Semantic Virtual Factory supporting interoperable modelling and evaluation of production systems

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Modelling, simulation and evaluation of manufacturing systems are relevant activities that may strongly impact on the competitiveness of production enterprises both during the design and the operational phases. This paper addresses the application of a semantic data model for virtual factories to support the design and the performance evaluation of manufacturing systems, while exploiting the interoperability between various Digital Enterprise Technology tools. The paper shows how a shared ontology-based framework can be used to generate consistent 3D virtual environments and discrete event simulation models, demonstrating this way how the proposed solution can provide an interoperable backbone for heterogeneous software tools.

1. Introduction

One of the main challenges in manufacturing today is to design and operate systems producing a high variety of customized products as efficiently and quickly as possible, while dealing with uncertain and highly volatile demands. Managing manufacturing companies and systems requires both long-term and short-term decisions, which all deeply influence the performance of these firms. From strategic point of view the decisions have impact on longer time horizon (usually more than two years) and involve major commitment of financial resources [1]. For instance, strategic decisions may regard the number of plants or facilities to be built, their size and their location, the variety of products to be manufactured, the appropriate manufacturing technologies, and, within a plant, the number and type of production resources, the characteristics of the transportation and handling systems and the degree of automation, to mention the most important aspects only. From tactical and operational points of view the decision makers should consider changes like expansion, reduction or reconfiguration of production structures, mid-term planning, short-term scheduling and optimized control of the systems in question. On all levels of hierarchy the complexity of these decisions and their importance from the point of view of the profitability emphasizes the need to have formal and structured approaches to support the design, management and performance evaluation of production systems.

Nowadays managers and engineers usually apply Digital Enterprise Technologies (DET) as decision support tools in handling the challenges enumerated above [2]. The concept of digital enterprise – the mapping of the key data and processes of an enterprise to digital structures by means of information and communication technologies – gives a unique opportunity for planning and controlling the operation of production systems [3]. Although DET provide all the necessary components for modelling, analysis and evaluation of production systems, in real scenarios these tools and solutions are concurrently used by different decision makers with various objectives. Mainstream commercial Digital Factory (DF) tool providers already offer integrated solution of their modular products but, on the one hand, the procurement and deployment of such integrated solutions are severely expensive and usually without the warranty to effectively exploit all provided functionalities, on the other, they require specific knowledge and expertise frequently inaccessible even in big enterprises.

This paper introduces a research work aiming at homogenizing the modelling basis of production system and on this normalized foundation allowing the smooth interoperation of different DF tools that can be both commercial and self-developed.

2. Modelling production systems on semantic basis

Production system modelling may use different formalisms and approaches, depending on the characteristics of the considered problem and the expected results. Whether the system is a machine tool, a production line, a distribution network or a communication system, we can use modelling for formalizing and gaining knowledge from the system at different life-cycle phases, for evaluating a certain feature, for making comparison between several reconfiguration options, for problem detection or for evaluating and improving the system performance.

Formal, descriptive modelling methods proposed in Enterprise Engineering (EE) discipline [4] support the analysis and re-engineering (design) of existing (new) business entities – namely business processes, application systems, business departments, industrial plants and in the broadest sense, complete enterprises or networks of enterprises. Descriptive methods like UML or IDEF\textsubscript{xxx} [5] consist of modelling languages, defined in their syntax and usually in correspondent graphical notations. In the most complete cases, formal methods provide a reference architecture where the supported modelling languages are organized according to pre-defined criteria (e.g. GERAM, ARIS) [6], [7].

2.1. Standardization efforts

From standardization point of view, several contributions have faced the problem of developing a holistic and complete data model for representing manufacturing systems, both considering
tangible (e.g. machine tool, workpiece to be produced, etc.) and intangible (e.g. process plans, production logics, etc.) aspects.

ANSI/ISA-95 is an international standard for developing an automated interface between enterprise and control systems. It aims at providing both consistent terminology and information models as well as reliable operations models [8]. A different approach in the modelling of manufacturing process is offered by the Process Specification Language (PSL) standard. PSL is an ontology providing a way to formally describe a process and its characteristic. The ontology has been developed at the National Institute of Standards and Technology (NIST) and has been approved as an international standard in the document (ISO 18629) [9].

Partially based on Standard for the Exchange of Product model data (STEP), the Industry Foundation Classes (IFC) represents an open specification for Building Information Modelling (BIM) data that is exchanged and shared among the various participants in an architecture, engineering and construction project [10].

2.2. The role of ontologies in production systems modelling

Several research efforts were already made to apply semantics and create ontologies aiming at modelling the components and the interconnections in manufacturing systems and/or supporting the simulation model building of such systems. In [11] the study introduces a component-based modelling and simulation approach that supports model reuse across multiple application domains called CODES. The attributes and behaviour of the components are abstracted as meta-components and are described using COML (Component Markup Language). The integrated approach is supported by a component-oriented simulation and modelling ontology called COSMO. Authors in [12] presents the main issues and challenges of creating a simulation-based modelling ontology. On the base of the experience coming from the creation of the Discrete Event Modeling Ontology (DeMO) the authors propose the decomposition of the models in behavioural and observable parts on the base of Hidden Markov Models. An overview of the DeMO ontology is also given, focusing on the semantic modelling of a discrete-event simulation kernel including both event-driven and process oriented approach.

In [13] the authors explain the role of ontologies in facilitating simulation modelling and highlighting the importance of integrating and modularizing different simulation systems. Special view is taken on the process of simulation model creation and the authors underline the most relevant project phases where ontology supports the common understanding. Further possible roles of ontological modelling are also introduced like distributed and component-based simulation. Finally the authors present the Ontology driven Simulation Modelling Framework (OSMF) solution, which provides a “visual programming environment” to rapidly compose, build, and maintain distributed, federated simulations.

The research presented in [14] focuses on reusability and composability aspects in simulation modelling of large-scale systems independently from the type of simulation.

On the base of our review it was clear that semantic web technologies, even if promising, were only partially used in different, well-bordered segments of production systems’ modelling field. Inspired by this fact and the supplementary knowledge manipulation opportunities provided by ontology-based modelling, the European FP7 Virtual Factory Framework (VFF) [15] project aimed at creating a new framework based on semantic web technologies to manage the data and models related to the whole factory life.

3. The Virtual Factory Framework

The Virtual Factory Framework (VFF) can be defined as “An integrated collaborative virtual environment aimed at facilitating the sharing of resources, manufacturing information and knowledge, while supporting the design and management of all the factory entities, from a single product to networks of companies, along all the phases of the their life-cycles” [16]. As presented in Figure 1, the VFF architecture is based on three main pillars:

- **Virtual Factory Data Model (VFDM)**, i.e. a coherent, standard, extensible, and common data model for the representation of factory objects related to production systems, resources, processes and products, i.e. the Data & Knowledge.
- **Virtual Factory Manager (VFM)**, i.e. the software application that manages and provides access to the shared repository containing data structured according to the VFDM. A prototype implementation of VFM as web-service is presented in [18].
- **Digital Factory tools (or VF modules)**, i.e. the software tools that are able to communicate with the VFM to retrieve and send shared data formalized according to the VFDM. Specific VF modules (e.g. Factory Image in Figure 1) may access real factory data to synchronize the real and virtual representations.

![Figure 1](image.png)

**Figure 1.** The architecture of the Virtual Factory Framework.
transforming the product (or a work in progress). These resources can be human operators, machines, transportation and logistics related devices, etc.

- **Process**, modelling the data regarding the processes that are adopted by the system to directly (e.g. manufacturing system, assembly system) or indirectly (e.g. logistic processes, maintenance processes) transform a product.
- **System**, modelling the data of a transformation system (e.g. manufacturing, assembly, transportation and manipulation systems) that affects a product by means of physical resources and/or human resources within a process.
- **Building**, modelling the data related to the physical structure of the factory and important for 3D layout planning and visualisation aspects (e.g. walls, columns, floor, power supply lines, etc).

Further details about the VFDM with a comprehensive description of relations between classes and properties are described in [20].

4. VFF-based integration of Digital Factory tools

This section delves into the process of integrating a Digital Factory tool into the VFF, by developing a software layer named Virtual Factory Connector (VFConn) that takes care of Input/Output conversions from data stored in the shared repository to the internal data structures of the Digital Factory tool, and vice-versa. A proper VFConn may be developed only if the following fundamental requirements are met:

- The developer knows both the VFDM and the specific data model adopted by the Digital Factory tool, at least those parts that are relevant for supporting the data exchange.
- The Digital Factory tool offers a way to access and modify (if needed) its internal data structures, typically an application programming interface (API).

3. Population of the shared repository with data and knowledge required as input by the newly integrated Digital Factory tool. Such population can be accomplished by means of Graphical User Interface (GUI) tools, by transferring data from existing databases or legacy systems, or by integrating further digital tools within VFF.

Figure 2. shows how a DF tool can be integrated in VFF thanks to a specific VFConn, while referring to the common VFDM. The functionalities of the DF tool can be used during the creation, modification of data and relations about the model of the system in question.

The following sub-sections address how two Digital Factory tools were integrated into VFF and can be employed to concurrently create and evaluate factory projects while sharing consistent data. Specifically, a 3D layout design tool and a commercial discrete-event simulation tool will be presented and then applied to a common industrial case representing a production line, as described in [22]. This production line consists of seven machine tools, characterized by failure modes that have to realize a part type by executing a process plan decomposed into five stages that include a drilling, two sequential milling, a quality control and a grinding operation.

4.1. Production system design and visualization

The production line of the industrial case can be designed and placed in its building by using 3D software tools, like for instance GIOVE Virtual Factory (GIOVE-VF) [21]. GIOVE-VF is a 3D virtual reality collaborative environment aimed at supporting the factory layout design. In particular, GIOVE-VF offers the user the possibility to design factories by selecting machines, operators and other resources from available catalogues and place them in the 3D scene of the virtual factory (Figure 3). The virtual environment can schematically display performance measures that are provided by simulators and/or monitoring tools.

GIOVE-VF has been developed in C++ and can import/export ontologies serialized in RDF/XML format thanks to a specific VFConn that was developed using a C++ library named VFConnectorLibCpp providing functionalities to parse, create and modify the ontologies by exploiting an internal map between OWL classes/restrictions and C++ classes/methods. The VFConnectorLib library is based on the Redland C libraries and makes use of an in memory RDF storage.

4.2. Production simulation with a commercial DF tool

Not only self-developed but also commercial DF tools can interoperate thanks to the VFDM while designing a production
The research reported in this paper has been funded by the European Union 7th FP (FP7/2007–2013) under the grant agreement N°: NMP2-2011-226955, Virtual Factory Framework (VFF), the grant agreement N°: 26244, VISON Advanced Infrastructure for Research (VISIONAIR) and National Office for Research and Technology (NKT) grant "Digital, real-time enterprises and networks", OMFB-01638/2009.

Acknowledgment

The research reported in this paper has been funded by the European Union 7th FP (FP7/2007–2013) under the grant agreement N°: NMP2-2011-226955, Virtual Factory Framework (VFF), the grant agreement N°: 26244, VISON Advanced Infrastructure for Research (VISIONAIR) and National Office for Research and Technology (NKT) grant "Digital, real-time enterprises and networks", OMFB-01638/2009.

References


