An Integral Model for Mapping Variant Production in Supply Chains

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Abstract

The capability to efficiently manage product-variety is nowadays a critical success factor for many companies. However, existing models still lack a suitable support for mapping and analyzing variant productions. The paper contributes to this area with a comprehensive but practicable approach. Product families are defined through common attributes with differentiating characteristics. Product structures and process plans of variants belonging to the same product family are represented using generic "plan skeletons". It is shown how the approach can thereby reduce modeling efforts and enhance the clarity of the resulting model. Furthermore, linking such a model to a simulation allows for assigning performance indicators to the product family's attributes instead of many product variants. Variant-induced costs can thus be disclosed as additional costs compared to a base product for each characteristic.

Keywords

Modeling, Simulation, Product Variety, Supply Chain Management

1 Motivation

The number of product variants offered by companies has strongly increased within recent years. This becomes obvious by an example of the automobile industry: whereas in 1914 the slogan of Henry Ford applied "you can have your car in any color, so long it is black", in the years 2003 and 2004 only two of the 1.1 million Mercedes A-class-cars produced in the Raststatt plant were identical [1]. This development can be observed across all industries. In a European-wide evaluation of studies about the future of production the increasing product variety was identified as one of the main challenges for the coming years [2].

The reasons for this trend are manifold. Often companies try to meet the growing individualization of customer needs by differentiation strategies and thereby to gain a competitive advantage. Many enterprises hope that with sinking or stagnating sales they can secure the turnovers by offering additional product variants and special features to less attractive market segments. Furthermore, the increasing internationalization requires an adaptation of products to regional distinctions (e.g. different voltages and/or frequencies).

Hayes and Wheelright stated already in 1979: "Coping with product variety forces a manufacturing firm to confront a fundamental trade-off – the increased revenue that can result from more variety versus increased costs through the loss of economies of scale." [3]. Efficiently managing and controlling the product variety thus has turned out to be a critical success factor. According to Ramdas [4] two fundamental types of approaches can be differentiated: on the one hand the containment and/or decrease of product variety during the product development, on the other hand the efficient management of existing variants in the production network. Given the complexity of today's production and logistics networks the utilization of models can provide an important decision support for the latter approach. First, mapping the reality in a structured and clear model simplifies the understanding of the numerous interdependences, especially across company borders. In addition, with the help of such models alternative scenarios can be analyzed and evaluated. However, this demands for robust, tangible and efficient approaches, which are able to model the value adding network and to support variety-related decisions.

2 State of the art in modeling

In scientific literature numerous authors deal with modeling and analyzing production and logistics networks. Beyond that, a vast number of commercial software solutions is offered under the designation "supply chain management (SCM) software". Those solution claim to support the planner in the decision making process (see for example [5]).

Although different kinds of modeling approaches have been developed and applied (e.g. network models or reference models) many authors consider simulation models as the most promising technique. This is mainly due to the fact that they are able to map dynamic changes, stochastic events, and thus uncertainties [6]. Terzi and Cavalieri state: „Among these quantitative methods, simulation is undoubtedly one of the most powerful techniques to apply, as a decision support system, within a supply chain environment." [7]. The Eureka study already mentioned confirms that industry also expects simulations to become very important especially when dealing with a high product variety [2]. However, one of the main problems when using simulations is the large number of necessary input parameters, resulting in a high model complexity and large efforts for gathering those data. In addition, often specific knowledge is required, e.g. simulation languages [8].

Modeling concepts can be divided into resource-oriented and product-oriented approaches. It is notable that almost all models belong to the first category, which means that first resources (i.e. suppliers, machines, storages etc.) are modeled and afterwards the material flows between these resources are defined. Mainly this is due to the fact that most of those approaches have evolved from modeling and simulation of rather "isolated" manufacturing systems on shop floor level. The focus thereby is on the production resources and their performance (e.g. utilization, maintenance intervals, down-times etc.). These approaches, however, are lacking a sufficient support of the fundamental idea of supply chain management, which is the alignment of the entire value creation towards the final customers: "the supply chain (…) encompasses every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer." [9]. Even more, in hardly any of the models the particularities of product variants are considered. Instead, most of the approaches model variants of the same product family similar as completely different products. The well-known and beneficial concepts of product and process configuration are not used in this context (see e.g. [10]).

Among the few product-oriented models is the "Product Chain Decision Model" which utilizes the concept of Petri Nets [8]. Here "place nodes" represent product components, "transition nodes" model process steps. The "Supply Chain Analyzer" - a simulation software developed by Nienhaus - is based on the product structure, too [11]. However, both approaches are not capable of modeling product variants in an appropriate and efficient way.

3 The Modeling Approach

3.1 Different Views on a Supply Chain

In order to map the complexity of production networks with conflicting objectives integral models – as opposed to singular models such as flow charts – have to be used. They incorporate different views on the system to be analyzed, i.e. a product view, a process view, and a resource view. Only the combination of these views can answer the question "Which things *(product)* are processed by whom *(resource)* in which order and according to which rules *(process)*?" (following [11]).

3.2 Product View

The modeling approach to be presented is primarily based on the product view. Therefore, the model belongs to the "product-oriented" approaches. When modeling a variant production entire product families rather than single products should be considered. According to APICs product families are defined as a group of products (also called "variants") with similar features or functions, similar product structures, and a high percentage of same processes in the process plan [12]. Product families are designed as such during the product design phase and – if necessary – expanded throughout their life cycle [13]. A variant is a specific product of a product family and can be derived from the model of the product family ("product configuration"). The variants within a product family can be distinguished by the different characteristics of common attributes, e.g. an attribute "color" with the characteristics "green", "yellow", and "red". Inversely, for a certain variant all characteristics of the attributes of the product family are definite.

Consequently, building the supply chain model starts with modeling a product family and defining its attributes and characteristics. For every product family (0..n) attributes each with (1..m) characteristics need to be defined resulting in $\prod n_i$ (for i=1..m) potential variants. For this set of variants rules can be created which describe all valid or exclude all invalid combinations of product characteristics, e.g. "IF (material = leather) THEN (color = black OR beige)". If the model is connected to a discrete event simulation these rules can dynamically be changed during the simulation run in order to e.g. model product phase-ins and phase-outs. Figure 1 shows an example for a product family with three attributes and the resulting set of variants.

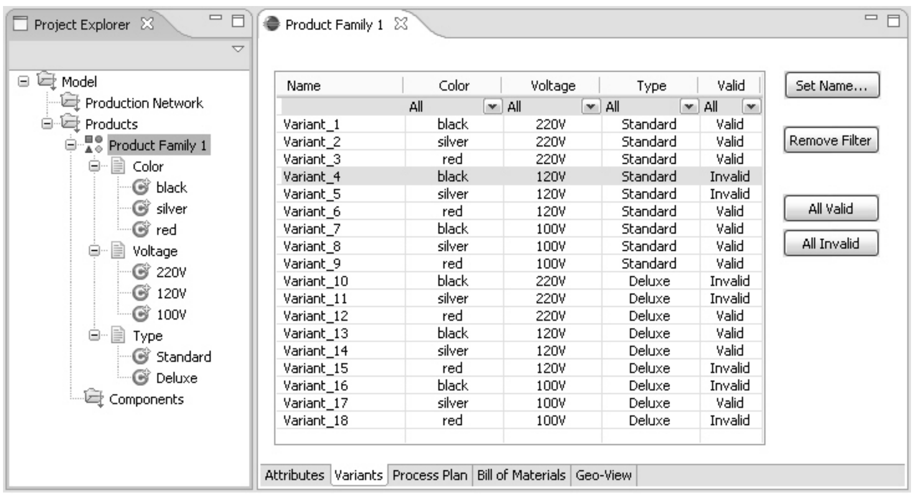

Fig. 1. Modeling a product family with its attributes and characteristics

This concept of modeling a product family has important advantages, especially when using the model as input for a discrete event simulation. In the course of the simulation performance indicators can be assigned to few attributes of a product family instead of having to analyze a large number of product variants. This way e.g. the effects of offering additional features to the customer (in terms of more characteristics such as more colors or even in terms of new attributes) can easily be determined. For each characteristic variant-induced costs can be disclosed as additional costs compared to a base product. Furthermore, the modeling effort can be reduced by a generic representation of the product family, resulting in a clear and comprehensible model. This will be explained further in the following.

The product structure – and the structure of the product family respectively – forms the basis of the entire supply chain model. It is described through a maximum bill of materials which can be determined by combining the bill of materials held at various companies. As the model currently only allows for convergent product structures, these can be represented in a tree-like structure. The "leafs" located to the left represent the inputs (e.g. raw materials or parts purchased at suppliers which are not relevant to the analysis). These are then processed and assembled resulting in the final product to the right. For each of the components in the tree the required input quantity has to be defined. Depending on the attributes of the product family the product structure (i.e. the bill of materials) of the variants may differ. Hence, the information needs to be represented in a generic way. From this the product structure for a certain variant can be generated during the so called product configuration.

The product structures of all variants within a product family are therefore represented in a so called *plan skeleton*. The plan skeleton is an ordered graph with its nodes depicting product components and process steps. Different from a common bill of materials comprises ramification nodes with associated decision rules which describe in which situation a specific component is to be chosen. This allows for an efficient and concise representation of similar plans while at the same time keeping redundancy low. This concept will be further explained in the following chapter.

3.3 Process View

The process view is the secondary view on the supply chain. It observes the system with respect to the order in that elementary functions (e.g. manufacture product, store product) are carried out. In the model on hand it is derived by adding process steps to the plan skeleton which defines the product structure.

Similar as for the product structure the processes may also differ depending on the variant's characteristics. The process configuration then selects the process steps needed to manufacture a certain product variant from a predefined set of processes and puts them into a feasible sequence. Plan skeletons also allow for representing this process-related knowledge of a product family. To further ease the supply chain model only three different types of process nodes are used within the plan skeleton: production, assembly, and storage processes.

- Production nodes define a production process. Thereby the model doesn't differentiate between different types of production processes but uses processes with generic parameters to describe production planning and control, lead time, as well as material and production costs.
- Storage nodes define a storage process. Again, to simplify the model only one type of storage is used, no matter which kind of material is stored (raw materials, in-process inventories or finished goods). Parameters relate to production planning and control, lead time, material management and storage costs.
- Assembly nodes unite parallel production paths. An assembly node can also have only one predecessor. For each of the predecessor paths an input quantity is defined, i.e. the number of components per unit of the super ordinate part, into which the component is built.

In addition, ramification nodes (so called "decision nodes") can be inserted to define parallel paths of the graph. Each of those paths can again comprise any number of process nodes or even other decision nodes. The parallel paths are merged in a "join node". Using the decision nodes a maximum process plan can be modelled which comprises all process plans of the different variants within the product family. To each decision node an attribute of the product family is assigned. Furthermore, the characteristics of that attribute are allotted to the paths. This is done in a subtractive process, which means that one path is set as default for all characteristics and each characteristic that is assigned to another path is subtracted from the default set. Here the advantage over resource-oriented approaches becomes especially apparent as those approaches require the definition of each individual manufacturing process for every product variant which is often quite time-consuming and leads to a high complexity of the model. A simple example for a plan skeleton is given in Figure 2.

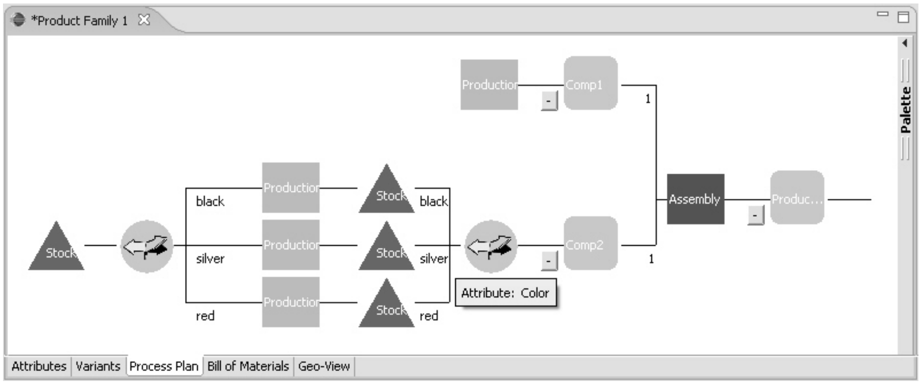

Fig. 2. Example for a simple plan skeleton with one decision node.

From the plan skeleton of a product family different views can be generated by filtering the plan skeleton with respect to certain characteristics: The bill of materials can be derived by hiding all process steps. It can be displayed either for an individual or for several product variants. A process plan for a certain variant can be deduced by omitting the decision nodes and only showing the paths referring to the characteristics of the product variant. It is also possible to display the process plan for several selected variants. In this case all necessary decision nodes of the attributes of the selected variants are included.

3.4 Resource View

The modeling approach especially aims at small and medium sized enterprises. Such companies are often involved into supply chain networks with legally and financially independent partners. Consequently, all of the partners should be able to understand and use the model although each of them has a different understanding of the roles within the value chain, e.g. the supplier of one partner might be the customer of another partner. Hence, in the present model suppliers, OEMs, and customers are not differentiated but all represented by a class *company*. The supply chain model focuses on the value-added chain up to the final product; therefore it doesn't include the distribution network. Retailers and distributors are not taken into account.

A company stands for an owning entity of the supply chain. Each company can comprise several *sites* representing the premises the company owns. They are defined by their name and a geographic location. A site manufactures or assembles finished or semi-finished products from raw-materials and/or sub assemblies for which *machines* are needed. In addition, a site may comprise one or more *storages* to store raw materials, work in-process, and finished goods.

These production network objects can then be combined with the plan skeleton. Thereby, the resource view becomes the tertiary view in the supply chain model. The site responsible for performing a process step is assigned to the respective process node in the plan skeleton. If the site is assigned to a production or assembly node then the usage of a machine within that site is assumed. If it is assigned to a storage node then a storage location of that site is accessed. Of course a site can be assigned to multiple nodes mapping the different process steps which are performed in that plant. Again, the difference to resource-oriented approaches becomes apparent: The proceeding is exactly the opposite from those approaches, which assign the material flows needed to produce a product to a network of resources.

3.5 Modularization of the Model

There is a major difference between product-oriented and resource-oriented models: In product-oriented approaches the product view is the primary view and the process and resource view are dependent views (secondary and tertiary); for resource-oriented approaches this is exactly the opposite. Therefore, in the latter case inheritance as one of the main features of object-oriented modeling is often used to provide a modeling library for supply chain resources such as site, machines etc.

Using a product-oriented approach even allows for going a step beyond this. As the entire model is based on the product structure, any component node within a plan skeleton can be "exported" together with its subtree as plan skeleton of a new product family (e.g. a module or subassembly). All attributes assigned to the decisions nodes within the subtree become attributes of the new product family, and the assignment of production resource to nodes is inherited, too. This module can then be inserted as component node into the plan skeletons of other product families. For example first the product family "drilling machine" is modelled. As the same motor is used for other product as well it is exported as new product family. It can then e.g. be inserted into a plan skeleton of the product family "chipping hammers" without having to model all processes and resources again. This way the model can easily be modularized and even a library of reusable components can be developed.

4 Conclusions and Outlook

The modeling approach presented in the previous chapter has been implemented in a prototypical software solution using the object-oriented programming language Java 1.5 (the Figures 1 and 2 were taken from this software). This allows for a 1:1 representation of the supply chain model and ensures platform independency. A main requirement is to keep the software small – though comprehensive – so that it can be run on any standard personal computer or laptop. Furthermore, it should guide the user and thereby require no specific IT knowledge or modeling expertise.

First applications of the prototype in industry proved that the product-oriented approach is well suited for modeling variant productions. Modeling efforts could be reduced especially through inheriting entire components together with the resources assigned to them. Also, the clarity of the model was increased remarkably.

In a next step the supply chain model will be connected to a discrete event simulation. The results of that simulation can then again be displayed along the product structure. The representation of the simulation results in the same structure that is underlying the model facilitates the interpretation. The user can thus directly and visually grasp bottlenecks and potential for improvement along the product creation process without having to analyze complex tables or figures. Finally, the decision support for variant-related problems will benefit from the generic representation of product families through their attributes and characteristics as mentioned earlier.

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