Towards Virtual Confidence - Extended Product Lifecycle Management

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Abstract. Product lifecycle management (PLM) systems maintain amongst others the specifications and designs of product, process and resource artefacts and thus serve as the basis for realizing the concept of Virtual Manufacturing, and play a vital role in shortening the leadtimes for the engineering processes. Design of new products requires numerous experiments and test-runs of new facilities that delays the product release and causes high costs if performed in the real world. Virtualization promises to reduce these costs by simulating the reality. However, the results of the simulation must predict the real results to be useful. This is called virtual confidence. We propose a knowledge base approach to capture and maintain the virtual confidence in simulation results. To do so, the provenance of results of real, experimental and simulated processes are recorded and linked via confirmation objects.

Keywords: Virtual Confidence, Simulation Data Management, Provenance, Ontology

1 Introduction

The move towards shorter product lifecycles in industry has been going on for decades. One reason is the stricter legal requirements for sustainable environmental product footprints. Another reason is the increased customer demand for personalized and customizable products. Last but not least, the global economy forces companies to increase on quality and productivity to stay successful and profitable[1].

Traditionally, companies have emphasized efficiency in the operation, i.e. to rapidly deliver high quality products to the customers. This strive has been one of the key motives for efforts in implementing production philosophies such as lean production. Today, the scope has been widened since shorter product lifecycles

naturally puts a higher focus on a rapid, reliable and efficient development and decision processes preceding the operation phases.

This scope also includes a request for a fast ramp-up of production speed after start of production. In many cases both product- and process development need to be completed months or years before start of production just to offer an opportunity to deal with mistake recovery and system touch-up. Another time consuming activity can be development of operator work instructions and training.

In order to meet the demand for an efficient development process companies started adopting the concept of Virtual Manufacturing (VM), often in parallel with organizational principles such as concurrent engineering and others. VM is a set of computer-aided engineering (CAE) tools empowering engineers to work and express their knowledge based on computer models in order for a business to make informed decisions. The models may include products as well as the required manufacturing processes and their related manufacturing resources (machinery, tools etc.). This is commonly known as the Product – Process – Resource system (PPR). Typically, the use of VM tools is divided in two distinct steps; Modeling and Simulation. On top of these fundamental steps Optimization can be added [2].

A key advantage using VM is avoidance of costly and time consuming procedures using physical prototypes for tests and validation. Use of prototype parts is often connected with long lead times since they normally are made in a craftsmen manner. Characteristics of the prototype material can be different compared with the final serial production material, e.g. casted material is replaced by machined material which in turn displays different properties.

Previously, VM was characterized by solitary CAE tools were information and data was captured inside application specific models stored on a file server. The introduction of Product Lifecycle Management (PLM) implied an integration of data and information related to the PPR system. PLM offers an ability to manage the development process and fully realize the idea of concurrent engineering [3].

This paper presents a framework for an integrated management of information and knowledge stemming from VM and the Real world operation. At first, the term *virtual confidence* is defined and motivated. Then, *provenance* and *ontologies* are proposed as means to extract and manage knowledge related to the framework.

2 Virtual Confidence

Even though VM is a powerful concept, the level to which companies have integrated VM in their practice varies considerably. One divider is the level of confidence an organization has in VM and the specific CAE tools. Use of virtual manufacturing can be classified in different levels with respect to the confidence you have in the results from simulation, and to which extent you can rely on CAE technology. The term *virtual confidence* (VC) captures this level of trust and utilization. The vision for VC is avoidance of all tests, validations and training based on physical products, prototypes and real-world machines. All analysis, tests, decisions and trainings shall be made based on numerical data, e.g. CAD-models, simulations etc. prior to the start of production.

Virtual confidence can be divided in different levels which also can serve as a definition of the term:

Level 0:   CAE technology not available

Level 1:   CAE technology available but immature
            CAE technology not used in industry for the development processes

Level 2:   CAE technology available and recognized
            CAE technology is used as a complement to physical testing and support decisions

Level 3:   CAE technology available and well established
            CAE technology used for product-, process- and resource development. Results from CAE are used as a base for a majority of decisions. Physical prototypes are used as a complement to virtual verification.

Level 4:   CAE technology commonly used
            Analytical sign-off, project gates are closed based on results from CAE. Serial (hard) tools etc. are ordered based on simulation results. No physical prototypes used for tests or verification

Level 0 means that reliable CAE technology is not available for use and should be subject to research and development. Level 1 designates that CAE technology is available but need further development and verification before it can be used in a commercial project, i.e. the results from modeling and simulation are not trusted by professionals. Level 2 implicates that CAE technology is available and verified in itself, but is not used in commercial projects. There are several reasons for this including corporate culture, lack of knowledge or legal reasons. One example of the latter is the medical technology industry, which for implants requires clinical tests and verifications, first on animals and later on humans prior to a market release. Level 3 is a level where a company uses CAE to a large extent during the development process, but not completely. Still some physical tests are done, perhaps on a 'just to be sure' basis. Reasons may be lack of knowledge or experience from the CAE technology used. Level 4 is the most mature level. The company has identified which CAE tools are required and have implemented them fully into the development process. No physical prototypes are used; all decisions are made based on results from models and simulations. Normally means this that suppliers and OEM's are well integrated in the development process and shares data on-line.

The type of business and its products and processes dictates the specific need for CAE tools to be used within a specific company. However, it is not a wild guess that utilization on level 3 and 4 will for most companies include a spectrum of different CAE technologies. Furthermore, it is obvious that companies on level 3 and 4 has a large need for PLM in order to manage all information and data generated in the virtual world.

3   Simulation Data Management

Adopting the concept of VM using various CAE tools automatically brings about numerous computer models and related information. Hence it will be important to keep track on which models have been developed and which simulations have been made. Otherwise is it a substantial risk that models will be re-built unnecessarily, resulting in engineering waste when thinking in Lean terms.

It is natural to use a PLM-system as a hub for managing simulation models, results and other related information such as model limitations and simplifications in order to manage them, as exemplified below:

Building a CAE model raises questions about issues such as model limitations, i.e. shall the model reflect the entire physical system or only a significant portion of it. An example of a typical limitation would be modelling of a production line for assembly using a Discrete Event Simulation tool. Shall the model include any fork lifts which supplies the assembly operators with parts or not? If no, then the model may assume that assembly stations never runs out of raw material. Such a limitation will affect the simulation result when compared to the real world outcome.

Other issues affect decisions regarding model simplification i.e. are there aspects related to the physical system which is considered unnecessary to reflect in the model. One example would be modeling of a product assembly. In reality the final appearance of that assembly would be affected by the individual variation of the components as specified by the assigned manufacturing tolerances. This may not be necessary to reflect if, for instance, the aim is a component interference (or collision) analysis using a 3D CAD system.

In [4] Gedell & Johannesson discusses re-use of detailed part designs in a context of product design carryover or commonality for platform based development and manufacture.

In a situation when carryover of a detailed design to a new product variant not is possible, e.g. due to other considerations regarding model limitations and simplifications, engineering lead time can be shortened significantly and quality improved if the underlying design rationale is retrievable during the new model design phase. The same need goes for re-use of simulation models for manufacturing processes and system, see figure 1.

This insight is supported by a white paper published by CIMdata [5] which addresses the area of simulation & analysis governance including a need for simulation data management. This is captured by the Zachman Framework which presents the`7 W's of Provenance': Who, What, Where, Why, When, Which, and How [6, 7].
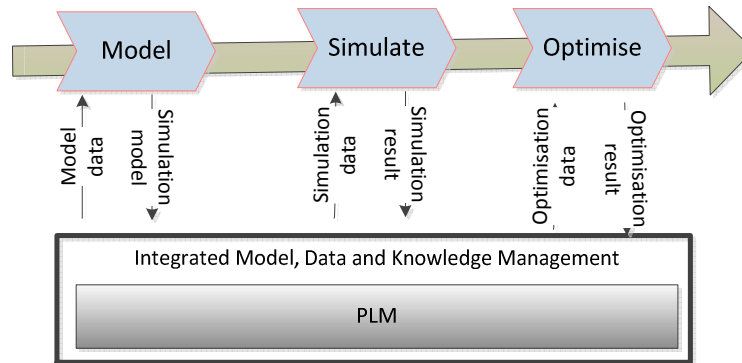
Figure 1: Simulation Data Management

Examples of model data can be from various sources and includes all kinds of requirement specifications, FEMA protocols, control plans etc. Simulation data includes Design of Experiment information, input parameters etc. If optimization is part of the development process data and results shall be managed in a similar way.

Simulation data management also includes extraction and management of knowledge which will be the result from modeling, simulation and eventual optimization.

4   Tacit Knowledge and Experience

One problem in most businesses is organizational learning. All humans make experiences and learn from them during their career, building knowledge. A key challenge for an organization is to accumulate this experience based knowledge. As an individual we tend to forget over time, and during the career we move to new posts. The replacing newbie will for natural reasons normally not have the detailed experience based knowledge from the specific product or process [8].

In order to reach the vision of virtual confidence, information and knowledge developed during the design and development phases ought to be combined with experience based knowledge from products and manufacturing processes in operation. This should be done in a way that offers those working in the engineering process a natural way to combine new knowledge with proven experience based knowledge. In the vision of virtual confidence PLM play a natural role as being the platform for managing both experiences based on real world findings and knowledge developed during the engineering process. This integration of information and findings from the Virtual world and the Real world is expressed by the term *Extended Product Lifecycle Management* as shown in figure 2 [9].
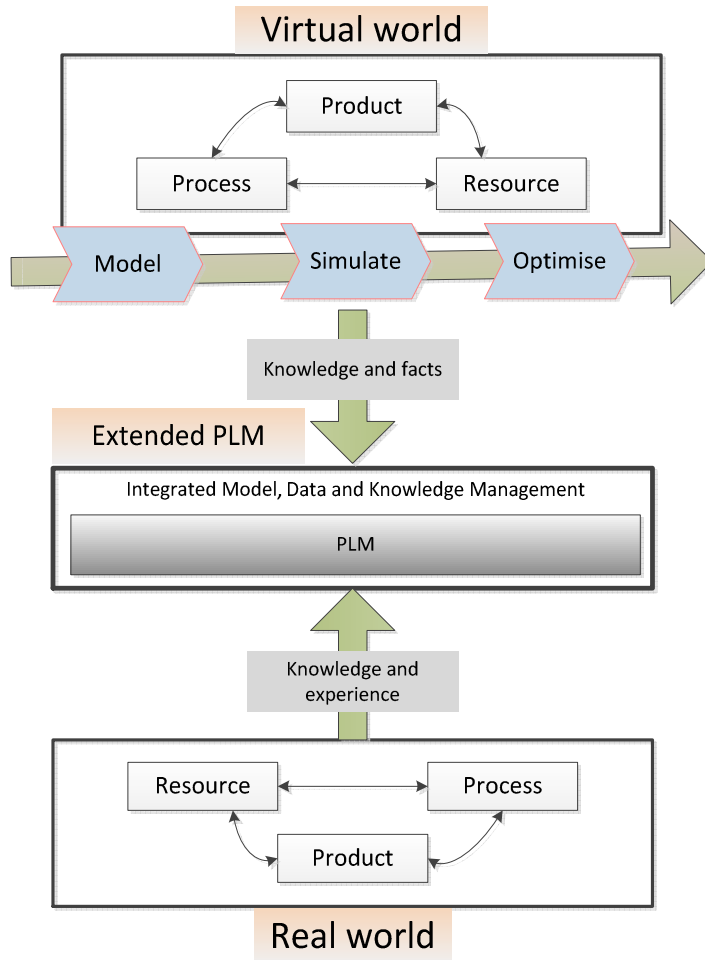
Figure 2: Facts and knowledge is captured inside the Extended PLM-system

5   The Provenance of Virtual Confidence

In the knowledge management area, work is currently being made addressing the challenge of capture, structure, store and use of knowledge [10]. Regardless if the knowledge is generated in advance using virtual manufacturing or comes from real life findings it needs to be managed in order to support high-quality decisions. Much of the knowledge in an organization is tacit, i.e. only exists in the heads of the people. Some of the knowledge is externalized in documents (memos, manuals, project reports, etc.). Normally natural language is preferred in such reports, posing a challenge to manage such knowledge. Failing to do so will limit the possibility to become a learning organization.

The information system domain has proposed various approaches for knowledge management including ontology-based information sharing, which can be used to index the documents [11].

The externalization of the tacit knowledge is key to move up in the level of virtual confidence, which in turn allows results gained from the virtual world to be used as if they were confirmed by the real world. The rationale behind this argument is as follows: If the results from virtual world models about products, processes and resources have been confirmed by real world data in the past, then such (parameterized) models have a high level of confidence and are candidates to be re-used for future projects. The past experiments or results from real execution should also ideally contain ranges for the model parameters for which the virtual world results are matching the real numbers. Hence, the *first requirement* for trusted models is the ability to link data from real experiments and operation to VM models. The reality confirms the models.

A *second requirement* is to be able to identify, link and classify products, processes and resources that are referenced by models. Products consist of parts, processes have sub-processes, and resources such as machines have various functions and capabilities, all interacting with each other. A product part like an engine may be used for different car models, and will also perform differently depending on the car model. A PLM system addresses the problem of identifying product, process and resource elements. However, we need to augment the services of a PLM system with a knowledge layer that allows capturing the virtual confidence. One candidate is semantic web technologies bridging the gap by means of domain ontologies. *Manufacturing domain ontologies* [12] provide names for classes of objects and their interrelationships. These names (also called concepts) are used to uniformly express and index knowledge so it can be searched and re-used later. The *third requirement* is about the ability to trace back a result (e.g. the cycle time of a production step) to the context in which it is regarded as valid. We propose to use provenance ontology to capture this knowledge. Provenance is about memorizing the context in which an entity can be interpreted. The W3C provenance ontology PROV_O [13] specifies the dimensions of provenance data: the time when the entity was created, the entities from which it was derived, the activity that generated the entity, and the agents/persons that were involved with the creation or use of the entity. The entities linked by the provenance data establish a dependency network that supports deriving the confidence level of the results as shown in figure 3.

The domain ontologies provide sub-class hierarchies of concepts and standardized names for possible associations between concepts. Both are the basis of a semantic search for product, process and resource components which is independent from the data structures used in the PLM system. The link to the PLM system, also called *commitment*, still has to be done. We propose to use RDF [14] and techniques from the Linked Data community for this purpose. In a nutshell, the identifiers for the objects stored in the PLM system are translated into the RDF notation and can then be used for forming knowledge statements in terms of the domain and provenance ontologies.
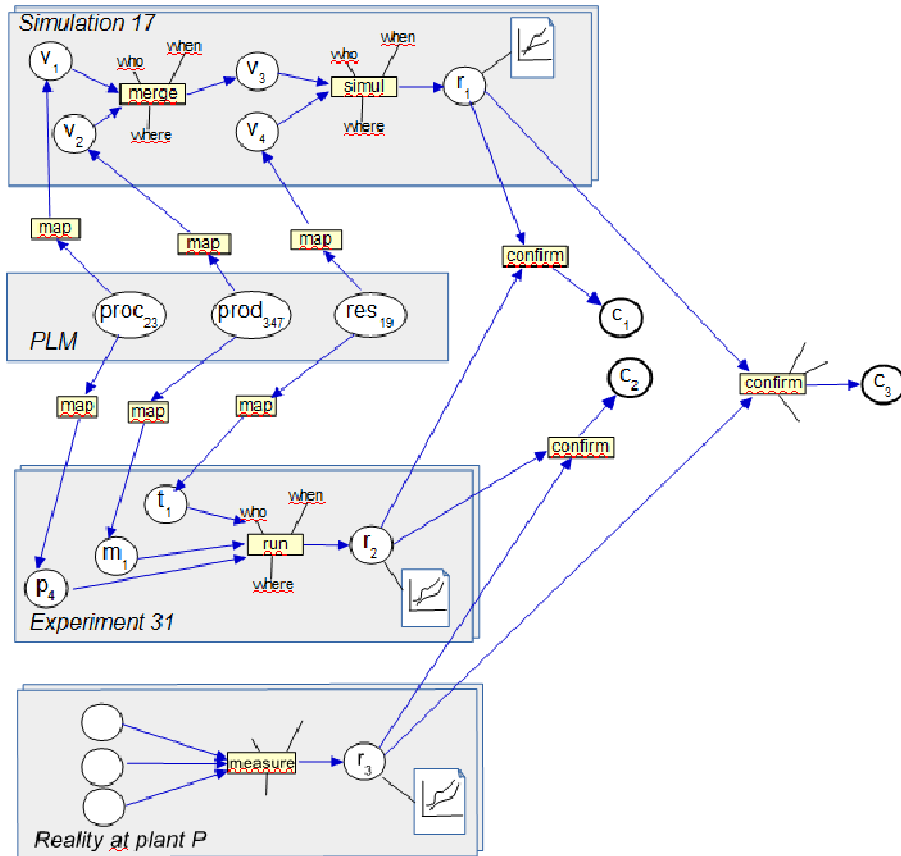
Figure 3: Representing the provenance of virtual confidence

Figure 3 shows how we envision the use of provenance data for supporting virtual confidence. In figure 3 are the labels of the circular objects placeholders for information objects referenced in the knowledge base. 'V' labels represent simulation models including their configurations. 'R' labels stand for result report. 'C' labels represent confirmation objects, i.e. objects that establish the confidence in a result. The PLM database contains the master data about processes, products, and resources in the enterprise, master data is mapped to models and to the physical setups of experiments

The starting point is the models and objects stored in the PLM system. These objects are used to specify experiments and simulations. The rectangular nodes represent the result of actions. For example, the partial simulation model v1 has been mapped from the PLM process model $proc_{23}$. Storing an object like "map" with input $proc_{23}$ and output v_1 allows tracing the dependencies of intermediate artefacts. Each record about an action comes with information about who executed it, when, and

where. The simulation result in figure 3 is the object r_1 which comes with data about properties such as cycle time, resource utilization, and others. Hence, we can reconstruct the context in which the result r_1 was obtained. In the same way, the creation of experimental results is recorded with provenance data, leading in figure 3 to the result object r_2. The action object "confirm" (executed by an expert) records that the result r_2 is conforming the simulation results r_1. As a consequence r_1 is a (more) trusted simulation result that is a candidate for being re-used. Likewise, the observation of the reality about the same products, processes and reality at a plant leads to results like r_3 that both confirm (or dis-confirm) the experimental and virtual results. The virtual confidence is thus encoded in the objects c_i, which can be traced back to the PLM objects representing the participating products, processes, and resources.

Assume now that a new product variant $prod_{348}$ is being designed which only marginally differs from $prod_{347}$. In particular, the simulation model component v_2 derived from $prod_{347}$ is similar to the model that is derived from $prod_{348}$. Then, the simulation 17 is a candidate to be re-used without having to repeat the experiments.

6   Conclusions

Adoption of Virtual Manufacturing for the development process promise faster and more cost-efficient implementations of new products. The problem is that models as well as simulations simplify the reality, for example by reducing the number of variables. Using VM as a basis for business decisions demands a high level of confidence for the model and simulation results. This paper proposed five levels of virtual confidence. If a VM setup is confirmed by data collected from reality, then we are confident that it is a valid model. If a new model matches with a parameterized representation of a model that has confirmed simulation results, then the performance and quality data can be obtained via the simulation models. This allows companies to reach the higher levels of virtual confidence.

Our approach to establish the virtual confidence is to create a knowledge base on top of a PLM system that records the provenance of result data. If results of experiments or measurements from the reality match the predictions of a simulation model, then the result of the simulation model is marked as confirmed. This requires a possibility to manage not only the real world PPR-system data but also the provenance for model and simulation data. Keeping the provenance allows re-creating the context in which the results were obtained, i.e. who has performed which steps at which time using which inputs and tools to come to the result. All results are eventually rooted in the definitions of the PLM system. In particular, the link to the PLM system specifies which versions of products, processes, and resources were the starting point for the simulation model, or for the experiment, or for the measurements at the real world operation.

There are a number of open issues. First, a new product variant may only slightly differ from its predecessor. If this difference is not captured adequately in the virtual models, then the results could drastically differ from the predictions. Second, the provenance approach requires recording many dependencies between the objects of

the PLM system and the models used for simulation, experiments, and for creating measurements in the real world.

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