“Product-Process-Machine” System Modeling: Approach and Industrial Case Studies

Alexander Smirnov[1], Kurt Sandkuhl[2,3], Nikolay Shilov[1], and Alexey Kashevnik[1]

[1] St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences,
39, 14th Line, St. Petersburg, 199178, Russia
{smir,alexey,nick}@iias.spb.su
[2] Institute of Computer Science, Rostock University,
Albert-Einstein-Str. 22, 18059 Rostock, Germany
kurt.sandkuhl@uni-rostock.de
[3] School of Engineering, Jönköping University,
P.O. Box 1026, 55111 Jönköping, Sweden

Abstract. Global trends in the worldwide economy lead to new challenges for manufacturing enterprises and to new requirements regarding modeling industrial organizations, like integration of real-time information from operations and information about neighboring enterprises in the value network. Consequently, there is a need to design new, knowledge-based workflows and supporting software systems to increase efficiency of designing and maintaining new product ranges, production planning and manufacturing. The paper presents an approach to a specific aspect of enterprise modeling, product-process-machine modeling, derived from two real life case studies. It assumes ontology-based integration of various information sources and software systems and distinguishes four levels. The upper two levels (levels of product manager and product engineer) concentrate on customer requirements and product modeling. The lower two levels (levels of production engineer and production manager) focus on production process and production equipment modeling.

Keywords: Product-process-machine modeling, enterprise engineering, knowledge model, product model, production model.

1 Introduction

Enterprise modeling has a long tradition in the area of industrial organization and production logistics, which is manifested in the field of enterprise engineering with its many techniques and developments (see, e.g. [1, 2]). Similar to business modeling or process modeling, the subjects of enterprise models in industrial organization are processes, organization structures, information flows and resources, but for manufacturing and logistics tasks, not for business processes. Global trends in the worldwide economy, like agile manufacturing, value networks or changeable production systems, lead to new challenges for manufacturing enterprises and to new requirements regarding modeling industrial organizations. Traditional enterprise

J. Grabis et al. (Eds.): PoEM 2013, LNBIP 165, pp. 251–265, 2013.

models need to be enhanced with product knowledge, real-time information from operations, and information about neighboring enterprises in the value network. Consequently, there is a need to design new, knowledge-based workflows and supporting software systems to increase efficiency of designing and maintaining new product ranges, production planning and manufacturing.

However, implementation of such changes in large companies faces many difficulties because business process cannot simply be stopped to switch between old and new workflows, old and new software systems have to be supported at the same time, the range of products, which are already in the markets, has to be maintained in parallel with new products, etc. Another problem is that it is difficult to estimate in advance which solutions and workflows would be efficient and convenient for the decision makers and employees. Hence, just following existing implementation guidelines is not advisable (confirmed, e.g., by Bokinge and Malmqvist in [3] for PLM), and the adaptation process to changes has to be and iterative and interactive.

Within enterprise modeling for industrial organizations, this paper focuses on modeling an essential aspect of production systems, the product – process – machine (PPM) system. While a production system includes all elements required to design, produce, distribute, and maintain a physical product, the PPM system only includes design and production of a product, i.e. a PPM system can be considered a subsystem of a production system. The paper presents an approach to "Product-Process-Machine" system modeling, which focuses on integrating product, production and machine knowledge for iterative and interactive product lifecycle management (PLM). The main contributions of this paper are (a) from a conceptual perspective we propose to integrate information at the intersection of product, process and machine models essential for planning changes and assessing their effects, (b) from a technical perspective we propose to use a knowledge structure suitable for extension with domain specific components and (c) from an application perspective we show two industrial cases indicating flexibility and pertinence of the approach.

Based on related work in the field (section 2) and experiences from two industrial cases, the paper introduces the overall PPM system modeling approach (section 3) and shows its use for different roles in PLM (section 4). Section 5 discusses experiences and lessons learned, and summarizes the work.

2 Modeling PPM Systems

Due to the trends and challenges identified in section 1 enterprises need to be quick responsive to changes in their environment, which basically means the ability to identify (a) the potential options how to react to changes and (b) the effects of acting in a certain way, without endangering current operations of customer relations. As a basis for this "agility" an integrated view on knowledge from the product, process and machine perspective and mechanisms tailored to the needs of decision makers in the enterprise are recommendable. In this context, an integrated view to knowledge should encompass:

- Dependencies and relationships within the PPM perspectives:
    - Product perspective: products consist of components, fulfill customer requirements, are built according to design principles, use certain materials and apply specific design principles and rules.
    - Process perspective: processes are cross-connected between each other by information, material and control flows
    - Machine perspectives: machines consist of sub-systems offering capabilities depending on other sub-systems and production logistics components.

  The above are only some examples of information relevant for decision makers in manufacturing enterprises when evaluating options and their effects.
- Dependencies and relationships between the perspectives: products are developed and manufactured in processes; processes are performed using resources, like machines; machines are operated by roles, which in turn are responsible for certain processes and products or product parts. These examples show that there are many relationships between different perspectives that have to be understood when developing and assessing options for reacting on environmental changes.

This integrated view primarily requires information quantifying and qualifying the dependencies between the different perspectives, i.e. not all available information within the different perspective has to be included. Details of product design, operations of productions as provided by CAD or CAX systems usually are not required. Most existing approaches in engineering for manufacturability, PLM and production line engineering strive for an information integration and functional integration covering all life cycle phases. Our focus is on integrating essential information for key roles in a change process (see section 3).

Important roles in an enterprise when it comes to evaluating options and effects are the product manager and the production engineer. They would be among the primary user groups of a PPM system model and knowledge base. The product manager is responsible for the short-term and mid-term development of a product in terms of translating customer requirements to product features (target setting), guidance and supervision of the design process from customer features to the way of implementing them as functions, control of variability indicated by new and existing product functions, interface to sales and marketing, etc. If changes in the environment occur, the product manager has to investigate options on product level how to act or react. In cooperation with the product manager, the production engineer is responsible for making the product "manufacturable", i.e. adjust product design, material or features to what the machines in the production system can manufacture. Furthermore, the production engineer designs the overall production system by developing an appropriate composition of sub-systems and the flow of resources, materials and products.

Modeling in manufacturing and control has a long tradition, which does not only include the above mentioned perspectives, but also business aspects of manufacturing and the design, construction and operations part. This is manifested in reference models and frameworks, such as GERAM [4] and CIMOSA [5], and in a variety of standards for modeling the different perspectives (e.g. STEP [6] and CMII [7]). Furthermore, large European research projects and networks, like ATHENA [8], developed approaches for integrating enterprise system modeling and production system modeling into a joint framework. PLM systems address the complete lifecycle of products including production systems aspects and both, logistics in the supply chain and in production.

Integrated modeling of PPM systems has been investigated before. Many approaches exist which integrate two of the above mentioned perspectives. Examples are [9] that combine product and machine perspective, [10] where Buchmann and Karagiannis partly integrate process and product, and [11] with an approach for integrating product and machine perspective. Sandkuhl and Billig [12] propose the use of an enterprise ontology for product, process, resource and role modeling. However, this approach is limited to the application area of product families in automotive industries. Lillehagen and Krogstie [13] use active knowledge models for capturing dependencies between different knowledge perspectives. They use active knowledge models, which fulfill most of the requirements regarding the knowledge to be included, but their representation as visual models is not appropriate for reasoning and knowledge creation.

3 Approach

The proposed approach to PPM-System modeling originates from experiences in two industrial case studies. These cases served as basis for developing the approach and were used for implementing it and each of the cases implemented a different part. The first case is from a project with a global automation equipment manufacturer with more than 300 000 customers in 176 countries. The detailed description of this project is presented in [14, 15]. The automation equipment manufacturer has a large number of products consisting of various components. The project aimed at product codification, i.e. structuring and coding the products and their components and defining rules for coding and configuration. This coding forms the basis for quickly adapting to new market requirements by facilitating easing configuration of new products and the production system.

The second case is from manufacturing industries and resulted in a tool called DESO (Design of Structured Objects). This tool supports part of our approach and is capable of describing production processes and production facilities [16, 17]. It distinguishes two planning levels: the central planning area and the decentralized planning area of distributed plants. Every production program project or planning activity is initiated by a request asking for manufacturing of a product in a predefined volume and timeframe. Starting from this information, the central planning staff has the task to design a production system capable of fulfilling the given requirements and consisting of different plants. The involved engineers prepare the requests for different plants using the production system design.

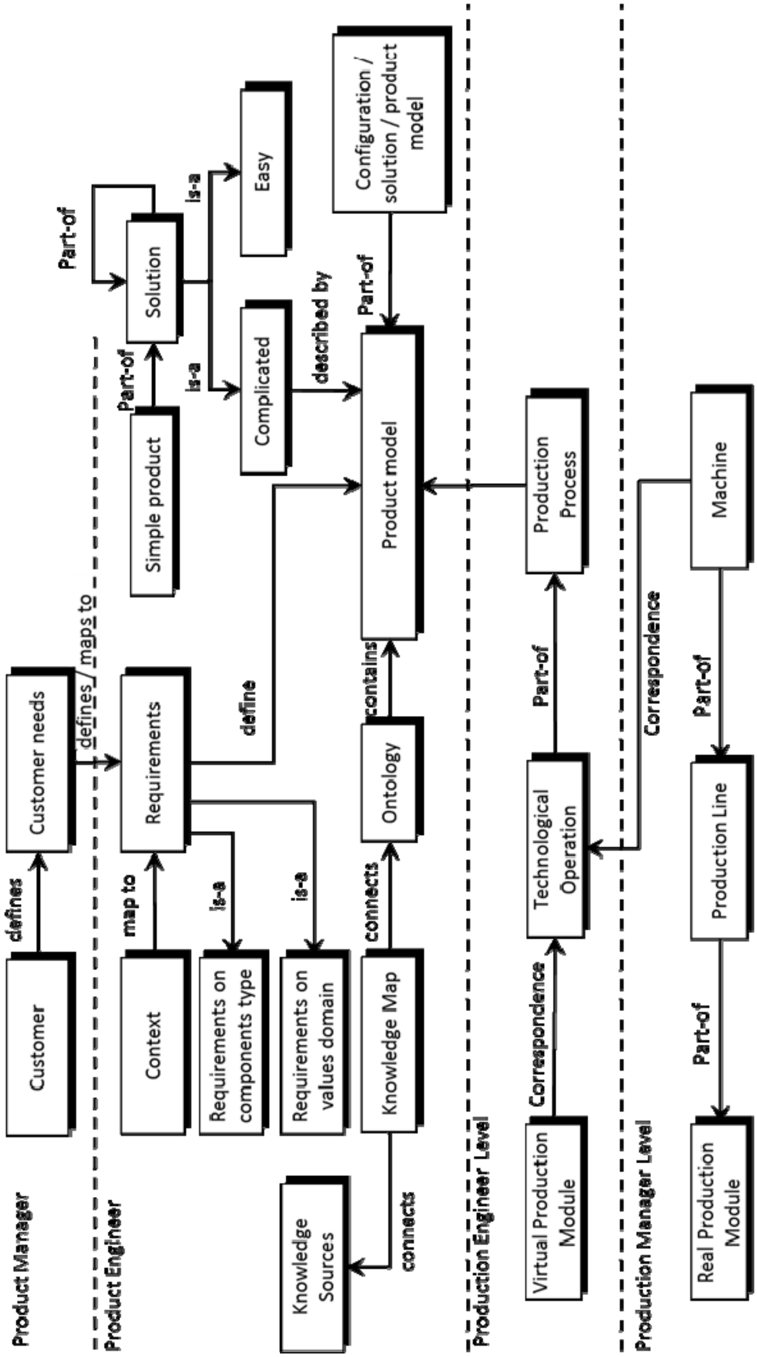

Fig. 1. Multi-level enterprise modelling concept

The engineers harmonize and aggregate parallel incoming requests for different planning periods. The different plants offer their production modules as a contribution to the entire network system. On plant level, engineers have to analyze the manufacturing potentials concerning capacity and process capability of their facilities. Only in the plants is the specific and detailed knowledge and data regarding the selection and adaptation of the machining systems to the new production tasks available. The expertise for developing and engineering of the production modules is available only in the plants.

In the context of these two cases, we propose from a conceptual perspective to distinguish two levels when representing knowledge required for central and decentral planning. The approach is illustrated in fig. 1. The first level describes the structural knowledge, i.e. the “schema” used to represent what is required for the two planning levels. Knowledge represented by the second level is an instantiation of the first level knowledge; this knowledge holds object instances. The object instances have to provide information at the intersection of product, process and machine models essential for planning changes and assessing their effects. What information is essential can be judged from different perspectives. Our approach is to put the demand of the main target groups presented in section 2 into the focus, i.e. product manager and production engineer. Since the PPM perspectives cannot be seen as isolated (see section 2), the common and “interfacing” aspects are most important.

The knowledge of the first level (structural knowledge) is described by a common ontology of the company's product families (classes). Ontologies provide a common way of knowledge representation for further processing. They have shown their usability for this type of tasks (e.g., [18-20]).

The major ontology is in the center of the model. It is used to solve the problem of knowledge heterogeneity and enables interoperability between heterogeneous information sources due to provision of their common semantics and terminology [21]. This ontology describes all the products (already under production and planned or future products), their features (existing and possible), production processes and production equipment. Population and application of this ontology are supported by a number of tools, described in detail in section 4. A knowledge map connects the ontology with different knowledge sources of the company.

At the level of product manager, the customer needs are analyzed. The parameters and terminology used by the customer often differ from those used by the product engineers. For this reason, a mapping between the customer needs and internal product requirements is required. Based on the requirements new products, product modifications or new production systems can be engineered for future production.

The approach distinguishes between virtual and real modules. Virtual modules are used for grouping technological operations from the production engineer’s point of view. The real modules represent actual production equipment (machines) at the level of production manager.

The first case study addressed the requirements and support for product manager and product engineers. Production engineers and production managers are supported by the tool developed in the second case study.

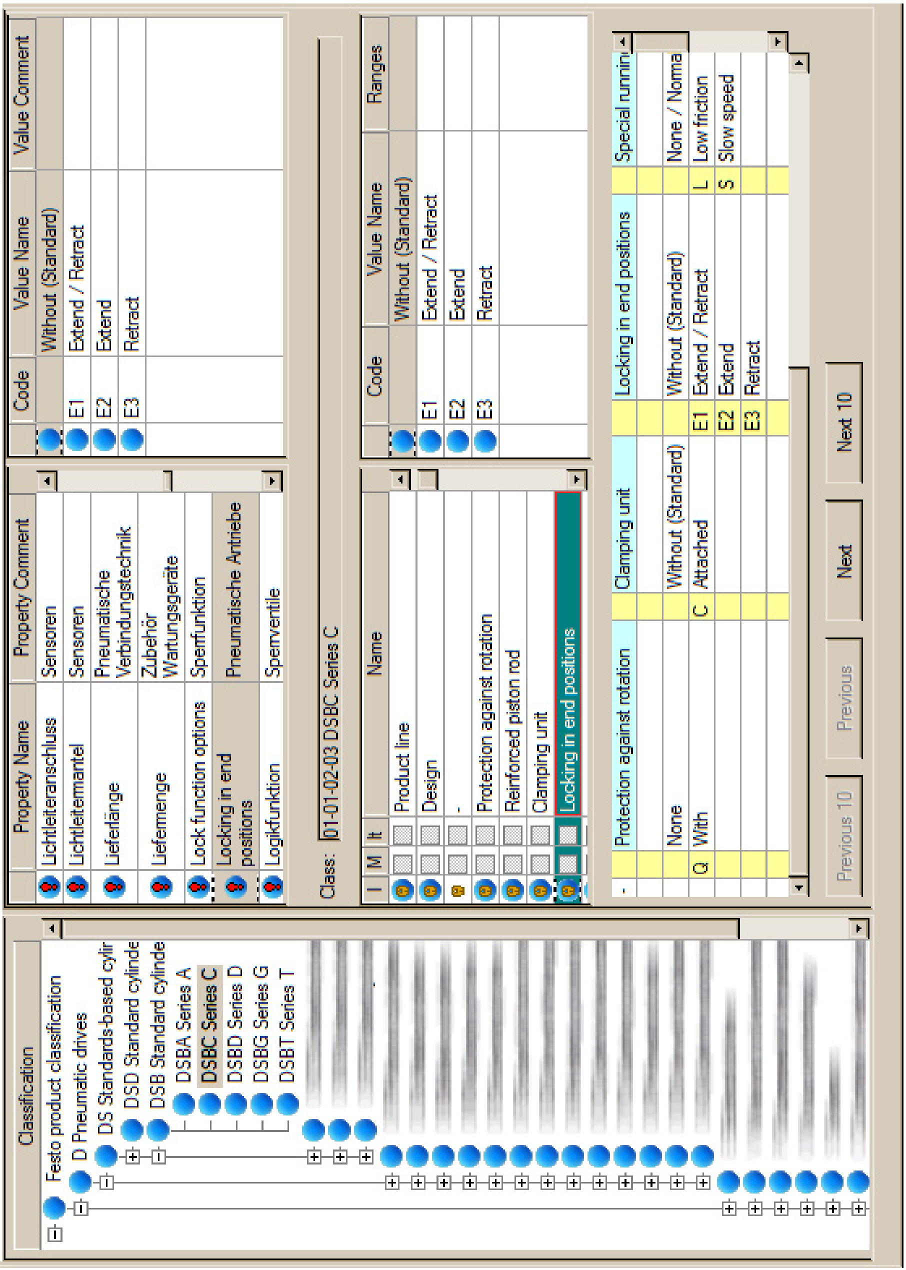

Fig. 2. Main window of the product hierarchy description tool [14]

4 The Modeling Approach in Practice

4.1 Product Engineer Support

The first step to implementation of the approach is creation of the ontology. This operation was done automatically based on existing documents and defined rules of the model building. The resulting ontology consists of more than 1000 classes organized into a 4 level taxonomy (fig. 2).

Taxonomical relationships support inheritance that makes it possible to define more common attributes for higher level classes and inherit them to lower level subclasses. The same taxonomy is used in the company's PDM and ERP systems.

For each product family (class) a set of properties (attributes) is defined, and for each property the possible values and their codes are specified. The lexicon of properties is valid ontology-wide, i.e. the values can be reused for different families. Application of the common single ontology provides for the consistency of the product codes and makes it possible to reflect incorporated changes in the codes instantly.

4.2 Complex Product Modeling

An experience from the first industrial case is that customers nowadays wish to buy complete customized solutions (referred to as “complex products”) consisting of numerous products, rather than separate isolated products which have to be integrated into a solution. Whereas such complex products in the past were configured by experts based on the customer requirements, they nowadays to a large extent have to be configurable by the customers, which requires appropriate tool support and automation. However, inter-product relationships are very challenging. For example, the most common use case is the relationship between a main product and an accessory product. While both products are derived from different complex products there are dependencies which assign a correct accessory to a configured main product. The dependencies are related to the products’ individual properties and values. E.g., ”1x3/2 or 2x3/2-way valve” cannot be installed on a valve terminal if its size is “Size 10, deviating flow rate 1”. The depth of product-accessory relationships is not limited, so accessory-of-accessory combinations have also to be taken into account. These relationships can be very complex when it comes to define the actual location and orientation of interfaces and mounting points between products.

Complex product description consists of two major parts: product components and rules. Complex product components can be the following: simple products, other complex products, and application data. The set of characteristics of the complex product is a union of characteristics of its components. The rules of the complex products are union of the rules of its components plus extra rules. Application data is an auxiliary component, which is used for introduction of some additional characteristics and requirements to the product (for example, operating temperatures, certification, electrical connection, etc.). They affect availability and compatibility of certain components and features via defined rules.

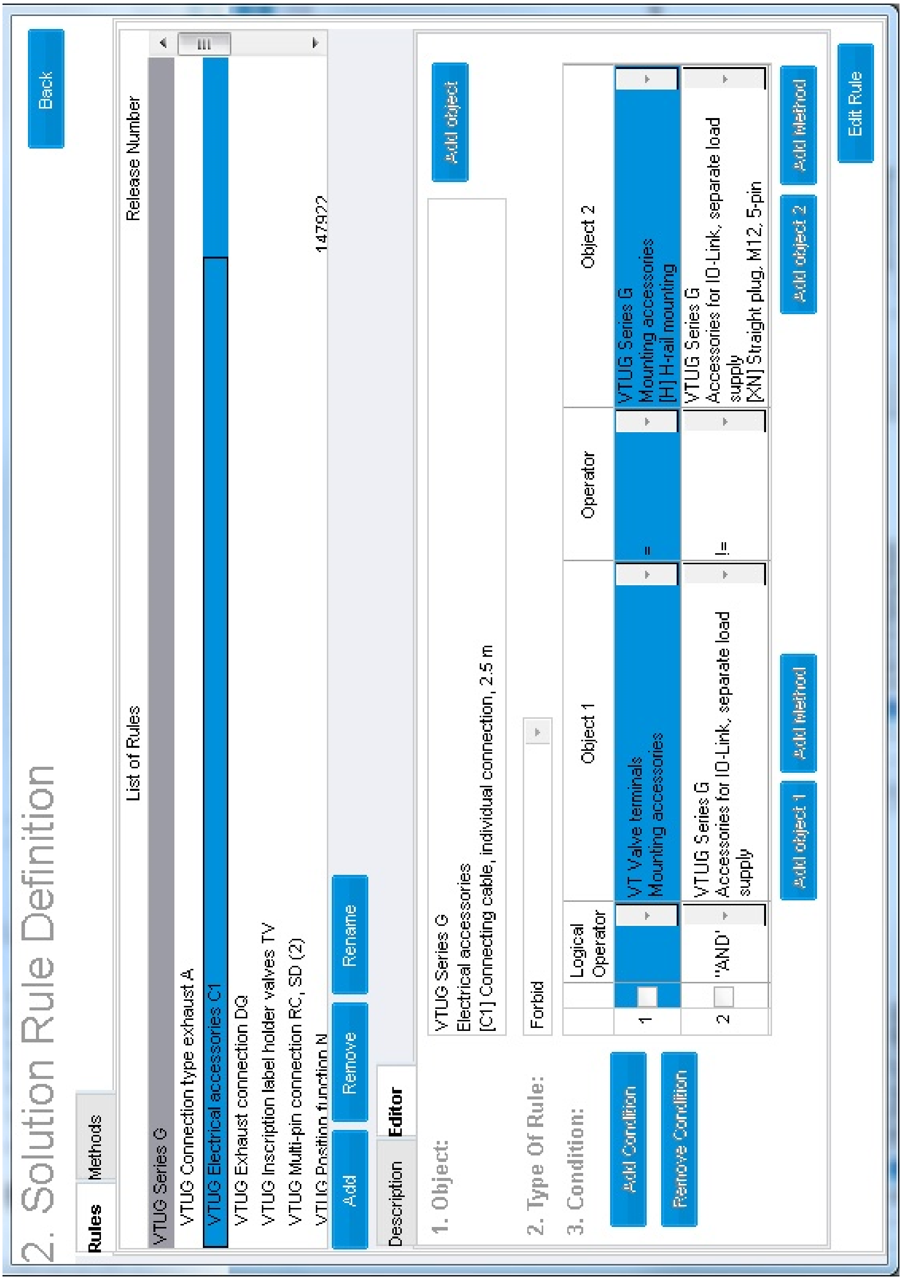

Fig. 3. Solution rules example [15]

Some example rules are shown in Fig. 3. The figure presents a valve terminal (VTUG) and compatibility of electrical accessories option C1 (individual connecting cable) with mounting accessories (compatible only with H-rail mounting) and accessories for input-output link (not compatible with 5 pin straight plug M12). These rules are stored in the database and can later be used during configuration of the valve terminal for certain requirements.

When the product model is finished it is offered to the customers, i.e. the customers could configure required products and solutions themselves or with assistance of product managers.

4.3 Production Facilities Modeling

The DESO system is a tool for management and structured storage of information in knowledge domain, and for processing this information. Depending on the domain under consideration, the system can be extended by additional components for solving specific problems using the information stored in the DESO database. Up to now, components for enterprise production program planning, for production module design, and for industrial resources distribution and planning were developed.

Initially, the DESO system was developed in a project focusing on the early stages of planning investments including (a) derivation of production scenarios, (b) determination of investment cost, (c) assignment of locations and (d) estimation of variable product cost. The system aims at providing a knowledge platform enabling manufacturing enterprises to achieve reduced lead time and reduced cost based on customer requirements through customer satisfaction by means of improved availability, communication and quality of product information. It follows a decentralized method for intelligent knowledge and solutions access. The configuring process incorporates the following features: order-free selection, limits of resources, optimization (minimization or maximization), default values, freedom to make changes in Global Production Network model.

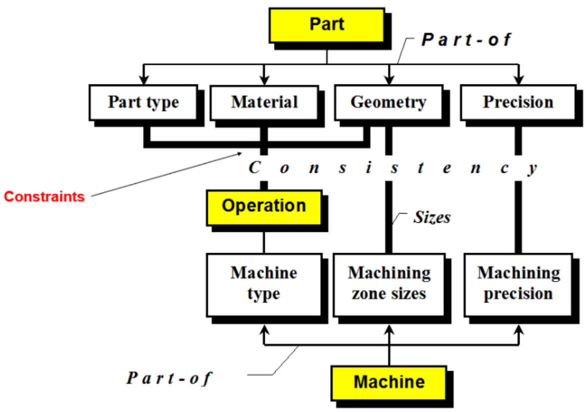

Fig. 4. Product-Process-Machine system modeling

The architecture of the system reflects the structure of "Product-Process-Machine" system. It includes three main IT-Modules or software tools (fig. 4).

The hierarchy editor (fig. 5) is a tool for creating, editing and managing hierarchical relations between objects. These relations may show structures of objects, sequence of operations for a part production, possible alternatives of accommodation etc. The hierarchy editor supports inheriting subordinate objects, what allows creating of complex hierarchical systems of objects by some stages, and using templates automating the user's work.

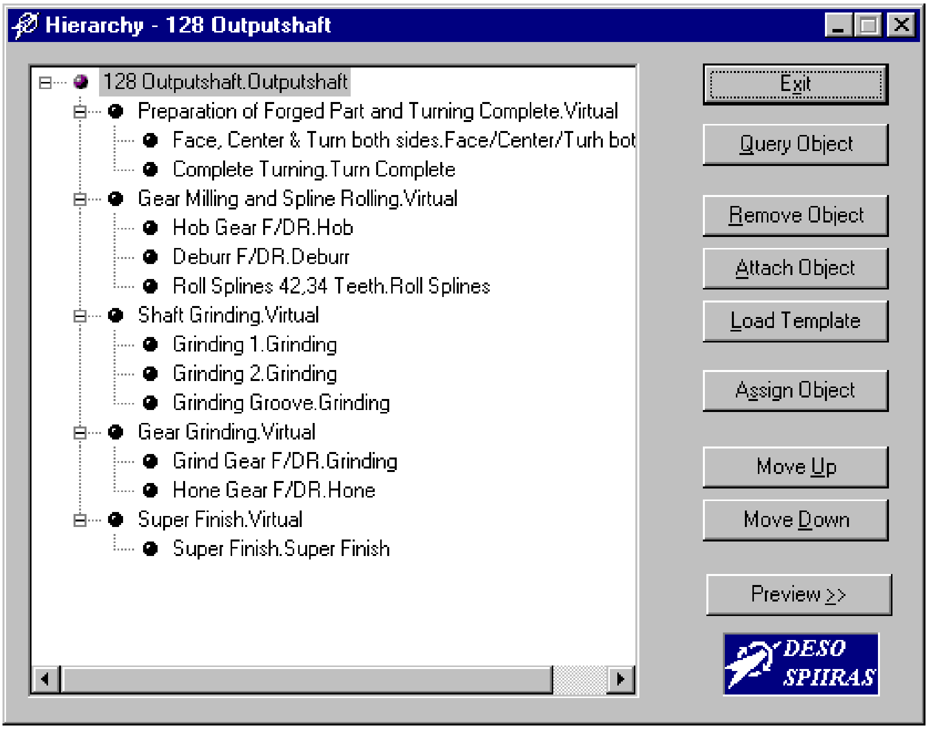

Fig. 5. Hierarchy editor of DESO [16]

DESO distinguishes between virtual and real modules. In accordance with the approach, the virtual modules are used for grouping technological operations from production engineer's point of view (fig. 5). The real modules stand for the real equipment used for the actual production (fig. 6). The production engineer sets correspondences between the technological operations of virtual modules and machines of real modules (fig. 7).

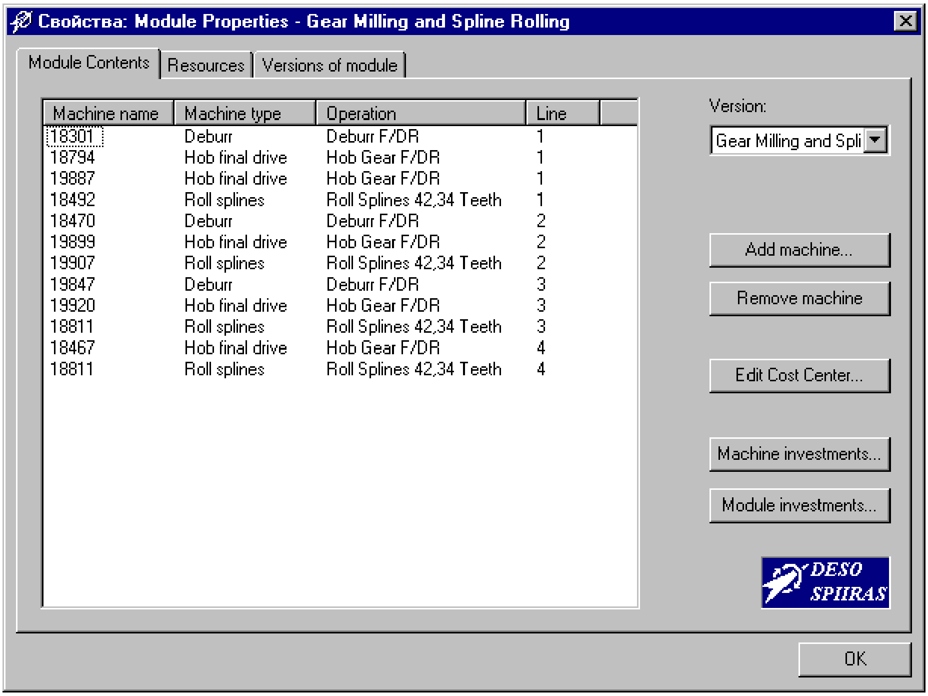

Fig. 6. Real module description

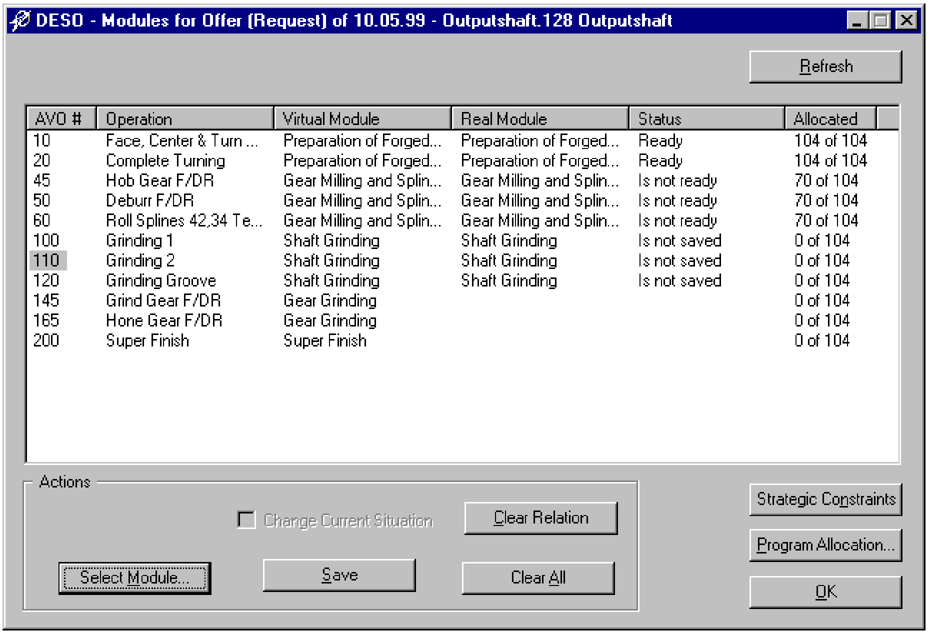

Fig. 7. Setting correspondences between operations of virtual modules and machines of real modules

5 Summary and Discussion

The paper presents an approach to product-process-machine modeling derived from two real life case studies. Compared to existing approaches in the field, which strive for the integration of all available information in the different PPM models, our focus is on integrating essential information for two key roles in an adaptation process to new market requirements, i.e. product manager and production engineer. The approach is based on the idea of integrating various information sources and software systems and distinguishes four levels. The upper two levels (levels of product manager and product engineer) concentrate on customer requirements and product modeling. The lower two levels (levels of production engineer and production manager) focus on production process and production equipment modeling.

As already mentioned, just following existing guidelines for implementing new workflows often is not possible for number of reasons. Engineers and managers do not have sufficient information to decide in advance which solution would be more convenient and efficient for them. As a result, the implementation of new workflows is more a "trial-and-error" process.

This was in a higher degree visible when working with product managers and product engineers in the first case study. In the second case study (aimed at the levels of production engineer and production manager) this issue was less obvious, because the "explorative" production planning could be done in parallel with the actual one. In this context, the modeling of the "product-process-machine" system proved to be an efficient solution.

The model built enabled automation of a number of processes previously done manually. The main advantages of the developed solution are [15]:

- Automatically creating master data in SAP models;
- Automatically creating data for the configuration models and services;
- Automatically generating an ordering sheet for the print documentation (this ordering sheet was generated earlier with much effort manually);
- Automatically generating a product and service list which is needed in the complete process implementing new products.

Based on the experiences from the two cases, our conclusion is that the aim of integrating information from the perspectives product, process and machine was achieved and that it supports identifying potential options in case of changes and the effects of these options. Examples are parallel incoming requests with respect to product features or their effects on re-scheduling and re-configuring the production facilities. Product managers and production engineers are supported in their tasks and responsibilities, both with respect to the central planning level and for the distributed plants.

Experience from the implementation of the mentioned projects shows that deep automation of the Product-Process-Machine system could be achieved if it is considered as one complex system. This requires consideration of all levels of the production system indicated in sec. 3. To facilitate implementation of such projects, first, the structural information has to be collected followed by identification of the relationships. This can be done only through long-term time-consuming communications with experts from the company. As a consequence, we consider using typical structural models or recurring "patterns" for such models as promising and beneficial for such processes.

The limitation of the approach is that it focuses only on the "integrating links" between the different perspectives, i.e. we do not attempt to integrate all existing information regarding construction, design, operation of administrative aspects of products and production systems. Future work will include conceptual extensions and gathering more experiences from practical cases. Conceptual extension will be directed to support more roles in the area of industrial organization by implementing additional features. An example is the extension towards integration of suppliers or partners in the value network.

Acknowledgements. This paper was developed in the context of the project COBIT sponsored by the Swedish Foundation for International Cooperation in Research and Higher Education. Some parts of the work have been sponsored by grants 12-07-00298 of the Russian Foundation for Basic Research, project # 213 of the research program #15 "Intelligent information technologies, mathematical modelling, system analysis and automation" of the Russian Academy of Sciences, and project 2.2 "Methodology development for building group information and recommendation systems" of the basic research program "Intelligent information technologies, system analysis and automation" of the Nanotechnology and Information technology Department of the Russian Academy of Sciences.

References

1. Martin, J.: The great transition: using the seven disciplines of enterprise engineering to align people, technology, and strategy, p. 455. Amacom, New York (1995)
2. Vernadat, F.B.: Enterprise modelling and integration, pp. 25–33. Springer US (2003)
3. Bokinge, M., Malmqvist, J.: PLM implementation guidelines – relevance and application in practice: a discussion of findings from a retrospective case study. International Journal of Product Lifecycle Management 6(1), 79–98 (2012)
4. Williams, T.J., Li, H.: PERA and GERAM - enterprise reference architectures in enterprise integration. In: Information Infrastructure Systems for Manufacturing II, pp. 3–30. Springer US (1999)
5. Kosanke, K., Vernadat, F., Zelm, M.: CIMOSA: enterprise engineering and integration. Computers in Industry 40(2), 83–97 (1999)
6. ISO 10303 Industrial automation systems and integration - Product data representation and exchange (2011), http://www.iso.org/
7. CMII Research Institute: CMII Standard for Product Configuration Management. Document CMII-105C (2010), http://www.cmiiresearch.com
8. Ruggaber, R.: ATHENA-Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Applications. In: Interoperability of Enterprise Software and Applications, pp. 459–460. Springer, London (2006)

9. Osorio, J., Romero, D.: A. Molina: A Modeling Approach towards an Extended Product Data Model for Sustainable Mass-Customized Products. In: PREPRINTS of the International IFAC Conference on Manufacturing Modelling, Management and Control (MIM 2013), Saint Petersburg, Russia, June 19-21, pp. 609–613 (2013)
10. Buchmann, R., Karagiannis, D.: Modelling Collaborative-Driven Supply Chains: The ComVantage Method. In: PREPRINTS of the International IFAC Conference on Manufacturing Modelling, Management and Control (MIM 2013), Saint Petersburg, Russia, June 19-21, pp. 597–602 (2013)
11. Mun, D., Do, N.: W. Choi: Information model of ship product structure supporting operation and maintenance after ship delivery. In: Proceedings of the PLM11 Conference, Eindhoven University of Technology, The Netherlands, July 11-13. IFIP Working Group 5.1 (2013)
12. Sandkuhl, K., Billig, A.: Ontology-based Artefact Management in Automotive Electronics. International Journal for Computer Integrated Manufacturing (IJCIM) 20(7), 627–638 (2007)
13. Lillehagen, F.M., Krogstie, J.: Active knowledge modeling of enterprises. Springer (2008)
14. Oroszi, A., Jung, T., Smirnov, A., Shilov, N., Kashevnik, A.: Ontology-Driven Codification for Discrete and Modular Products. International Journal of Product Development, Inderscience 8(2), 162–177 (2009)
15. Smirnov, A., et al.: Knowledge Management for Complex Product Development: Framework and Implementation. In: Proceedings of the IFIP WG 5.1 10th International Conference on Product Lifecycle Management (PLM 2013), Nantes, France, July 6-10 (2013)
16. Golm, F., Smirnov, A.: ProCon: Decision Support for Resource Management in a Global Production Network. In: The Proceedings of the 13th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems (IEA/AIE 2000). New Orleans, Louisiana, USA, Springer Verlag, pp. 345–350 (2000)
17. Golm, F., Smirnov, A.: Virtual Production Network Configuration: ACS-approach and tools. In: Advances in Networked Enterprises: The Proceedings of the 4th IEEE/IFIP International Conference on Information Technology for Balanced Automation Systems in Production and Transportation (BASYS 2000), Bosten/Dordrecht/ London, pp. 103–110. Kluwer Academic Publishers, Berlin (2000)
18. Bradfield, D.J., Gao, J.X., Soltan, H.: A Metaknowledge Approach to Facilitate Knowledge Sharing in the Global Product Development Process. Computer-Aided Design & Applications 4(1-4), 519–528 (2007)
19. Chan, E.C.K., Yu, K.M.: A framework of ontology-enabled product knowledge management. International Journal of Product Development, Inderscience Publishers 4(3/4), 241–254 (2007)
20. Patil, L., Dutta, D., Sriram, R.: Ontology-based exchange of product data semantics. IEEE Transactions on Automation Science and Engineering 2(3), 213–225 (2005) ISSN: 1545-5955
21. Uschold, M., Grüninger, M.: Ontologies: Principles, methods and applications. Knowledge Engineering Review 11(2), 93–155 (1996)