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This paper aims to increase understanding of the impact from using product-modelling techniques to structure and formalize knowledge in configurator projects. Companies that provide customized products increasingly apply configurators in support of sales and design activities, reaping benefits that include shorter lead times, improved quality of specifications and products, and lower overall product costs. The design and implementation of configurators is a challenging task that calls for scientifically based modelling techniques to support the formal representation of configurator knowledge. Even though extant literature has shown the importance of formal modelling techniques, the impact of utilizing these techniques remains relatively unknown. Therefore, this article studies three main areas: 1) the impact of using modelling techniques based on Unified Modelling Language (*UML)*, in which the phenomenon model and information model are considered visually, 2) *non-UML-based modelling techniques*, in which only the phenomenon model is considered, and 3) *non-formal modelling techniques*. This study analyzes the impact to companies from increased availability of product knowledge and improved control of product variants. The methodology employed is an exploratory survey, followed by interviews with 18 manufacturing companies providing customized products. The results indicate that companies using UML-based modelling techniques tend to have improved documentation of their product knowledge and an improved ability to reduce the number of product variants. This paper contributes to an increased understanding of what companies can gain from using more formalized modelling techniques in configurator projects, and under what circumstances they should be used.

Keywords: information systems; product modelling; product configurators; documentation; object-oriented modelling; knowledge management.

1. Introduction

In today's business environment, customers increasingly demand high-quality, customized products with short delivery times at competitive prices (Hvam, Mortensen, and Riis 2008; Forza and Salvador 2007; Zhang 2014). To respond to these challenges, configurators are used to support design activities, which involve gathering information from customers and generating the required product specifications (Forza and Salvador 2002a, 2007). A configurator is a knowledge-based system that supports the user in the specification process of personalized products by providing design choices, in which a set of components, along with their connections, are pre-defined and constraints are used to prevent unfeasible configurations (Felfernig, Friedrich, and Jannach 2000; Zhang and Rodrigues 2010; Eigner and Fehrenz 2011; Long et al. 2016). Thus, the use of configurators means that the generation of product specifications (e.g., quotes, sales prices, bills of materials, CAD models) can be automated (Hvam, Mortensen, and Riis 2008).

Configurator projects can be defined regarding the tasks required to build a configurator, which includes analysis and redesign of the business processes, modelling of the product range, selection of configurator software, programming of the configurator, implementation, and maintenance (Hvam, Mortensen, and Riis 2008). In configurator projects, one of the primary tasks is to structure and represent the knowledge of the configuration model (Aldanondo, Rougé, and Véron 2000; Ardissono et al. 2003; Forza and Salvador 2002a; Felfernig et al. 2004, 2014; Hvam 2006a; Stark 2007; Shafiee et al. 2017). However, if companies are highly dependent on domain experts' knowledge, there is a risk of incomplete communication or cognitive conflicts, which can result in loss of knowledge, making it difficult to formalize and document (Tseng, Chang, and Chang 2005). Furthermore, with configurator projects, there is a risk that the documented knowledge is low-quality or not properly maintained (Tiihonen et al. 2013; Shafiee et al.

2017). Research has shown that a configuration model without adequate documentation can lead to a lack of overview, and even require restructuring of the configurator (Haug, Hvam, and Mortensen 2009). Furthermore, past studies emphasize the importance of standard-knowledge representation in configurator projects for an effective integration of configuration technologies into software environments that deal with highly complex products (Felfernig 2007). Tiihonen et al. (1996) describe the challenges of configurator projects concerning knowledge: 1) knowledge is rarely documented systematically, and 2) long-term management of knowledge is difficult, as knowledge changes over time to be aligned with companies' product offerings. Furthermore, the need for a general methodology supporting the representation of the configurators' product models is emphasized (Tiihonen et al. 1996).

Product modelling focuses on representing structure and product knowledge to ensure that it is understandable to all parties involved, which, in configuration processes, includes both domain and configuration experts (Lars Hvam, Mortensen, and Riis 2008). In configurator projects, four basic representations are proposed for structuring configurator knowledge, as Figure 1 shows (Duffy and Andreasen 1995). First, the real world represents the product knowledge available within a company, in which a formal representation of the knowledge has not been established. Second, the phenomenon model describes a product's structure, function, and other properties, including the product's lifecycle, in a way that can be communicated to domain experts. Third, the information model is formalized, which is an IT representation of the phenomenon model, often supporting Unified Modelling Language (UML) notation (Felfernig, Friedrich, and Jannach 2000; Hvam 2001; Hvam, Mortensen, and Riis 2008). Fourth, the actual computer model is built on the previously described representations of the product knowledge.

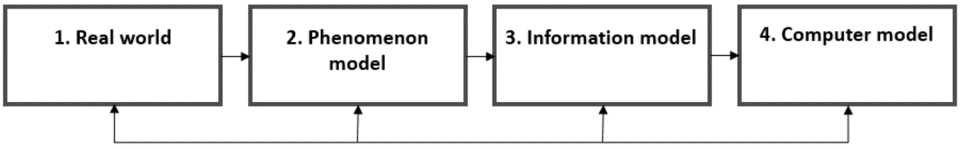

Figure 1. Four basic representations of product modelling for configurators. Revised from Duffy and Andreasen (1995).

The literature describes modelling techniques for constructing the phenomenon model (e.g., Hegge 1992; Ulrich 1995; Erens and Verhulst 1997; Eppinger and Ulrich 2000; Stone, Wood, and Crawford 2000; Gonzalez-Zugasti, Otto, and Baker 2000; Dahmus, Gonzalez-Zugasti, and Otto 2001; Du, Jiao, Tseng and Zou 2001; Fixson 2005; Huang, Zhang, and Liang 2005; Harlou 2006). Modelling techniques for building the phenomenon model and information model also have been detailed (e.g., Chao and Chen 2001; Felfernig 2001; Hvam 2001; Hvam, Mortensen, and Riis 2008; Magro and Torasso 2003). UML has been proposed as a way to represent the information model in configurator projects (Felfernig, Friedrich, and Jannach 2000; Hvam 2001; Hvam, Mortensen, and Riis 2008). UML is a visual modelling language that is used for visualizing, specifying, constructing, and documenting artifacts in software design (Booch, Rumbaugh, and Jacobson 2005). This article focuses on three different representations of knowledge in configurator projects: 1) *UML-based modelling techniques*, in which the phenomenon model and information model are considered in a visual way, 2) *non-UML-based modelling techniques*, in which only the phenomenon model is considered (e.g., structured bills of materials), and 3) *non-formal modelling techniques (*e.g., making a list of features in Word or Excel without any formal structure or modelling directly in the configurator). The Center for Product Modelling (CPM) procedure is a modelling technique that represents both the phenomenon and the information model by using UML notation. To represent the phenomenon model, product variant master (PVM) and class responsibility collaboration (CRC) cards are used, and to represent the information model, class diagrams and CRC cards are used (Lars Hvam 2001; Lars Hvam, Mortensen, and Riis 2008). To represent UML-based modelling techniques, the CPM procedure is used in this study, partly because it is based on UML---also used to make phenomenon models---and partly because the authors have access to companies using the CPM procedure, along with companies using other methods (*non-UML* based and *non-formal* modelling techniques).

Although the previously mentioned modelling techniques are proposed in extant literature, the impact of applying modelling techniques when making the phenomenon model and the information model remains relatively unknown (Hvam et al. 2014). Even though a few studies have analyzed this impact, it is limited to single-case studies of one specific modelling technique (e.g., Stumptner, Friedrich, and Haselböck 1998, Chao and Chen 2001, Yang et al. 2009). Thus, a comparison of different modelling techniques is required both to compare their impact and to determine which circumstances require more formalized modelling techniques (e.g., supporting both the phenomenon and information models).

The literature describes numerous benefits that can be gained from utilizing configurators, e.g., reduced work-hours to prepare specifications, routine work, lead time and improved quality, certainty of delivery, control of product variants and knowledge availability (Tiihonen et al. 1996; Forza and Salvador 2007, Hvam, Mortensen, and Riis 2008; Trentin, Perin, and Forza 2011; Forza and Salvador 2008; Tenhiälä and Ketokivi 2012; Zhang 2014; Myrodia, Kristjansdottir, and Hvam 2017). However, the modelling techniques used in a configurator project impact knowledge availability, as knowledge is made more explicit and thereby more accessible to a greater number of employees within the company. Additionally, choice of modelling technique impacts the company's control of product variety by providing increased insight and overview of product variants and relations/constraints between components/modules. Thus, to explore the impact of utilizing product-modelling techniques in configurator projects, the following propositions are presented, in which it is assumed that more formalized modelling methods (UML-based) will have a greater impact on both knowledge availability and control of product variants:

Proposition 1: The use of a UML-based modelling technique will result in increased availability of product knowledge in organizations.

Proposition 2: The use of a UML-based modelling technique will result in improved control of product variants.

Due to the exploratory nature of this study's objectives, the research methodology is an exploratory survey, followed by interviews (Yin 1989). All contacted companies manufacture customized products and use configurators to support their sales and design processes. The results presented in this paper include responses from 18 companies. Research has shown that small sample sizes are justifiable in the context of exploratory research, which this study employs (Isaac and Michael 1995; Dattalo 2007). Because of the small sample size, a statistical analysis on the findings does not provide reliable/informative data (Isaac and Michael 1995; Dattalo 2007). Instead, this exploratory study aims to provide further insight into the impact of using different modelling techniques in configurator projects.

The remainder of this paper is structured as follows: Section 2 discusses relevant extant literature, and Section 3 elaborates on the CPM procedure. Section 4 explains the research method, and Section 5 presents research results. Section 6 discusses the research results, and Section 7 concludes the paper, re-examining the research question and noting the study's limitations, which can be used as a starting point for further research.

2. Literature review

Configurators can be traced back to the 1980s, when the first configurators were developed as rule-based systems (Barker et al. 1989). However, the maintenance of those systems proved to be challenging due to the vast knowledge within the systems and frequent updates (e.g., Mailharro 1998; Felfernig 2007; Jannach and Zanker 2013). To address these challenges, researchers examined knowledge representation and conceptual modelling for configurators, which are further elaborated in this section.

Mittal and Frayman (1989) propose a generic component-port approach for solving configuration problems. Their approach of configurable systems is based on a pre-defined set of components, in which each component is described by a set of properties and ports that enable connections to other components, under certain constraints. The configuration task is restricted by functional architecture and key components. Their approach is still dominant and serves as the basis for many commercial configurators (Felfernig et al. 2004; Jannach and Zanker 2013).

Soininen et al. (1998) proposed a general ontology for configuration that combines connection-, resource-, product structure-, and function-based approaches. The ontology aims to reuse and share configuration knowledge and allow for interacting among configurators' agents. Felfernig, Friedrich, and Jannach (2000) proposed another approach, in which UML is used to represent domain-specific notation, both to make the knowledge understandable for domain experts and to describe the formalism of the configurator. Under their approach, contextual diagrams are proposed for more complex domain knowledge (Felfernig, Friedrich, and Jannach 2000). Yang et al. (2009) proposed a similar approach, in which a method-based semantic web technology (Web Ontology Language [OWL] and Semantic Web Rule Language [SWRL]) supports reuse and modelling of configuration knowledge. By using OWL, which is based on description logic, well-defined logic semantics can be created that do not need any translation, unlike the UML approach (Yang et al. 2009).

Another essential aspect of configurator projects is to structure the configuration knowledge sufficiently so that components and their relations are defined (Zhang 2014). To this end, Stumptner, Friedrich, and Haselböck (1998) propose a method based on a constraint-satisfaction problem, known as a generative-constraint satisfaction problem. The method allows for reasoning of both existing components and of large and variable numbers of components. Furthermore, Mailharro (1998) defines a configuration problem as both a classification problem and a constraint-satisfaction problem, in which a framework based on object-oriented and constraint-satisfaction paradigms is proposed that focuses on domain-knowledge representation. To address the challenges of semantic web applications, Felfernig et al. (2003) analyze the applicability of commonly used languages based on description logic concerning configuration-knowledge representation. Their research shows that description logics are synonymous with consistency-based definitions and are thereby useful in configurator projects (Felfernig et al. 2003). In another study, Felfernig (2007) extends this work to support product-structure constraints and complex structural properties of configuration problems, proposing model-driven architecture (MDA) based on UML and object-constraint language (OCL) for configurators. This should enable more efficient communication with other software applications and facilitate technical support (Felfernig 2007). To address the challenges of distributed configurators, Ardissono et al. (2003) propose a framework and develop the configuration shell. Jannach and Zanker (2013) later added to this work, offering an approach based on distributed constraint satisfaction in which generative constraint satisfaction is used to model the knowledge to solve the challenge of distributed configurators.

Conceptual modelling of configuration knowledge is a vital aspect concerning the structure of configuration knowledge. McGuinness and Wright (1998) propose a conceptual approach for structuring knowledge for configurators in which they emphasize the need for configurator accuracy over optimization by proposing a modelling technique based on description logic. Peltonen et al. (1998) define concepts for modelling configurable products based on hierarchical product structure, with the configuration model divided into an explicit structure (based on bills of materials [BOM], with optional, alternative pars and parametric components; other constructs also can be described, such as connection ports) and constraints (which can be related to specifications, implementation, or structure). Aldanondo, Rougé, and Véron (2000) propose a method that builds on a function-breakdown structure and a physical-breakdown structure that, in turn, build on an object-modelling technique that represents both functions and components regarding objects, dependencies, and composition operators. Felfernig, Friedrich, and Jannach (2001) propose a conceptual modelling technique for configurators, which they built onto their previous research (Felfernig, Friedrich, and Jannach (2000), in which UML is used to structure the domain knowledge, and that work is further extended to incorporate functional architecture (Mittal and Frayman (1989). Magro and Torasso (2003) describe decomposition strategies for configurations to improve performance and support interactive configuration, in which frame parts and components are used to represent configuration-domain knowledge.

Chao and Chen (2001) introduce an assembly model that includes information regarding functionalities and components for assembly in configuration management in product-data management systems. Jinsong et al. (2005) propose a method aimed at make-to-order manufacturers, in which the product architecture usually consists of modules and standardized components. The method is based on knowledge components and attributes that capture and represent configuration knowledge (Jinsong et al. 2005). Hong et al. (2008) offer an approach to identify optimal product configuration for one-of-a-kind products based on customer requirements for products' cost and performance. The approach builds on modelling products' functions and structure through an AND-OR tree (Hong et al. 2008). Hong, Xue, and Tu (2010) expand this approach and present a customer-centric product-modelling scheme to model one-of-a-kind products in which customers are grouped by product and customer patterns. Tseng, Chang, and Chang (2005) suggest using a graph-based bill of material and case-based reasoning to construct a new BOM in the configuration processes, in which previous similar cases are identified and adjusted to meet the constraints for the product under design. Yang, Dong, and Chang (2012) propose a method to deal with structured product-configuration problems in which an object-oriented configuration model is transformed into dynamic constraint satisfaction problems. Finally, Zhang, Vareilles, and Aldanondo (2013) analyze the SAP[2] configurator, in which the production view is considered, in addition to functional and physical structure. In that study, the generic bill of functions, materials, and operations (GBoFMO) is proposed to present the knowledge from different domains (Zhang, Vareilles, and Aldanondo 2013).

Alternative approach is offered by Hvam (2001) that is later extended by Hvam, Mortensen and Riis (2008), or the CPM procedure for conceptual modelling of configurators. The approach builds on the concepts of, object-oriented modelling (Bennet, McRobb, and Farmer 1999; Booch, Rumbaugh, and Jacobson 1999; Felfernig, Friedrich, and Jannach 2000), systems theory (Bertalanffy 1968; Skyttner 2005), and modelling mechanical products (Schwarze 1996; Hubka and Eder 1988; Jiao, Simpson, and Siddique 2007). To support this method, Haug and Hvam (2007) and Shafiee et al. (2017) proposed IT tools to model, communicate, and document product knowledge. The

CPM procedure represents both the phenomenon and the information model by using UML notation, in which the PVM and CRC cards represent the phenomenon model, and class diagrams and CRC cards form the information model. The CPM procedure is further explained in Section 3.

2.3 Summary

This section reveals that several researchers have addressed modelling techniques and knowledge representations for configurator projects. These studies benefit from different methods, providing both case studies (e.g., Stumptner, Friedrich, and Haselböck 1998; Magro and Torasso 2003 Tseng, Chang, and Chang 2005; Hong et al. 2008; Hong, Xue, and Tu 2010; Yang, Dong, and Chang 2012) and illustrative examples (e.g., Mailharro 1998; McGuinness and Wright 1998; Aldanondo, Rougé, and Véron. 2000; Felfernig, Friedrich, and Jannach 2000, 2001; Chao and Chen 2001; Zhang et al. 2005; Felfernig 2007; Yang et al. 2009; Zhang, Vareilles and Aldanondo 2013). The impact of using different modelling techniques is discussed in terms of managing the complexity of the configurator (McGuinness and Wright 1998), reducing the time needed for development and maintenance of the knowledge base (Stumptner, Friedrich, and Haselböck 1998), increasing efficiency in product development (Chao and Chen 2001), reusing product-configuration knowledge (Yang et al. 2009), and saving time and resources while improving configurator quality (Shafiee et al. 2017). However, none of the studies compares the actual impact of using different modelling techniques, such as UML-based, non-UML-based, or non-formal modelling techniques, on configurator projects. Thus, a comparison of different modelling techniques is required both to compare their impact and to see under which circumstances more formalized modelling techniques (i.e., UML-based or non-UML-based) are necessary.

3 CPM procedure

The CPM procedure was first proposed by Hvam (2001) and has since been extended (e.g., Hvam, Riis, and Hansen 2003; Hvam and Ladeby 2007; Haug, Hvam, and Mortensen 2010). Hvam, Riis, and Mortensen (2008) offer the most comprehensive version of the procedure, on which this section builds.

The primary application of the CPM procedure involves a PVM and class diagrams associated with CRC cards. PVM is a modelling technique used to structure the phenomenon model visually so that it can be used to communicate with domain experts while supporting UML notation. The PVM structure includes product features on multiple product variants according to the customer, engineering, and part/production views (Andreasen 1994; Harlou 2006). This is aligned with (e.g., Deciu et al. 2005; Zhang et al. 2013), who recommend that product structures be modelled from different views (Section 3.1). Class diagrams are used in the CPM procedure to represent the information model, in which the structure corresponds to the PVM structure (Section 3.2). Finally, CRC cards, associated with the PVM and class diagrams, are used to describe the individual classes in more details (Section 3.3).

3.1 Product variant master (PVM)

To obtain an overall view of the products, the product range is drawn up in a PVM to represent the phenomenon model (Hvam 2001; Hvam, Riis, and Mortensen 2008). The PVM consists of two structures: the *part-of structure* and the *kind-of structure*. The part-of structure represents the parts that appear in the entire product family. The classes are defined as object classes, which include the name of the class, description, attributes, and constraints. The kind-of structure describes the different variations that individual parts can have. Furthermore, the PVM contains a description of the most important connections between parts, i.e., the rules for how parts are permitted to be combined. To preserve the overview of the PVM, CRC cards are associated with the PVM to describe the individual parts in more detail (Section 3.1). The PVM represents knowledge from different domains, which include customers, engineering, and part/production views (Harlou 2006). The causal connection then can be drawn between views to identify complexity and non-value-adding variety in the product range. Figure 2 provides an illustrative example of the PVM, which supports UML notation and thereby can be transformed into a class diagram, which is a UML-based modelling technique (as explained in Section 3.2).

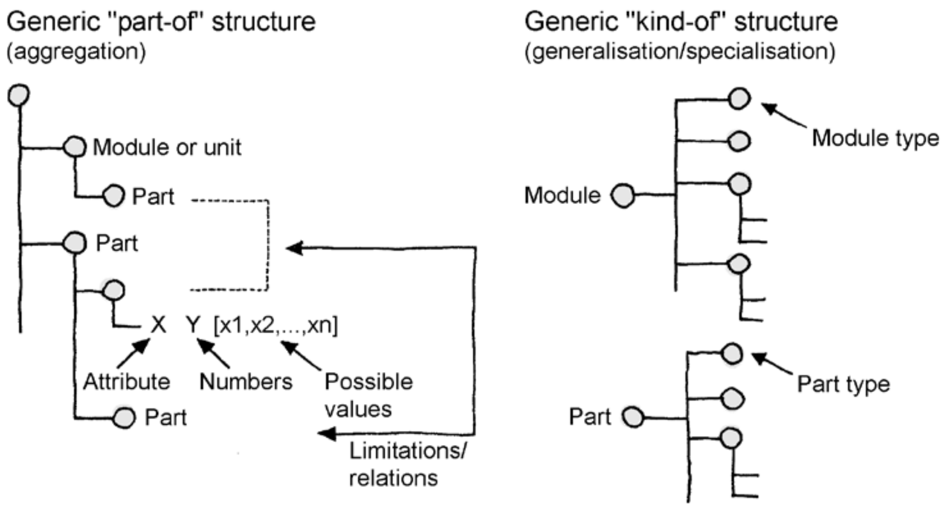

Figure 2. PVM structure regarding part-of and kind-of structure adjusted from (Harlou 2006, Hvam, Mortensen and Riis 2008)

3.2 Class diagrams

Class diagrams are used to represent the information model. Individual classes in the class diagram are defined from the PVM, in which a class in the PVM indicates a class in the class diagram.

Aggregation and association structures are used to indicate relationships between objects. The aggregation structure corresponds to the part-of structure in the PVM. The association structure is used if objects are associated with each other. Cardinalities can be used with the aggregation and association structures to represent the number of sub-parts needed to make a super-part (Hvam, Riis, and Mortensen 2008). Generalization and package structures describe relationships between classes. The generalization structure corresponds to the kind-of structure in the PVM. Figure 3 shows the relationship between the PVM and class diagrams. Since the PVM supports UML notation, a class diagram can be generated directly from its structure.

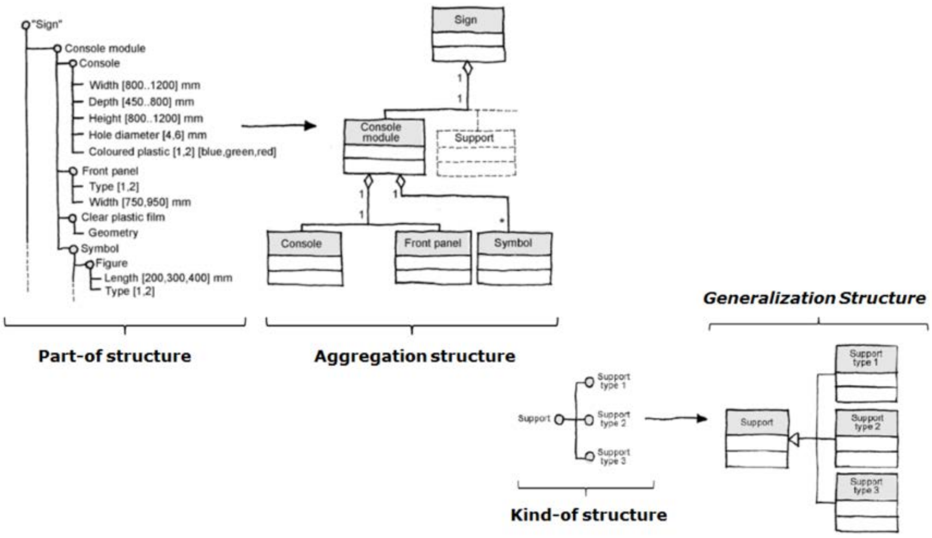

Figure 3. Class structures concerning the PVM adjusted from (Hvam, Riis, and Mortensen 2008).

3.3 Class responsibility collaboration (CRC) cards

The CRC cards, which are associated with both the PVM and the class diagrams, describe classes in more detail. The CRC card was first proposed as a way to teach object-oriented thinking (Beck and Cunningham 1989). Later, they were developed for use in configurator projects, in which they describe individual object classes of PVM and class diagrams in more detail (Hvam, Riis, and Hansen 2003; Hvam, Mortensen, and Riis 2008). In other words, the CRC card defines the class, including the class name and its possible place in the hierarchy, along with a date and the name of the person responsible for the class. Also, class task (responsibility), class attributes and methods, and collaboration classes are provided. Furthermore, a sketch of the product part represented by the class is included. CRC cards' purpose is to document detailed knowledge about the attributes and methods for individual object classes, as well as describe classes' mutual relationships. CRC cards serve as documentation for both domain experts and system developers. Thus, together with the PVM and class diagram, CRC cards become an essential means of communicating and documenting knowledge in configurator projects, thereby supporting UML-based modelling, along with the PVM and class diagrams. Figure 4 provides an example of a CRC card.

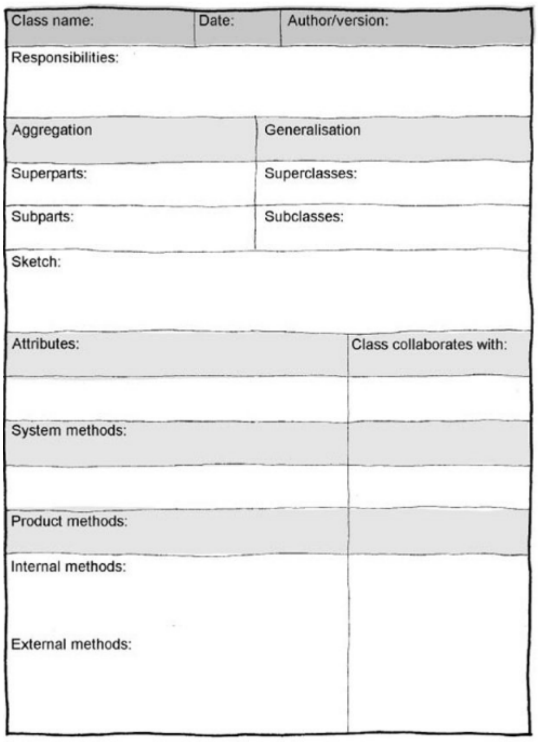

Figure 4. CRC card (Hvam et al. 2008).

4. Research method

Due to the exploratory nature of the research objective, the chosen research method is an exploratory survey followed by interviews (Bradburn, Sudman, and Wansink 2004; Yin 1989). A survey supported by interviews offers the advantages of structured and standardized questions while also allowing for qualitative explanations and a deeper understanding of companies' settings. A further advantage of this kind of research design is the ability to ensure that respondents understand the survey's questions and to clarify any misperceptions. This approach proved to be particularly helpful because of respondents' varying backgrounds and target organizations' differing industrial settings, definitions, and practices. The following sections provide a more detailed explanation of the sample population, respondents, questionnaire design, data collection, and data analysis.

4.1 Population and sampling

The selection criteria were that organizations had to be manufacturing companies providing customized solutions with experience using configurators to support their specification processes. To identify companies that fulfilled the selection criteria, the Danish Association for Product Modelling was consulted. To identify additional companies, a brainstorming session was conducted during the interviewing process in which respondents were asked for a reference list of other companies that might fulfill the criteria. A total of 18 companies provided valid answers to the questions included in the study, i.e., qualifying corporate respondents explained the modelling techniques that their companies used and stated the impact of using such modelling techniques. Research has shown that small sample sizes are justifiable in the context of exploratory research and pilot studies, under which this study falls (Dattalo, 2007; Isaac and Michael, 1995). Because of the small sample size, applying statistical-significance tests might not be very reliable/informative (Dattalo, 2007; Isaac and Michael, 1995). However, this is not the aim of this paper due to its exploratory nature.

The sample used in this study can be characterized by the size of the company in terms of number of employees, product types offered, number of configurators in use, and experience working with configurators (Tables 1 to 3).

Table 1. Companies' size in terms of numbers of employees

Distribution	Number of employees
Minimum	20
≤ 25%	400
≤ 50%	600
≤ 75	5,600
Maximum	15,000

Table 2. Product types that the companies offer

Product types	Number of companies
Agricultural systems	2
Boiler systems	1
Building systems	5
Components and systems	1
Control boards	1
Control systems and components	1
Heating systems and components	1
Hydraulic components	1
Mechanical systems	1
Plants and electronic systems	1
Plants and machines	1

Tools and components	1
Ventilation systems	1

Table 3. Years since the first configurator was implemented and number of configurators used

Distribution	Number of years since the first configurator became operational	Number of configurators used at the companies
Minimum	3	1
≤ 25%	7	1
≤ 50%	9	2
≤ 75%	13	3
Maximum	25	20

4.2 Respondents

At each company, only one person was responsible for completing the survey and agreeing to an interview. Aligned with the study's focus, the companies' respondents were selected based on their familiarity with configurators. It was decided that in-depth knowledge of configurators was required, which top-level management at the companies might not have.

4.3 Design of questionnaire

In the design phase, a rough draft of the questionnaire was developed from the literature review. Hereafter, a brainstorming approach was used to specify the survey's primary constructs. The questionnaire was divided into three sections, as summarized in Table 4.

Table 4. Design of questionnaire

	Description/Key areas	**Examples**
Section 1	Industrial settings and size of companies' configuration areas	- Number of employees [open] - Number of employees working on configurator projects [open] - Number of users [open]
Section 2	Complexity of configurators used at companies. If the companies had more than one configurator in use, the respondents' answers were based on the most complex configurators.	- How many attributes? [0-199, 200-499, 500-999, 1,000-2,000. If more, how many?]. - How many constraints? [0-199, 200-499, 500-999, 1,000-2,000. If more, how many?][1]. - Is the configurator integrated with the following systems: ERP, CRM, CAD, PLM, calculation system, and/or "other"? If "other," what?]
Section 3	Gain understanding of modelling techniques used by companies in configurator projects and the impact of using them.	- Were modelling techniques used during development and maintenance of the configurator? [Yes or No] - If modelling techniques were used, please indicate whether some of the following techniques were used: class diagrams, product variant master (PVM), CRC cards, structured bills of materials, flowcharts, and/or "other." If "other," what? - To what extent do you agree that the company has obtained the following benefits (on a five-point scale, with one representing "strongly disagree," three "neither agree nor disagree," and five "strongly agree")? • Improved documentation of knowledge

[1] This includes any kind of rule-based formalization.

		• Improved availability of product knowledge • Reduction of product variants (item numbers) • Increased use of standard parts • Improved quality of products

To establish external validation of the questionnaire and ensure that the respondents were familiar with how the questionnaire worked in practice, three pilot studies were conducted. The criteria for selecting the subjects for the pilot studies were that the respondents should be sufficiently experienced with configuration and represent an organization with a distinct configuration setting. Thus, one selected company was a manufacturer of consumer electronics, one was a one-of-a-kind manufacturer, and one was a manufacturer of industrial equipment. These criteria were established to test the applicability of the questionnaire for the configuration settings of different types of industries. The questionnaire was first e-mailed to the companies' respondents, then follow-up interviews were conducted. The pilot studies focused partly on testing the relevance of the questions and instruments—particularly whether the questions made sense, the formulations were accurate, and the assumptions made were explicit—and partly on discussing configuration practices at the companies to identify further relevant topics for the questionnaire. The pilot studies led to a moderate update of the questionnaire concerning wording to increase clarity.

4.4 Data collection

The first step was to e-mail the questionnaire to the respondents with a description of the study's purpose, the interview procedure, and a follow-up notification. Appointments were made for phone interviews. One person conducted the interviews to increase consistency. The interview process provided room for clarification and elaboration of questions to ensure accurate and consistent interpretation of the questions listed in the questionnaire and for the interviewer to gain a complete understanding of the companies' settings. Immediately after each interview, the completed questionnaire was e-mailed to each respondent for verification while the interview was still fresh in the respondent's mind. Few interviewees used the opportunity to modify registered answers. The interviews took 40 to 90 minutes each, depending on the complexity of the configuration setting and the organization's situation.

4.5 Data analysis

In the analysis phase, interviews were cross-checked for data-entry errors before answers were analyzed. Concerning the complexity of the configurator, company No. 6 and No. 15 did not provide all the required information. No. 6 could not estimate the number of rules and attributes, and No. 15 provided answers only on number of attributes and not rules. Finally, No. 1 did not provide answers to whether the use of modelling techniques influenced the improved control of product variants. However, it was decided to keep these companies in the data sample, as the exploratory nature of the research aim meant that their responses still provided vital insights. Out of the companies included in this study, one company is identified as an outlier regarding its large numbers of rules and attributes, the reason being that the company's configurator consists of several sub-configurators. To validate the findings, the analysis was repeated by excluding this company to evaluate the impact on the overall results. However, it did not change the overall results, so the company remained in the sample.

5. Results

This chapter presents the primary results from the research regarding the modelling techniques used by the companies included in the sample.

5.1 Modelling methods used at the companies and characteristics of the configurators and companies

The companies were divided into three groups, based on the modelling techniques applied: a UML-based modelling technique (CPM procedure), a non-UML-based modelling technique (e.g., structured bills of materials), or a non-formal modelling technique *(*e.g., making a list of features in Word or Excel without any formal structure or modelling directly in the configurator).

In the first group, six companies were using UML-based modelling methods, meaning they used the CPM procedure, which is based on UML notation both for the representation of the phenomenon model (the PVM and CRC cards) and the information model (class diagram and CRC cards). The companies in this category used either PVM, class diagrams and CRC cards, or at least either the PVM or class diagrams. The second group consisted of six companies that utilized non-UML-based modelling techniques or structured BOM in addition to Excel spreadsheets, Word documents, and modelling tools provided by the configuration software. Finally, the remaining six companies said they did not use any formal modelling techniques outside of configuration software besides spreadsheets and Word documents. Table 5 summarizes how the different modelling techniques are used at the companies.

Table 5. The types of modelling methods used to represent the knowledge in configuration projects

Number of companies	**Company ID**	**UML-based modelling techniques**	**Non-UML-based modelling techniques**	**Non-formal modelling techniques**
6	1, 3, 4, 5, 7, 8	x		

6	2, 6, 9, 10, 11, 13		x	
6	12, 14, 15, 16, 17, 18			X

To determine the companies' characteristics and the configurators used at each company, respondents were asked to provide the number of employees at their companies to represent company size. To describe the size of the configuration areas at the companies, the respondents were asked to provide the number of configurators utilized at their companies, the number of employees working on configurator projects, and the number of configurator users. Finally, they were asked to describe the configurators' complexity that is based on, rules, attributes, and integrations. In Table 6, this information is grouped according to the approach used for the companies' product modelling.

Table 6. The use of different types of modelling techniques related to configuration area size and configurator complexity

	No. employees	**No. configurators**	**Number of employees involved in configurator**	**Number of users**	**No. attributes**	**No. constraints**	**Total integrations**
Companies using UML-based modelling techniques							
Average	7,833	4.2	7	190	2,725	2,391	3.2
Companies using non-UML-based modelling techniques							
Average	4,600	2.3	6	130	720	730	1.7
Companies using non-formal modelling techniques							
Average	370	1.3	3	37	1,000	708	1.7

According to the results presented in Table 6, companies using UML-based modelling techniques are characterized as having more employees than companies listed in other groups, thereby indicating more formalized modelling techniques are required at larger companies. Furthermore, these companies also have more configurators in operation, and the configurators are characterized as being more complex regarding the number of attributes, rules, and integrations with other software applications. In three of the six companies using UML-based modelling techniques, the respondents reported that they started to model their configurators using non-formal modelling techniques. However, as the configurators grew bigger and the number of people involved in the configurator projects increased, the companies realized the necessity of working in a more structured way and taking more control of the models implemented in the system. Therefore, in these cases, UML-based modelling techniques were applied at a later stage in those configurator projects.

Comparing the companies using UML-based modelling techniques with the companies using non-UML-based or non-formal modelling techniques reveals that the latter companies are smaller in terms of numbers of employees and system users, and the configurators are less complex with respect to numbers of rules, attributes, and integrations. However, the results show that companies using non-UML-based modelling techniques were larger than those using non-formal modelling techniques and have more configurator users, but the configurators were similar in terms of complexity. These results could indicate that for a minor configurator project that does not involve too many employees, the product modelling can be managed by using non-UML-based or non-formal modelling techniques.

5.2 The impact of applying different modelling techniques

The impact of using UML-based modelling techniques compared with non-UML-based or non-formal modelling techniques is analyzed concerning the propositions or availability of product knowledge and control of product variants. The respondents rated the impact on a five-point scale, with "one" indicating they strongly disagreed with the statement and "five" indicating they strongly agreed with the statement. Table 7 provides the results concerning the propositions, and the values given in the table are based on a five-point scale representing to what extent the companies agree with the obtained benefits. Appendix 2 lists the answers from the individual companies.

Table 7. Comparison of the impact of using different types of modelling techniques in configurator projects concerning propositions (in which "one" represents strongly disagree and "five" represents strongly agree).

	Increased availability of product knowledge		Improved control of product variants		
	Improved documentation of knowledge	**Improved availability of product knowledge**	**Reduction of product variants (item numbers)**	**Increased use of standard parts**	**Improved quality of products**
	Companies using UML-based modelling techniques				
Average	**4.7**	**4.7**	**4.0**	**4.7**	**4.4**
	Companies using non-UML-based modelling techniques				
Average	**4.3**	**4.5**	**2.5**	**4.3**	**4.2**
	Companies using non-formal modelling techniques				

Average	**3.7**	**3.8**	**2.2**	**4.0**	**3.8**

First, increased availability of product knowledge is measured through ratings of improved documentation of knowledge and improved availability of product knowledge. The companies using a UML-based modelling technique gave higher ratings to improved documentation of knowledge, improved availability of knowledge, and improved availability of product knowledge. Furthermore, companies using non-UML-based modelling techniques gave a higher rating than companies using non-formal modelling techniques. This indicates that the more formalized the method, the more the availability of product knowledge increases. However, especially between companies using UML-based and non-UML-based techniques, there is only a small difference in responses.

Second, improved control of product variants is measured through ratings of reduction in product variants (item numbers), increased use of standard components, and improved product quality. Companies using a UML-based modelling technique claimed to be better able to reduce the number of product variants than companies not using UML-based modelling techniques, which may be related to an increased ability to document and gain access to product knowledge. Furthermore, the companies using UML-based modelling techniques rated higher with respect to benefits from increased use of standard parts and improved product quality. The findings in relation to improved control of product variants align with results from increased availability of knowledge, or the control of product variants increases as more formal modelling technique is used.

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6. Discussion

The literature emphasizes the need for formal modelling methods to structure and formalize knowledge in configurator projects (Aldanondo, Rougé, and Véron 2000; Forza and Salvador 2002a; Ardissono et al. 2003; Felfernig et al. 2004, 2014; Hvam 2006a; Stark 2007; Shafiee et al. 2017). However, the impact of utilizing modelling techniques in configurator projects remains relatively unaddressed. Studies addressing the impact of utilizing modelling techniques in configurator projects show that reduced time for development and maintenance, increased efficiency of product development, reuse of knowledge and better utilization of employees in configurator projects can be achieved (Stumptner, Friedrich, and Haselböck 1998; Chao and Chen 2001; McGuinness and Wright 1998; Yang et al. 2009; Shafiee et al. 2017). However, these studies are all based on case studies in which the impact of applying the method is compared with when a structured modelling technique was not used. In contrast, this study explores the impact of using different modelling techniques within 18 companies.

In this study, which examined three types of modelling techniques---UML-based, non-UML-based, and non-formal, the findings show that the importance of using more formalized modelling techniques increases when companies get larger and configurators' complexity (numbers of rules, attributes, and integrations) increases. In support of this, the findings show that UML-based modelling techniques are used at larger companies and in configurator projects in which the configurators include greater numbers of rules, attributes, and integrations. Furthermore, three of the six respondents from companies using UML-based modelling methods reported that they started to use them as the number of configurators and configurator projects grew and involved more people. This indicates that UML-based modelling techniques are required for larger companies to be successful in managing a setup with several configurators in operation with high complexity and numerous employees involved (often geographically dispersed).

The impact of applying the different modelling techniques is analyzed regarding improved availability of knowledge (Tiihonen et al., 1996; Slater, 1999) and improved control of product variants (Forza and Salvador 2002, Tenhiälä, and Ketokivi 2012), which are commonly reported benefits from configurators that can be linked directly to companies' capability to formalize and represent knowledge. The findings show that companies utilizing UML-based modelling techniques perform better concerning knowledge availability and control of product variants than the ones using non-UML-based and non-formal modelling methods. These findings indicate that by investing time in structuring knowledge by using formalized modelling methods, companies can gain additional benefits aside from configurator aspects. This especially applies to larger companies with more complex configurators. The ability to keep the number of product variants low is an important enabler for reducing complexity and thereby keeping costs down in companies (Hvam, Mortensen, and Riis 2008; Lindemann, Maurer, and Braun 2008).

7. Conclusion

This paper aimed to investigate the impact of using different modelling techniques to structure and formalize knowledge in configurator projects. The exploratory nature of the research aim means an exploratory survey with in-depth follow-up interviews is employed. The findings show that out of a sample of 18 companies, six used UML-based modelling techniques, six used non-UML-based modelling techniques, and the remaining six used non-formal modelling techniques. To represent UML-based modelling methods, the CPM procedure is used, in which both the PVM and class diagrams support a UML notation. Aligned with the study's focus on analyzing the actual impact of using different modelling techniques, this paper analyzed two propositions.

The first proposed that use of a UML-based modelling method would result in *increased availability of product knowledge in organizations*. This is measured through (1) improved documentation of knowledge and (2) improved availability of product knowledge. The results revealed that companies using a UML-based modelling technique scored the highest. However, there was only a small difference between those companies and the companies using non-UML-based modelling techniques. One explanation is that product knowledge is still documented in the latter group, even though the information model is not structured. Another factor influencing this finding is that the companies using non-UML-based modelling techniques have less-complex configurators concerning numbers of rules, attributes, and integrations, making the complexity more manageable.

The second proposition was that the use of a UML-based modelling technique would result in improved control of product variants. This is measured through (1) reduction of product variants (item numbers), (2) increased use of standard parts, and (3) improved quality of products. The companies using UML-based modelling techniques were more in control of their product knowledge and product variants than the companies using non-UML-based or non-formal modelling techniques. This may be partly due to an increased ability to involve domain experts in the modelling process, thereby ensuring that the right decisions are being made regarding which product variants to include in the configurators. Furthermore, a UML-based modelling technique makes it possible to keep track of product variants, features, and rules implemented in the configurators.

This paper contributes novel insights to the research community and practitioners by analyzing the impact of different modelling methods used in configurator projects based on the availability of product knowledge and control of product variants. Furthermore, the findings can be used to determine a sufficient level of documentation, e.g., at larger companies with complex configurators, more formal documentation is required, making UML-based techniques more desirable. Finally, the results presented in this paper can be used to guide further studies in this area of configurator research.

7.1 Limitations and further research

As this research is exploratory, the focus was on gathering in-depth information from companies, instead of having a large sample size that does not allow for the same in-depth information gathering. Thus, both survey and interview methods were used to ensure high-quality data. To be able to generalize from these findings based on a statistical analysis, a larger sample of companies is needed, providing an avenue for further research.

In this study, the CPM procedure is used to represent UML-based modelling techniques. The CPM procedure has been used by the authors' research team for more than 16 years and has proven its usability in different industrial settings. The main reason for selecting the CPM procedure is accessibility, as the authors had worked with some of the companies in the past. However, to avoid bias in the results, the respondents chosen had not, prior to this study, worked with the research team. Therefore, further studies should include an analysis of other modelling techniques.

The impact of using different modelling techniques is based on preserved benefits rated on a five-point scale, so they are based on the respondent's perspective. Additionally, approximate values are used to represent numbers of rules and attributes when exact numbers were not available. This is aligned with the exploratory nature of the study, which aimed to determine whether there are any relationships between the constructs, thereby providing guidelines for further studies (descriptive or explanatory surveys), not to prove their existence or the relationships between constructs. Therefore, further studies should include more objective measures to quantify the impact (e.g., percentages of variant reductions (item numbers), numbers of product modelling/coding errors, or corrections and product-modelling workloads).

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Appendix 1

Company ID	No. employees	Configuration team	Number of users	No. PCS	No. attributes	No. constraints	No. integrations ERP	No. integrations CRM	No. integrations CAD	No. integrations PLM	No. integrations calculations	Total integrations
Companies using UML based modelling techniques												
1	15,000	3	14	6	10,000	10,000	1	1	1	0	1	**4**
3	600	6	100	10	2,000	2,000	1	1	1	0	1	**4**
4	600	2.5	50	2	1,000	1,000	1	1	0	0	0	**2**
5	800	7.5	40	1	1,000	500	1	1	1	0	1	**4**
7	15,000	9	135	2	350	350	1	0	0	1	1	**3**
8	15,000	12	800	4	2,000	500	1	0	1	0	0	**2**
Average	**7,833**	**7**	**189**	**4.2**	**2,725**	**2,392**						**3.2**
Companies using non-UML based modelling techniques												
2	1,200	6	350	4	2,000	450	1	0	0	1	0	**2**
6	1,000	2	8	5	NA	NA	0	0	1	0	0	**1**
9	15,000	2	80	2	300	350	1	1	0	1	0	**3**
10	300	6	12	1	1,000	2,000	1	1	0	0	0	**2**
11	100	2	30	1	200	500	1	0	0	0	0	**1**
13	10,000	15	300	1	100	350	1	0	0	0	0	**1**
Average	**4,600**	**6**	**130**	**2.3**	**720**	**730**						**1.7**
Companies using non-formal modelling techniques												
12	500	8	50	2	2,000	1,000	1	0	0	0	0	**1**
14	500	4	80	1	500	500	1	0	0	0	0	**1**
15	20	0	3	1	NA	350	1	0	1	0	0	**2**
16	500	3	45	2	250	200	1	0	0	0	0	**1**
17	200	1	40	1	250	200	1	0	0	0	1	**2**
18	500	2	5	1	2,000	2,000	1	1	0	0	1	**3**
Average	**370**	**3**	**37**	**1.3**	**1,000**	**708**						**1.7**

Appendix 2

Company ID	Improved documentation of knowledge	Improved availability of product knowledge	Reduction of product variants (item numbers)	Increased use of standard parts	Improved quality of products
Companies using UML based modelling techniques					
1	5	4	3	4	NA
3	3	5	5	5	5
4	5	5	5	5	4
5	5	4	4	4	3
7	5	5	3	5	5
8	5	5	4	5	5
Average	**4.7**	**4.7**	**4.0**	**4.7**	**4.4**
Companies using non-UML based modelling techniques					
2	5	5	1	5	4
6	5	5	4	5	5
9	3	4	2	5	4
10	5	5	2	5	4
11	5	5	1	1	5
13	3	3	5	5	3
Average	**4.3**	**4.5**	**2.5**	**4.3**	**4.2**
Companies using non-formal modelling techniques					
12	3	3	4	4	3
14	4	3	1	4	3
15	5	5	1	5	5
16	3	4	3	3	4
17	3	4	3	4	3
18	4	4	1	4	5
Average	**3.7**	**3.8**	**2.2**	**4.0**	**3.8**