State-of-the-practice in product configuration – a survey of 10 cases in the Finnish industry

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Abstract

The design and production of goods that satisfy the special needs of individual customers are of central interest to the European industry. A major trend is to improve customer specific adaptation with configurable products. We are interested in the methods, practices and tools that support product configuration tasks. The research described in this paper is meant to guide our future work. We have 1) established a framework for understanding the problem area of product configuration in a fairly wide sense by identifying a number of factors and 2) carried out ten actual case studies using the proposed framework.

Our framework consists of five problem areas that are further refined into a number of factors characterising the areas. The problem areas cover the *economic importance* of product configuration, the complexity of the *configuration task*, the nature of the *configuration process*, *long term management of configuration related product knowledge* and the *interfaces* to other processes and systems. These areas and the included factors are quantified and qualified with "metrics" to help in analysing and comparing configuration problems. The preliminary results indicate that configurable products and the related configuration processes are very important to many companies. The main reasons for using configurable products are the ability to meet a wide range of customer requirements, the increased control of production and the reduced lead times in the delivery process. However, configuration activities and related knowledge are usually not systematised. The case companies are not yet using computer based configurator tools, but nearly all of them intend to have computer support within the next few years. There is considerable variation in the maturity of the companies to make this transition. The long term management of products and product knowledge are considered risk factors.

Keywords

Product configuration, conceptual framework, survey, industry, delivery process

1 INTRODUCTION

This paper reports ongoing work in the field of product configuration. Our group has worked on product data management and product configuration for several years. We have developed an engineering document management system that is being used in the Finnish industry (Peltonen 1993), gained practical understanding of product configuration by developing an experimental product configurator (Tiihonen 1994) and begun the development of a prototype based model for supporting the long term management of product configuration knowledge (Peltonen 1994). In addition, we cooperate with a number of companies in the domain of product configuration. We are currently carrying out a survey of 10 companies to study their actual product configuration problems. The companies have been motivated to spend a considerable effort on the survey to get some feedback on their plans and to be able to compare their situation with that of other companies. For us this has given a possibility to increase our understanding of the real problems, indispensable to guide our future research into areas of practical and scientific importance.

The paper has the following structure. Section 1 summarises previous work in the field of product configuration and gives our view on the subject. It goes on to present our current research problem, goals and research method. Section 2 presents the conceptual framework used in analysing the cases. Section 3 gives an overview on some of the preliminary results and conclusions. Section 4 describes how the results affect the development of knowledge-based configuration systems. Section 5 outlines some research issues that have arisen during the survey. The field study has been finished and analysis has only begun; therefore some of the proposed results may not be fully conclusive.

Previous work

Product configuration has been an area of active research. There are many definitions and models of product configuration (Mittal and Frayman 1989, Najman and Stein 1992, Heinrich and Jungst 1991, Klein 1991, Snavely and Papalambros 1993, Klein 1994, Schreiber 1994, Tong and Sriram 1992). Many research oriented and commercial product configuration systems and systems advertised as suitable for product configuration have been developed; examples include PLAKON (Cunis et al. 1989, Cunis et al. 1991), Trilogy SalesBUILDER (Hales 1992), the SAP configurator (SAP 1994), Design++ (Design++ 1993), ICAD (ICAD 1994), Wisdom and Platypus (Havens and Rehfuss 1989). In addition, numerous single purpose configurators for narrow scopes have been developed. Probably the most famous and best documented ones are XCON (McDermott 1981, Barker and O'Connor 1989, McDermott 1993) and VT (Yost 1992, Marcus et al.1992).

In our view, the scope of much of the previous work has been quite limited. There is surprisingly little research on the way product configuration problems are understood in the industry. For example, we have seen no large-scale studies on the organisations and processes by which products are configured in practice. Existing definitions cover some aspects of product configuration, but ignore others. For example, parametric components are seldom mentioned in configuration related literature. The implemented general purpose product configurators support just those aspects that the designers considered relevant for some subfield of product configuration.

We feel that as a research area product configurators will stay with us for a long time. The real world priorities and requirements should be respected in order to make wise selections in research problems. Any promising technique, be it constraint programming, logic approaches or rule based systems, is judged by how well it solves relevant configuration problems. We need a broader view of product configuration. This paper tries to make a small contribution in that direction.

Product configuration and configurable products – our view

Configurable products are pre-designed products that

- Are adapted according to the requirements of the customer for each order.
- Consist of (almost) only pre-designed components.
- Have a pre-designed product structure.
- Are adapted by a routine, systematic product configuration process.

The definition tries to capture many relevant characteristics of product configuration and to us it reflects reality in a way that is easy to communicate to companies and relate to their view of the subject. In this form the definition is quite general and covers a very broad range of problems.

The *product configuration process* produces a *configuration*, which is a consistent and complete plan that specifies, in relevant detail, the make-up of an instance of the product adapted to requirements of the customer, within limitations set by the product architecture. Individual products are configured within the possibilities and limitations of the general product. These are expressed in product configuration knowledge. In our view each configurable product is described by a *product configuration model.* The information contents, degree of systemisation, degree of understandability and other factors of the model may vary. A computer system supporting product configuration tasks, a *product configurator*, must be able to utilise product configuration models.

Configurable products offer an alternative to standard products and one-of-a-kind products. Numerous companies have turned to configurable products to increase their profitability in markets with low to moderate volumes and a requirement for customer specific adaptation that can be done in a more or less routine manner. The emergence of product configuration is a reflection of a trend to reduce customer requirement satisfaction into an engineering process without innovative or creative design of new solutions. To achieve this goal, companies invest in the design of configurable products that have provisions for anticipated customer requirements. Effectively one configurable product defines a very large family of different concrete product instances.

Research problem and goals

Our long term research goal is to develop methods, practices and tools to support product configuration tasks. The research issues we are interested in are:

- Modelling and configuring products in a manner that enables product designers to model the products and sales persons or sales engineers to configure them.
- Long term management of product configuration knowledge and maintenance of product configurators.
- Practices for improving the processes related to product configuration.

We try to approach these areas from an engineering perspective where concrete problem understanding must precede any effort to solve it. This approach aids us to appreciate also some of the "softer" aspects of this area, such as how to develop systems and concepts that are relevant, understandable and familiar to the actual designers, not only to computer scientists.

The research goals of the work presented in this paper are threefold. The first goal is to establish a framework for understanding the product configuration area in a wide sense. This framework is used to analyse product configuration cases and to derive qualifying and quantifying factors for characterising product configuration tasks and processes. Furthermore, it is used to compare product configuration problems of different companies, to identify the most relevant issues and to evaluate the feasibility of a product configurator in a particular case. The framework can be utilised as an extended checklist when assessing the usability of proposed models, solutions and tools. The second goal is to analyse ten actual product configuration cases using the initial version of the framework as a tool. This part of the work is called "The National Product Configuration Survey 1995." The third goal is to use the achieved results to guide our future research into areas with industrial and scientific significance.

Research method

We approached approximately 180 companies with a letter describing the research and its objectives. We chose the companies on the basis of our understanding of their likely interest in configuration issues. Another requirement was that their annual turnover was more than USD 10M. Ten companies expressed their willingness to participate and were subsequently invited to the survey. A survey of ten companies was considered to be of manageable size for a relatively detailed study but still large enough to give interesting results for our purposes.
The survey consists of:

- a half day initial meeting at each company;
- a study of the case product, based on documentation provided by the company;
- a full day interviewing session with the key persons involved in the product configuration process in each company;
- writing, for each company, a detailed and confidential report structured by the framework;
- a feedback session of half a day based on the report for validation purposes;
- producing a summary report of the general results based on the results from companies and presenting the summary report in a seminar.

With the aid of the documentation supplied by the companies, one and a half day for the visits was considered enough for an adequate study of a configuration case.

2 FRAMEWORK FOR PRODUCT CONFIGURATION

In our view, most product configuration problems consist of roughly the same elements, albeit in different combinations. This observation has led us to the development of the proposed framework. The organisation of the framework is presented in Figure 1.

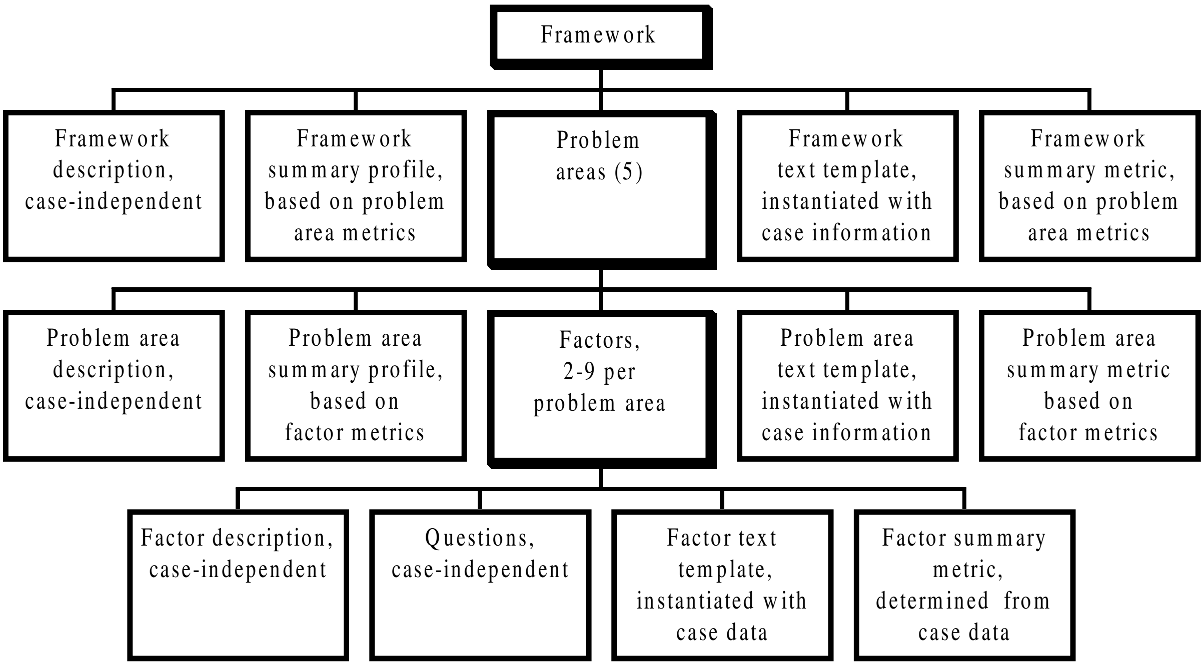

Figure 1 The organisation of the framework.

Our framework consists of *problem areas* that are further divided to *factors*. A factor characterises some aspect of the related problem area. The areas covered are (Figure 2):

- economic importance of product configuration;
- product configuration task;
- product configuration process;
- long term management of product knowledge and configurations;
- interfaces of the configuration process.

In addition to these areas, we collect some background information on the companies, on their products and processes.

We have developed characterising questions related to each factor and we will develop text templates and "metrics" for characterising the factors on the basis of the answers. For each factor and each summary metric derived from it, we will try to quantify how important it is for the operation of the company, how difficult it is to manage in an objective sense, and how well it is managed in the particular company. Results of the factors are aggregated at area and framework levels.

At the time of writing, most templates for case specific texts and metrics are not complete. We expect some difficulty in development of the metrics. Objective, sound and unambiguous criteria for deriving metric values for factors from the answers to the questions relevant to the metric are difficult to define. In some cases applying a metric will require considerable judgement.

We will briefly discuss the problem areas and some of the factors in this section. Related observations are discussed in section 3.

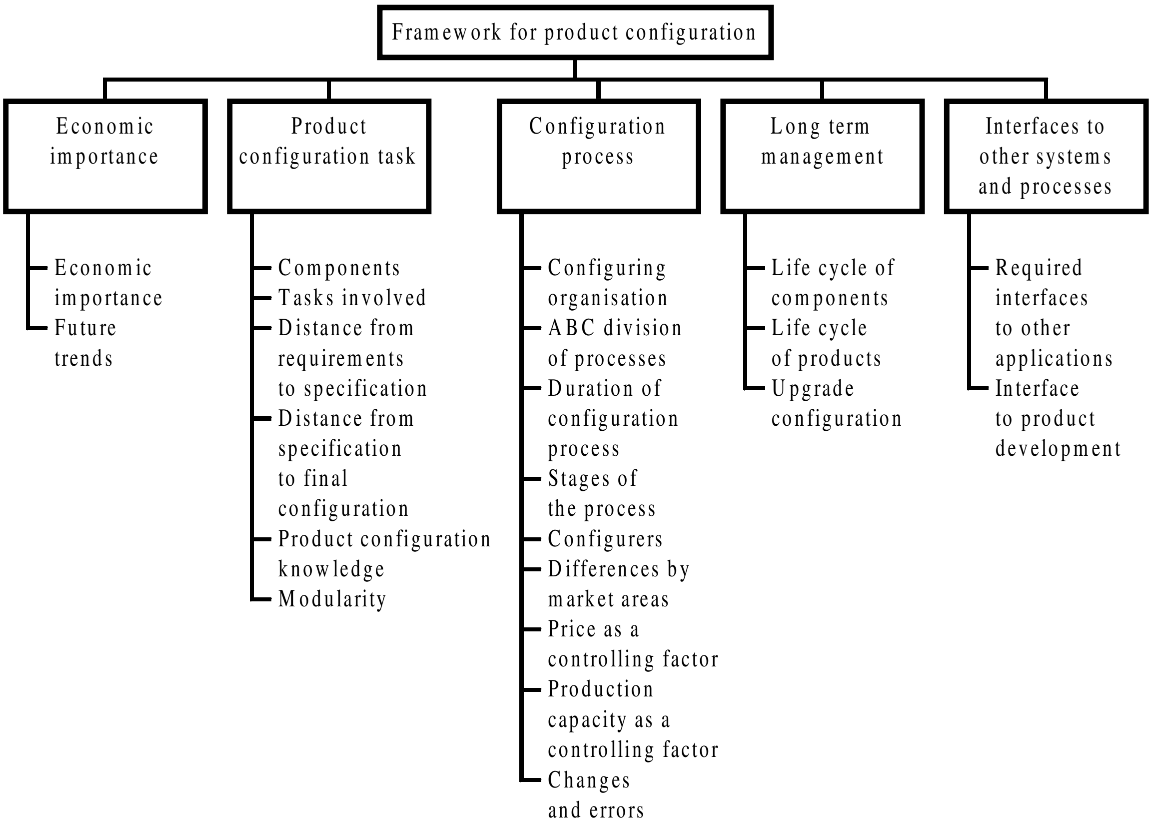

Figure 2 The structure of the framework.

2.1 Economic importance

The economic point of view gives a basis for understanding the importance and scale of product configuration in a company. Here we have identified only two factors: the current significance and the trend of significance. Both are dominantly characterised by the percentage of the total sales volume generated by configurable products. In addition, we collect information on the quantities of delivered products and on issues affecting the economic importance and its development.

2.2 Product configuration process

The product configuration process is a part of the order specific delivery process. It has interfaces to other parts of the delivery process and to other processes such as product development. Usually, the configuration process is not a single step within the delivery process; Figure 3 gives an overview of the process. Note that the actual configuration process extends from the customer-sales interaction to the logistics centre and the configuration and component orders specified by it. Other parts of the delivery process are shown for completeness.

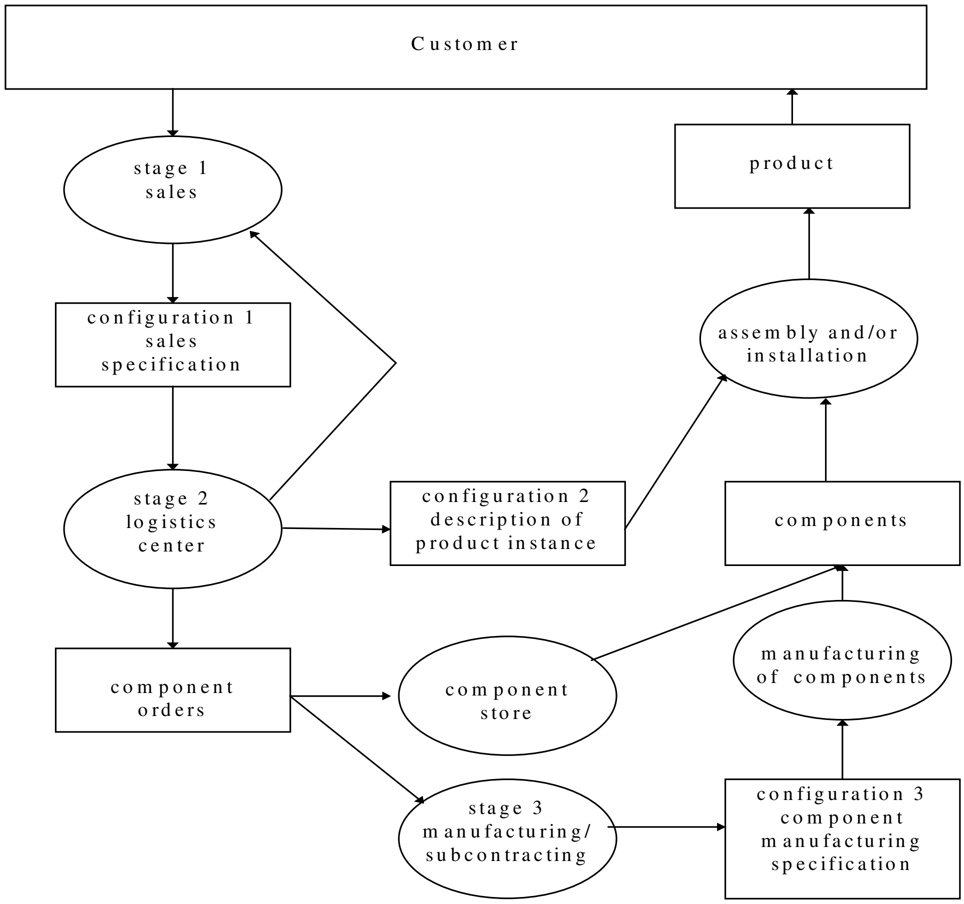

Figure 3 The configuration process.

Configuring organisation

The sales function produces in interaction with the customer the *sales specification* or *configuration 1*. It is sent to a *logistics centre.* This function produces component orders for the required components to the production units and subcontractors. Logistics centres also co-ordinate the manufacturing, purchasing and/or collecting of all the required components.

A logistics centre typically receives orders from many sales units. It translates an order into *configuration 2*, or in short *configuration,* that can be used as a basis for ordering the required components from the production and subcontractors. A configuration, or a document derived from it, can also be used as a specification when assembling the product. In some cases, the ordered components are themselves configurable products and there is a third phase in the configuration process. The manufacturing unit uses the configuration, a part of it, or a report derived from it as a specification for configuring the ordered component.

Configurers

The actual work being done in the configuration process and the requirements on its computerised support depend largely on the persons involved. The number of the people and their level of proficiency in the technical domain of products and in computer use are critically important factors. In global companies it may be necessary to support different languages and different configuration processes in different cultures, which naturally makes the maintenance effort of configuration systems harder and makes the configuration process more complex.

Changes and errors

The delivery and configuration processes do not operate without problems of their own. There are two kinds of changes we confront here. First, customers change their orders, this is a law of nature in some industries. The capability to cope with them at least to a certain degree is a competitive advantage. Second, due to the complexity of the internal delivery processes errors are committed within the company. According to a previous study (Luhtala 1994), companies delivering customer tailored products in Finland waste 10–15% of their annual sales in inefficient delivery processes.

Interesting problems arise if the production of a product has started and the product must be changed. How to change the configuration and manufacturing schedule so as to accommodate the change with minimal extra costs? Can we create a different, even a non-standard configuration and yet use the order-specific components being manufactured? In order to answer these kinds of questions, a product configurator would have to contain very specific knowledge on the components, their parts and interfaces. Less deep modelling is usually adequate for configuring products if no changes occur or exceptions are taken care of manually.

Other process related factors

Some companies have separate processes for configurable products and products requiring special modifications, for example, design of new components. ABC-classification of processes is quite common in Finland to characterise this factor. In this classification a routine delivery process of configurable products is referred to as A-process. Non-routine combinations of pre-designed components are delivered through B-process. In C-process, “real” order-specific design is needed.

The duration of the whole delivery process and the configuration process as a part of it varies and influences, among other things, the potential for labour cost savings and reduction in total lead time of the delivery process. Different market requirements in various geographic areas may necessitate, at least for some areas, the use of separate product databases or even different configurators which increases the amount of knowledge that must be managed. Finally, the supporting tools may have to deal with price and delivery time determination. If price and delivery time are crucial factors, one may face nontrivial optimisation with multiple goals: short delivery time, low price and acceptable functionality of the product.

2.3 Product configuration task

This problem area characterises the task of product configuration on the basis of:

- kinds of components used;
- required subtasks performed;
- distance from customer requirements to a sales specification;
- distance from the sales specification to a final configuration;
- modularity of the product;
- kinds of knowledge used in the configuration tasks.

In the following, a component is a part of the product considered relevant for configuration purposes. Defined this way, a component may correspond to a single component or an assembly of components. We have grouped components into three classes. *Standard components* are specified by their identification code. Once the component is specified, it can be manufactured without any additional information from the configuration system. *Modifiable standard components* are manufactured as standard components but they can be configured at assembly time, for instance, by means of settings, jumpers, dip-switches, etc. *Parametric components* have parameters whose values must be determined before the component can be manufactured. Typical parameters specify physical dimensions, surface material, colour, etc. In our view, the complexity of configuration tasks increases when moving from standard components to modifiable standard components or parametric components. This occurs, because the products that include parametric or modifiable standard components typically have more possibilities of variation.

The tasks performed during and after configuration process may include:

- component selection;
- parameter value determination;
- layout design;
- determination of component connections;
- determination of the price of the product based on the configuration;
- determination of the delivery time;
- preparing a bid;
- preparing a technical specification;
- completeness checks;
- consistency checks.

Configuration design typically includes at least component selection, determination of the price of the product, preparing a bid and a technical specification, and checking the completeness and consistency of the configuration. The complexity of the configuration design increases, if some of the remaining tasks are included, especially in the case of layout and component connection design.

The difficulty of mapping the customer requirements to a sales specification (used inside the company to specify the product a customer has ordered) depends on the difference, i.e., *distance,* in the level of abstraction between the customer requirements and the sales specification. Customers vary in their level of technical sophistication. The complexity of translating customer requirements to a sales specification increases with increasing distance from the requirements to the specification. Another mapping, where the concept of distance is also applicable, takes place when the sales specification is transformed to component orders and other necessary outputs of a configuration process. These tasks are at the heart of the configuration problem, so understanding and characterising their difficulty is essential.

The complexity of product configuration tasks is assumed to be largely determined by the degree of modularity of the product. This factor is surveyed by studying the ways companies define the modular structure of their products, the ways in which products have been modularised and how these affect the product configuration tasks.

2.4 Long term management

The issue of product evolution is complicated from many points of view. Product families evolve over time as new components and features are introduced. In some businesses the aftersales activities are becoming increasingly important emphasising the need to know exactly what each customer has, and possibly to enhance, in other words reconfigure, the particular product the customer has. These dynamic aspects raise the issues of long term management of product configuration knowledge, product configurators and delivered product instances. If the operation of the company requires that both kinds of changes must be managed, the configuration design process and the long term management become much more complex.

Product evolution inevitably leads to different versions of product configuration knowledge. The corresponding product configuration models must be kept consistent with the changes in products. This is one of the reasons that has slowed down the large scale use of product configurator technology. An example of these difficulties is the landmark XCON system at Digital. At one point, 59 persons were required to maintain and develop the system (Barker and O'Connor 1989). Although the system itself was claimed to be commercially successful at Digital, such a team is not feasible for most companies. It is quite possible that product improvements could be delayed because of the effort required to update the configurator. With the increasing pace of changes in the operating environment of the companies, the significance of this problem will probably increase in the future.

The management of delivered products raises a series of questions. In aftersales operations products are serviced and sometimes upgraded to achieve increased new functionality. In practise, it may be impossible to support upgrades with product configurators if the configuration knowledge is distributed among different versions of product configuration models.

In some industries components evolve independently of the products in which they are used. In many cases the lifetime, understood as the time a component type is used in delivered products, is shorter than the life time of the whole product or a delivered product. This can apply both to purchased components and self-manufactured components.

We have not seen any general models or solutions that would solve the related problems in a practical way. This problem area of the framework tries to survey current schemes of version management, versioning policies, upgrade policies and the magnitude of the long term management problem in companies. This should enable the development of a model for long term management of product configuration knowledge.

2.5 Interfaces to other systems and processes

Product configuration tasks use and produce information. The product configuration process and the supporting systems are linked, for example, to product development and production management systems. In this part of the framework we try to characterise factors related to these interfaces. Tight integration of product configurators to other systems such as production management and product data management systems with bidirectional flow of information makes the management of configuration process and related information much more complex.

3 PRELIMINARY RESULTS OF THE NATIONAL PRODUCT CONFIGURATION SURVEY 1995

At the time of writing, we have made all the half-day and full-day visits in the participating companies. The results presented in this chapter are preliminary observations that will be validated in later phases of the survey. Our results originate from the Finnish industry. We do not claim them to be globally valid, although we assume similar results would be obtained in other countries for companies delivering configurable products.

The nature of the configuration problems and the way the companies view them varies from one company to other. In terms of our framework the maturity of the companies is not even. Some areas are fairly well dealt with while others are quite undeveloped. None of the companies manages all the areas well.

The framework has evolved during the survey and is expected to change from the present form after a thorough analysis of the survey has been done. The areas, factors and related questions have proven to be useful in collecting data from the companies and subsequently analysing the cases. One aspect of the framework has been very visible. The issues and problems in product configuration and long term management of products and relevant information are tightly interconnected. As a result, it is almost impossible to organise the framework into strictly orthogonal areas and factors.

3.1 Economic importance and background

The idea of configurable products in the sense discussed earlier has been quite well adopted in the case companies. Current products follow this paradigm, at the least to a certain degree, and improvements in the configuration area are being made. The survey indicates that the economic importance of product configuration is significant and a number of companies can quantify it in real figures. All the companies surveyed generate 50–100% of their sales volumes from configurable products; the average is approximately 80%.

The companies have approached configurable products from two directions. On one hand companies that used to produce project oriented one-of-a-kind products have systematised their products and processes to reuse knowledge and reduce the lead times in design and delivery. On the other hand, producers of fixed off-the-shelf products have increased customer choice with configurable products to compete in a more demanding market.

The annual number of delivered products varies from a few dozens to a few thousands. None of the companies considers operation without configurable products possible. The primary reasons for having configurable products seem to include:

- The ability to fulfil a wide range of customer requirements.
- Increased control of production, for example, a large variety of end products with a fairly small number of components.
- Shorter delivery times and smaller stock.

3.2 Product configuration processes

The general process model in Figure 3 gained support, that is, the corresponding stages were identified by the companies. Sometimes the logistics centre and the sales functions interact quite tightly, and in some cases they are unified into a single function. Quite often, the configuration phase 3 is not present.

One of the primary motives for building a support system for product configuration is to assist in the transfer of up-to-date product configuration knowledge to the sales units and to enforce its proper use. The technical skills of salespersons vary a lot, but usually they are not technical experts. Sales units are usually numerous, and the number of salespersons involved is correspondingly in hundreds or thousands. The case companies do not always own the sales companies. This has implications on how to introduce a sales configurator to the process, since it may be necessary to facilitate also traditional means of sales configuration in parallel with some of the sales companies using a configurator.

In some cases, due to the complexity of the product, the logistics centres do the actual configuration task. Persons in the logistics centres are usually technically very competent. Their number is quite small and they provide configuration services to many sales units.

Another driving force for automated product configuration is the desire to reduce the number of errors to improve quality and to cut quality costs. Many changes to a configuration take place because of internal reasons, due to errors that must be corrected. Changes also occur because the customer changes his or her mind. Errors and changes that affect a configuration seem to be common. In extreme cases 80% of the sales specifications are either incomplete or inconsistent. This kind of operation is sometimes considered normal. Measures have been taken to manage the changes caused by internal errors and changes originating from the customer, but not to prevent the errors from occurring in the first place. An example statistic from a case company shows that less than 20% of the total working time used in order processing is used for productive work. The rest is caused by managing changes and errors.

Products and product families are often differentiated for different market areas. However, products are usually sold globally. The market area quite often affects the final configuration.

The configuration is usually created on the basis of customer’s technical requirements. The price of the product and the required delivery time do not seem to be major controls of the process. That is, the customer requirements are fairly fixed and can be satisfied in only a few ways. If the price or delivery time becomes a critical factor, the requirements are usually reconsidered, or the customer simply finds another supplier. The configuration itself is usually not changed to lower the price but there is usually a certain degree of freedom in adjusting the price of a given configuration.

3.3 Product configuration task

Product configuration models and their systemisation seem to be in their infancy. The companies lack good methods and tools to represent the models. For example, generic bills-of-materials (BOM) (van Veen 1991) or equivalent structures are not used. Computer support is available on the level of traditional fixed BOMs. Some companies have tested configurators, but they are not in day-to-day use. However, more automated support for product configuration tasks is considered desirable and most of the companies intend to proceed in this direction within a few years. The tools need not be fully automatic, but they should in some manner ensure the completeness and consistency of a configuration.

The consistency and the completeness of a configuration are checked at logistics centres by expert configurers on the basis of their experience on similar products and previous deliveries.

The knowledge required is very rarely systematically documented as a product configuration model. The few more advanced companies that document the knowledge as product configuration models do not have systematic formalisms for this purpose. Free form text, often of limited readability and accuracy, is typically used. In addition to text, selection tables and decision graphs are sometimes used. Selection tables can be difficult to use when there are several dependencies between components that are represented in several tables. The decision graphs can be very complex. The maintenance of product configuration models represented as text, selection tables and especially decision graphs is burdensome.

All the three component classes – standard, modifiable standard and parametric – are being used in the industry. However, most of the components used in configuration are standard. Parametric and modifiable standard components seem rarer.

In addition to configurable products, many companies deliver tailored products that involve both configuration and innovative engineering design. In several cases approximately 70-80 % of the tailoring can be done by a configuration process. The rest of the work is more innovative product design.

With some products, the sales specification can be quite directly used as an input for production. In other cases, the process of translating a sales specification to a configuration is long and complex, requiring most of the time and effort spent in the whole configuration process. The translation from a sales specification to a configuration can be simplified by the modularity of the product.

The modularity of products has a favourable effect on the complexity of product configuration tasks. Two ways to understand product modularity are apparent. One starts from the customer needs and modularises the product into functional modules, each of which corresponds to a set of anticipated customer requirements. The other looks at the modularity from the product structure and manufacturability. The first approach helps the configuration process at the sales stage because it simplifies the mapping from customer requirements to a technical specification. The second is more helpful at the later phases of the delivery process, as it enhances the control of production and reduces the work-in-process inventory. This is achieved by reducing the number of component types used in product assemblies, while still retaining a large variety of end products that can be assembled from the component types.

3.4 Long term management of product data

Long term management of delivered products is a considerable problem for the companies. Most companies do not even attempt to reconfigure existing product instances using the same methods as in configuring new instances. Rather, the reconfiguration task is done on a case by case basis. The process is difficult and disliked because of the trouble of accessing a large amount of old product information, which usually is not stored in an integrated, compact form, but has to be retrieved from various sources.

Long term management of product configuration models, as opposed to individual configurations, is also a problem. Products and components evolve; communicating the changes to the product configuration process is error-prone and, in many cases, causes unnecessary extra work. The processes that develop the products usually do not create the configuration related information as a part of the development effort. Rather, this is an additional task done by persons that are not product experts. This may lead to loss of data and erroneous configuration knowledge being used in the configuration process.

3.5 Interfaces to other systems and processes

Extraction of product configuration knowledge from the product development process seems to be a problem. The process is rarely systematised. The previously mentioned lack of methods and tools to represent configuration models is a problem.

The integration level between applications is not very high. Separate islands of automation seem to be common. The companies are moving towards tighter integration to facilitate a more effective process. The systems used for R&D related activities are not capable of handling information at the level of abstraction required for configuration knowledge. Therefore, the knowledge on the use of components within a product must first be recorded for design purposes in CAD drawings and other design documents, and then recreated when defining the configuration model. If there was a way to represent the configuration oriented knowledge in the R&D systems, this information could be entered only once and thereafter used and modified more or less automatically, thus eliminating the duplicate work.

4 IMPLICATIONS TO PRODUCT CONFIGURATION SYSTEMS

In this section the results of the survey are considered from the point of view of developing general knowledge based systems that can be used to model the configuration knowledge of different products and then to configure them on basis of this knowledge.

Configuration knowledge

Configuration knowledge in product configuration models typically describes the possibilities of modifying the product according to the customer requirements and the constraints on the products. The knowledge on how to actually configure on the basis of the configuration model is mostly not explicitly described. Below, we present the fundamental concepts and their relationships that, in our view, can best be used to represent product configuration knowledge.

Typical concepts that are used in the companies to describe their products are the components of which the product consists of, and the functions that the product provides to the customer. In addition to these, some companies use also parametric components with the attendant concepts of parameters and parameter values. The components relate to each other by *aggregation relationships*, which form BOM hierarchies with optional and alternative components. The components are related to the parameters and parameter values. The companies also describe configuration knowledge through incompatibility and requires relationships between components and parameter values. An *incompatibility relationship* records the fact that two components or parameter values cannot be used together in a product, since then the configuration would not describe a working product. A *requires-relationship* specifies, that a component needs another component for the whole product to work.

We feel that many of the surveyed products could more easily be modelled, if one were to use in addition to the above mentioned concepts and relationships also *connectors*, *ports* (Struss 1987) and *resources* (Heinrich and Jungst 1991). Connectors are things that connect components. These may be either physical components or more abstract concepts like air in the capacity of a heat connector that, e.g., connects a transformer (heat source) to the outside world (heat sink). Ports are things that the connectors are connected to. In the concrete case these may be boards or sockets, and in the abstract case a heat emanating place of a component. Resources are things that some parts of the product produce and others consume. Examples include electrical power or space in a rack. Thus, the above mentioned transformer would provide the resource heat, which is conducted through the connector air to the outside world, which consumes the resource. This kind of bond-graph-like modelling is presented in the paper by (Snavely and Papalambros 1993).

Additional relationship useful for modelling the cases include classification hierarchies formed by is a -relationships and instance of relationships between component types and instances. The specification mapping between required functions and components could also be modelled by a separate relationship.

Need of parameters

As the results indicated, standard components are much more common than parametric components. Therefore, fair coverage of configuration processes could be obtained by concentrating only on standard components. This could be a motivation for a restricted, and subsequently simpler, configurator system. However, a general system should also have to be able to represent and configure with modifiable standard and parametric components.

Component types used in products have a fundamental effect on a product configuration system: a configurator system dealing with standard components can do without parameters, but one supporting parametric components must support many kinds of additional concepts and operations discussed below.

Once a standard component has been identified, all its properties are known and fixed. Each standard component may have some attributes that describe its properties, but these properties do not change in each instance of the component. Therefore it is easy to describe relevant properties, for example, by storing them into a relational database by component type. There is no need to check for inconsistent attribute value combinations within a component but this may still be necessary between the attribute values of different components. One does not have to bother with storing descriptions of instance-specific parameter values, ways of determining parameter values or checking consistency of parameter values.

A product configuration system supporting modifiable standard or parametric components must be able to determine and record suitable values for parameters. This introduces the need to represent and store instance specific descriptions of components as it must be possible to store descriptions of configured instances. One must be able to describe the domains of the parameters, ways to determine parameter values (including complex expressions with references to other parts of the configuration and asking from the user) and ways to check for consistent combinations of parameter values. In addition, decisions may have to be changed or backtracked. Keeping the parameter values consistent after changes is yet another topic. Thus the need to present parameters adds another level of complexity to a system supporting product configuration.

Geometry and product configuration

It is sometimes necessary to generate instance-specific drawings of parametric components on basis of calculated parameter values. Generation of manufacturing drawings of parametric components is an example. Drawings may be generated either by the product configurator system, or with a separate, possibly model-based or parametric, drafting system. In these simple cases a configurator does not have to “understand” about geometric modelling and a decoupled system with unidirectional information flow from product configuration system to the drafting system may be appropriate. Many product configuration cases that require generating drawings fall into this category.

More complex topologic or geometric reasoning is also sometimes a part of the product configuration process. A typical example is 2D or 3D layout design. In some cases one may be able to design the layout in the configurator with simple topologic reasoning, in some other cases advanced 3D reasoning may be required. Complex 3D-layout generation problems would require that the configurator is able to model the spatial relationships of objects, possibly keeping dynamic behaviour of the system in mind. Because of the complexity involved, these tasks might be better done by humans.

Requirement for topological or geometric reasoning seems to be quite common in the industry. Due to limited use of parametric components, the generation of drawings of parametric components is not so common.

Customer requirements at different levels of abstraction

As mentioned, the distance from customer requirements to the specification and to the final configuration varies considerably. Some customer requirements can be given as a functional specification, while some other requirements are best formulated as low-level component-by-component selections and parameter value specifications, for example by directly giving the required part numbers. A system should be able to support this spectrum of specifications given at different levels of abstraction. In some cases, a combination of different abstraction levels of specifications might be preferable. This variation poses some challenges as, in a way, this is analogical to being able to give some inputs, some intermediate results and some final results of a complex calculation, then performing the rest of the calculation to get the rest of final results.

Fully automatic operation not always desirable

Companies have relatively strong disbelief in and bad experiences with expert systems. The users are not willing to trust the decisions made by an automatic system. They want to make the decisions themselves. In the problem solving sense, automatic operation is also more difficult to accomplish than semi-automatic, interactive operation, where the user can assist the system by making choices that guide the design effectively to correct solutions. Therefore, if automatic configuration is still desired, it may in most cases be better to first develop support on checking and validating configurations, and piece by piece extend this to more automatic operation. In this way the users can be convinced of the correctness of configurations and the risks of the development project reduced.

Emphasis on long-term management of product configuration models important
Perhaps the most severe restraint on using a product configurator is the difficulty of managing product configuration models. One way to make this easier is to abstract and extend the underlying modelling concepts in a direction that more accurately can capture the relevant aspects of configuration design without extra complexities or transformations. In our view this is needed as the first step. In addition one could integrate some kind of traditional Configuration Management (CM) machinery (Babich 1986, Buckley 1993), e.g., version control tools, into a product configuration system. Naturally these should be used with normal CM practises to yield the best benefits. To fully apply CM practices to product configuration, a model for describing changes to products should be available. This is a research issue described briefly in section 5.

In order to spread the maintenance effort of product configuration systems to nonprogrammers such as product developers, the systems must be able to describe product configuration models in declarative, high level terms familiar to the users. The basic concepts could be those discussed in the beginning of this section. A product configuration system should be able to represent these as data, without programming effort, to facilitate the maintenance. This poses interesting challenges both to visualising product configuration models and to the underlying data model of the product configuration system.

Semi-configurable products
As was mentioned in the results, the C-process products can often be partly configured and must be partly designed. In these cases the configurator should have an ability to integrate results of innovative or creative design into a configuration. A successful computer system for these processes would have to include a way to represent components that are not pre-designed along with the rest of the configuration consisting of pre-designed components.

Market areas
The differences between market areas indicated in the results suggest that a product configurator should take them into account. It seems that a single configurator and several product data bases or a single product database with rules to prevent the use of components not available to some market area(s) would correspond to the needs of the companies.

5 FUTURE RESEARCH

We hope to be able to elaborate the metrics emerging from our survey very much from their present form. In addition to this, the summary report of the results of the survey will be published. The remainder of this section discusses long term research issues.

5.1 Model of product configuration knowledge

There seems to be a need for a general methodology and tools for supporting the representation of product configuration models. On the basis of our first results, similar concepts are being used in different companies. It would seem to indicate the possibility of finding a general model of product configuration knowledge that would be feasible for a range of companies. In the simplest form, this model would include concepts like specifications, components, parameters and their values. In addition to the concepts, the model would include relationships such as a generalised has-part-relationship with optional and alternative components, a specification mapping between specifications and components or parameters, and two special relationships between components or parameter values, the requires relationship and the incompatibility relationship.

5.2 Model of long term management of product data

The long term management of products and configurations has not been solved in an adequate way in any company or system. Most of the companies recognise the risks involved. Our objective is to obtain a general view of the changes to the configuration knowledge in practice. This would facilitate researching and defining a general model of changes to the knowledge. This model would form a basis for computerising the long term management of product data in a manner that would support both the management of configuration models and related knowledge, and the management of delivered product instances.

5.3 Configuration maturity model

Companies seem to be in different stages of maturity and have varying capabilities in the area of product configuration. It is quite evident that it makes sense to first concentrate on the basics and then move on to more advanced topics. Fundamentally we are talking about an organisational learning process. For example, a well documented and systematic way to configure products facilitates automating the process. Besides other benefits, well-modularised products simplify the product configuration tasks significantly. Changes to the products and components must be under control to enable efficient and timely updates of product configuration information. All the above mentioned issues facilitate the implementation of computerised support for product configuration and help in reducing the maintenance burden of product configurators.

These observations seem to parallel the underlying thoughts of the Capability Maturity Model (CMM) (Paulk et al. 1993) commonly referenced in software industry. We aim to develop a similar, yet less ambitious model based on our observations. This model could be used for the evaluation of the maturity of a company in terms of configuration processes and product data management. It could also be used to suggest the most effective and relevant development actions to be taken in the company in order to gain maximal benefits from the improvement effort.

5.4 Design for configurability

The general configuration problem cannot be solved solely with better models and tools. Flexible configuration of products must be considered already while products and components are designed. For example, components and products should have well-defined interfaces and they should not place unnecessary constraints on other parts of the product structure. Therefore another future research issue is to produce guidelines for designing products that can be configured easily – an approach we call *Design for Configurability*. We hope to elaborate techniques for measuring the complexity and configurability of products. The modularity of products will probably be one of the factors in this area.

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