, MATLAB®). The MDDA visualization interface support the cross-functional team members in interacting with the outcomes of the modeling activity, so to evaluate options, assess changes and share knowledge during gate meetings and decision-making tasks. Eventually, if a satisfying combination of variables for the PSS hardware can be found, the design is selected for further investigation and moved into the detailed design phase. Otherwise, the cross-functional team might perform additional loops, testing more and new combinations to explore the entire design space for the solution.

4. Case study implementation

The proposed approach was applied in a case study related to the design of a zero-emission asphalt compactor. The introduction of a fully electrical solution aims at generating both environmental benefits (lower emissions, lower noise pollution) and economical savings (lower energy consumption, less maintenance, access to areas subjected to noise restrictions) in the customer process. Two alternative PSS business models [29] are considered for this solution: Product-oriented PSS (the machine is sold to the customer) and Use-Oriented (the hardware is part of renting agreement).

4.1. Generating and calculating machine performances

Figure 2 shows two design configurations for the electric roller platform. The first one mimics an existing machine, while the second one features more compact drums, an oversized middle joint as well as battery pack (which, in turn, affects several geometrical features of the machine).

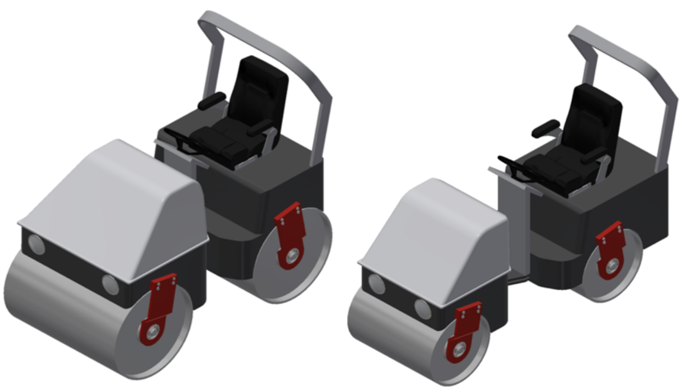

Fig. 2. Alternative design configurations for the electrical asphalt compactor.

After creating a fully parametric 3D CAD model of the machine, the cross-functional team identifies the set of design variables to be varied in the DOE. A total of 16 variables are considered in the study, ranging from alternative battery technologies (i.e., different types of lithium-ion batteries) to battery capacities, to electrical motor types (i.e., at different nominal powers, number of poles, bearings, etc.) to geometrical dimensions (e.g., width, breadth and height of the machine, water tank volume, middle joint length and more).

Each generated CAD model is then imported in MATLAB® to calculate speed, acceleration, and power consumption data, given the friction, drag, vibration, and aerodynamic constraints in three main application scenarios. The machine can be used for small road maintenances and repair operations, such as compacting potholes. It can also be applied to the realization of sidewalks and walking paths. Eventually, it can be used for larger construction works, such as parking lots. In these scenarios the machine always runs in three different modes: ‘transportation’, ‘propulsion/static’ and ‘vibration’, each of them featuring different energy requirements. In the first mode the machine stays ‘idle’ with only a few systems (e.g., warning lights) being switched on. The machine is used in 'propulsion' mode to perform compaction works with hot/cold asphalt. The 'vibration' mode is the most energy demanding as it activates the drums to ensure tighter compaction of the asphalt particles after the first passes in propulsion mode. Each mode affects the wear of the machine in different ways, with 'idle' being the less wear-prone and 'vibration' (i.e., full power mode) being the most demanding from a wear perspective. Importantly, each application (i.e., 'potholes', 'sidewalks' and 'parking lots') features a different mix of these working modes, with the first one featuring more 'transportation' (and hence being less energy consuming) than the remaining two.

4.2. Assessing usage and life cycle behavior

The asphalt compactor data are then imported via API into the DES environment (Figure 3), to study its behavior along the lifecycle with more detail. In the pothole scenario, for instance, the machine is first transported to a road compaction site by a truck (i.e., it runs in 'transportation' mode), and then waits to be activated until a worker (entity in the DES model) prepares the hole to be processed (cutting the damaged asphalt and laying down a new layer). The machine then moves in 'propulsion' mode between two 'transfer nodes' that indicate the size of the hole. Here the machine follows a 'free space' movement, where the distance between the physical element of the model corresponds (in scale) to the effective distance in the reality. The machine switches then to 'vibration' mode (as defined by the model user), and then back to 'propulsion'. When the work is completed, it moves to a new hole (e.g., of a different size), repeating the procedure until is transported back to its parking spot at the end of the day. The process is repeated considering a different mix of working modes in consecutive days, for a number of days in a year corresponding to the expected length of a 'road construction' season (e.g., 180 days).

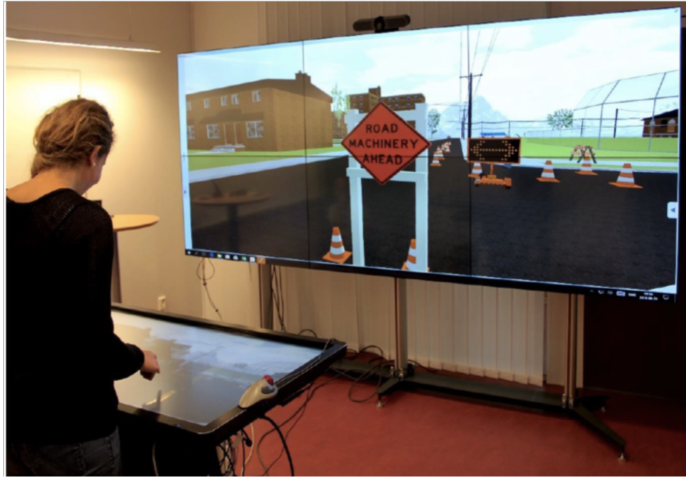

Fig. 3. DES model 3D visualization in the MDDA.

The machine is placed in the DES model as a subclass entity, creating user-defined behaviors to consider how it interfaces with other elements in the system (such as humans and other equipment). The entity is modelled by receiving speed, acceleration and power data obtained from MATLAB Simulink® as input parameters. Additional logic is added to calculate the battery consumption in the 3 different modes. A 'state variable' in the DES model tracks the battery state of charge while the machine is moving, using a function that takes as input the results of the previous analysis in MATLAB Simulink®. The DES model includes further additional logic to address service, maintenance, and repair aspects. For instance, it includes a 'state variable', which allows keeping track of the number of times the asphalt compactor stops. This value is later used to approximate the wear and the performance evolution over time of different components.

4.3. Computing and visualizing the value contribution

The DES results are eventually inputted in an NPV function. This considers potential revenues and costs associated with the usage of the machine in a 10-year time period. Energy, labor, water, transportation and battery acquisition/replacement costs, together with resale value, are main items in the NPV calculation. Figure 4 shows an example of how seven different battery technologies perform in the 2 PSS business models considered. The 2-dimensional graph summarizes the behavior of 150 PSS hardware designs at fixed battery capacity and varying dimensions of the machine middle joint.

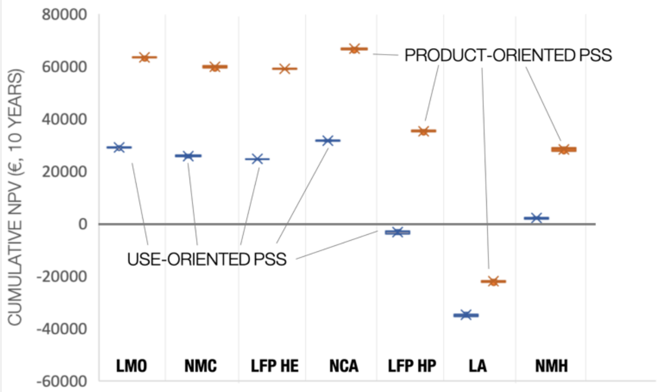

Fig. 4. NPV results for alternative battery technologies at fixed capacity (LMO= Lithium Manganese Oxide; NMC= Lithium nickel manganese cobalt oxide; LFP HE= Lithium iron phosphate high energy; NCA= Lithium nickel cobalt aluminum oxide; LFP HP: Lithium iron phosphate high power; LA= Lead-acid; NMH = Nickel Metal Hydride). NW! Data have been scaled due to confidentiality.

The differences in the diagram can be explained by the different revenue-generating ability of each machine, mainly due to their ability/inability to satisfy the daily energy requirements for the different applications. The design team can then dig into each specific technology to uncover, with higher granularity, the monetary impact of a given PSS configuration on manufacturing, transportation, shipping, assembly-disassembly, service, maintenance and recycling costs. The team may then choose to select a machine design for further investigation or to go back to activity A1 in the IDEF0 model (Figure 1) to assess more and new configurations.

4. Discussion and conclusions

The selection of PSS design concepts is an iterative process, which requires systematic support that is able to adapt to the pool of information and knowledge available during decision events. This paper illustrates how a life cycle simulation approach can be introduced to assess the value of PSS hardware concepts already in an early design phase. The main benefit of this 'frontloading' exercise is to raise awareness among decision-makers of the long-term consequences of their design decisions in alternative business scenarios. Several demonstrators have been developed during the research to iteratively verify the proposed process and its technological enablers. Verification activities have been mainly qualitative so far, featuring co-located physical meetings and interviews with system experts and process owners. The simulation-based approach is acknowledged to help decision makers in exploring the design space with more rigor. Yet, they also highlighted the need to further develop new constructs able to inform decision makers of maturity and impact of models used in a specific decision scenario.

Experimental sessions in ad-hoc design episodes are currently planned to provide more factual data about the ability of the proposed approach to reduce lead time and improve the quality of early design decisions. The results of a pilot experiment, focusing on activities A1 to A3 (Figure 1), have recently showed evidence of the ability of the proposed approach to leverage discussions across roles and disciplines in the organization, and indicated that the model-based environment (including the MDDA) can create a shared understanding across the cross-functional team about the solution strategy to pursue.

Future research will focus on the opportunity to further standardize model interfaces and simulation procedures. It will also ensure full integration of the enabling technologies with the ecosystem of tools that exist in today's engineering organizations. Eventually, data mining techniques will be explored to enhance the reliability and fidelity of the prosed process. For instance, it shall be possible to log data from existing hardware in operation and apply data mining algorithms to discover patterns and make predictions, so to seamlessly and automatically populate models at all levels.

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