31st Annual INCOSE international symposium
Honolulu, HI, USA
July 17 - 22, 2021

Product portfolio mapping used to structure a mature sub-system with large variation – A case study

Arne Odin Sundet
University of South-Eastern Norway
aorsundet@outlook.com

Elisabet Syverud
University of South-Eastern Norway
Elisabet.Syverud@usn.no

Satyanarayana Kokkula
University of South-Eastern Norway
Satyanarayana.Kokkula@usn.no

Gerrit Muller
University of South-Eastern Norway
Gerrit.Muller@usn.no

Abstract. Managing mature products with high variability is an increasing concern for industrial companies. Product variability affects the operational streamlining efforts from product design to production, inventory, selling, and service. In this research, we follow a case where the company faces challenges in manufacturing cost and configuration of both existing and new variants. The purpose of this study is to investigate how product portfolio mapping can structure technical product data to ease the challenges. We analyzed more than 13,000 sales orders executed between 1997-2019 of a mature sub-system with large variability. We used Systems Architecting principles in combination with requirements from manufacturing and logistics to create a generic architecture that allows variability in the manufacturing flow. We added interface mapping, the manufacturing view, and the logistic view to enhance product portfolio analysis found in literature. We found significant improvements in both configuration time and the cost prediction accuracy. The company evaluated this research as an overall quality improvement that standardizes the workflow and remove existing bottlenecks.

Introduction

Domain and Company. EFD Induction is a worldwide organization specialized in induction heating processes for industrial applications. They position themselves in the market as a full-service provider covering all aspects of their product's lifecycle. Since 1996, EFD Induction has delivered more than 20,000 induction heating solutions across 13 industries reaching many applications. The company employs 1100 people in 22 countries. EFD Induction has sales and service companies, manufacturing plants, workshops, and product development centers globally. Their headquarter is in Skien, Norway. We conducted this research at EFD Induction Norway (ENO) that has facilities for manufacturing/assembly and product development located in Skien. ENO employs 150 people.

System of Interest. The research investigates product management conducted in Norway for a subsystem manufactured, assembled, and tested in India. Figure 1 shows EFD Induction's product portfolio, what market and industry the specific solution is targeted, and if it uses the investigated sub-system Hand-Held Transformer (HHT). We highlighted the base systems that are involved in this research, i.e., Minac and Sinac systems. The HHT is a step-down transformer that consists of a transformer, a water circuit, power cables, and mechanical parts for interfaces and shielding. The company uses 38 parameters to describe and configure the HHT in its current architecture. Since 1997, it has been developed more than 1000 variants of the HHT's in 4 standardized designs.

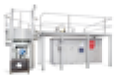
Product		Business segment	Industry	Investigated sub-system
	HardLine	Heat treatment machines for surface and through hardening	▲	✗
	Minac	Mobile induction heating equipment	▲ ■ ● — ▲ ■ ●	✓
	Sinac	Stationary induction heating systems	▲ ■ ● — ▲ ■ ● — ▲ ■	✓
	Weldac	High-output solid-state welders	■	✗
	HeatLine	Machines for melting and forging	▲	✗
	Brazing systems	Induction brazing, Auto, semi-auto and manual	■ ● ●	✓
	Seam normalizing systems	For advanced alloys and pipes	■	✗
	Induction straightening system Terrac	Deck and bulkhead straightening	■	✓

Figure 1 Product portfolio used to map sub-system segmentation

Problem Statement

ENO is experiencing uncertainty in product management of both the existing and newly developed HHT variants. The company designed the HHT to fit multiple needs using flexible and configurable parts that have resulted in large variability. The uncertainty is related to the sub-system overview and the understating of its cost drivers. ENO has investigated the case of this research through company processes and as an academic study to survey potential root causes (Sundet & Mansouri 2020). The company has identified the product data structure (Technically oriented data) as the main challenge due to the number of variants. ENO experience increased complexity in finding a solution as the product data is incomplete and lacks consistency. They are updating the product data as problems come by. However, they struggle to find a lasting solution that updates the full sub-system range with complete data within a reasonable time.

Research questions

We found two main challenges. Firstly, we want to find the root causes of the problem for the specific organization, which resulted in research question 1 (RQ1). Secondly, we are aiming to find a method to solve problems independent of the selected product, which resulted in research question 2 (RQ2). Our method inputs rely on RQ1 that is "As-Is" oriented. We use these inputs to answer RQ2 that is "To-Be" oriented. Research contribution to the Systems Engineering Body of Knowledge lies in product- and configuration management, while our contribution to the company lies in finding a solution for the specific case. We created sub-questions to address both contributions equally.

1. What causes unpredictable product cost and uncertainty in product development for the organization?
    a. What are the needs in the company for a solution that handles product variance?
2. How can Systems Engineering methods help to reduce the experienced uncertainty inside the organization?
    a. How can a product structure that follows architectural principles improve operational processes in the workflow?
    b. How can the product portfolio analysis help organizations to increase efficiency in managing product variability?

Literature

Recently, the company has focused on increasing the usage of systems engineering in various departments. Hence, this research focuses on systems engineering described in the Systems Engineering Body of Knowledge (SEBOK v.2.1 2019). One aspect of this study is to apply Product Systems Engineering and Systems Engineering Management from SEBOK to reverse engineer a specific product. The second aspect of this study is to look for similar projects executed in other domains and industries that deal with variability. We covered the second aspect by literature search for managing variability.

Managing Variants. The concept of product variability applies to products where the provider seeks to achieve economic benefits and increased customer value by fitting the product to personalized needs (Elmaraghy et al. 2013, Levandowski et al. 2013). Elmaraghy et al. 2013 discuss variety as a "number or collection of different things of a particular class of the same general kind." Elmaraghy states that increased variability increases expenses from product design to production, inventory, selling, and service. Levandowski et al. 2013 state that the costs are due to the complex processes of configuring products. One important cause of the complexity is traced to diffuse/tacit knowledge in the organizations (Levandowski et al. 2013, Ulonska & Welo 2014). Hence, revealing tacit knowledge is essential to supply personalized solutions at a competitive price. Elmaraghy et al. 2013 conclude that successful variety management must consider the product range, the product architectures, as well as manufacturing (Jiao & Tseng, 1999) and the supply chain (Nepal, Monplaisir & Famuyiwa 2012). Variety should not compromise cost, quality, or delivery if implemented successfully (Elmaraghy et al. 2013).

Architecting for variety. Architectures are essential concepts in designing, planning, and producing for variety as product variants evolve. Critical aspects for achieving operational efficiency in managing variants include principles as modularity (Anon, 2012), commonality (Jiao & Tseng, 1999), and differentiation (Elmaraghy et al. 2013). Architectures use these principles at various levels to increase efficiency. At a product level, architecting a product family or a product platform helps planning for variety (Elmaraghy et at. 2013). Product platforms are a means to reuse technology, parts, concept, or ideas (Levandowski et al. 2013). Product families are derived from the platform and are a group of products that are based on the same specified part of the platform (Levandowski et al. 2013). Configurable sub-systems enable product variety. Configurable sub-systems compose a product architecture based on input parameters from the design and the customers. Levandowski et al. 2013 use configurable components to fit a sub-system to a variety of contexts while still offering the same function. Several papers address the need for holistic thinking in planning for variety. The vast majority stresses the need to meet the in-house requirements of manufacturing, logistics, and product management (Elmaraghy et al. 2013, Levandowski et al. 2013, Ulonska & Welo 2014). Several authors created architectures on the higher abstraction levels to cope with variability. In many cases, such as Levandowsky et al. 2013, the reusability was in the higher abstract levels. In our situation, this functionality is indeed repeated. Hence, the abstraction levels are already reusable. In Ulonska & Welo 2014, we observed a similar problem with variability and management of these. We found the starting point and the desired goal of this research comparable with Ulonska's research.

Research methodology

This research is mixed-method research. The qualitative research involves open and prepared interviews and discussions with the company's domain experts. The quantitative research consists of analyzing the raw data stored in ENO databases that we use to evaluate the effectiveness or accuracy of our work. We had the engineering manager, industrialization manager, and product manager as key stakeholders who we updated regularly. Furthermore, experts from R&D, logistics, and manufacturing helped to obtain information about specific knowledge areas.

We started investigating the problem with open discussions with the key stakeholders. Then, we started understanding the problem with data gathered from both the databases and by performing open interviews of key personnel. We explored solutions using company-specific tools for Computer-Aided Design (CAD) and Product Data Management (PDM). We gathered data for optimization by assessing feedback from the key stakeholders that we used to adjust the solution. Finally, we evaluated the solution in two steps. Firstly, we compared the solution with the "As-Is" situation using the quantitative data. Secondly, we had the engineering manager and the industrialization manager evaluate the qualitative data. We evaluated qualitative data in a virtual meeting using predefined questions. The engineering manager and the industrialization manager answered the question as worse-neutral-better/disagree-neutral-agree with open comments.

Product Portfolio Analysis. Figure 2 represents the steps performed to analyze the product portfolio. We started with the analysis from Ulonska & Welo 2014 as a basis and modified it to fit our problem. We included stakeholders in advance of historical sales analysis to understand the problem. We used function-to-component mapping and interface management to structure the product. Furthermore, we added the manufacturing and logistic needs to the product structure.

Step 1 Stakeholder interview. We started by interviewing a representative person in Sales, Technical Sales, Project Management, Engineering, Logistics, Product Management, Manufacturing, Packaging, and Aftersales. This included the ENO departments as well as the supplier's manufacturing planning team in India. We aimed to capture the holistic view with the needs of the involved processes in the sub-system lifecycle. This was important to get a deeper understanding of the contributions from each process in the organization. We used the different perspectives to gain a deeper understanding of the technology and the operational challenges. We found that the product data and its structure connected the departments. We plotted the obtained information in a general workflow used to detect the root causes. After this step, we had an overview of the root causes and the key personnel involved.

Step 2 Analyze historical data. We analyzed the historical sales data to understand the existing variability. We analyzed 13,000 sales executed between 1997-2019 using Python Scripting. The company had lost the overview of the variants that had resulted in several personal documents. These documents existed locally on individual computers consisting of outdated information. We used this historical data, along with interviewing the experts, to separate obsolete or withdrawn sub-system variants from those still in use in the company. Hence, we managed to narrow the scope when mapping the existing variability.

Step 3 Interview experts. Step 2 provided us with an overview of the current variants still used in the company. The company experts guided us through the decision factors for making a new variant and what systems they are compatible with. Furthermore, they provided an in-depth explanation of the technology and the involved processes and engineering efforts. We used this information to understand the decision factors for developing new variants.

Step 4 Structure product data. We used principles from Systems Architecture in terms of function-to-part allocation, decision-to-design allocation, and interface mapping to understand the structural composition in realizing the sub-system. Furthermore, we aligned the structure with needs from manufacturing and logistics. We learned in step 1 that interface mapping, manufacturing, and logistics were necessary for our work. Therefore, we added them to the Ulonska & Welo's method to fit our specific problem. Along with the product segmentation and the in-depth understanding given by the experts, we aimed to standardize the processes in the workflow to increase product information consistency. We learned that consistency is essential when dealing with large variability as information about the product must be understandable and available for all stakeholders. By standardizing the workflow, we think the quality and efficiency increases in the long-term.

Step 5 Present and discuss. We iterated along the way and had continuous feedback from the domain experts. In the final stages, we presented the work to the key stakeholders with the potential "To-Be" scenario. We iterated back to step 4 if the solution did not meet the needs during the presentation discussions.

Step 6 Adjust product data. Finally, we had an initial solution that presented the needed work required for the company to address their needs. We evaluated the solution by comparing the "As-Is" with the "To-Be" using a selected population of the sales volume. More specifically, the range of one standardized HHT design.

Case

Background. ENO has challenges in the overview of existing sub-system variants and its cost drivers. Stakeholders involved in bringing the sub-system to the customer have diverse sources of information available. The stakeholders make decisions based on that information, which leads to misunderstandings and confusion in manufacturing. We found the product data documented in two separate databases, where the engineering department uses one database, while the other is the common platform for product data management (PDM). ENO has started a project to transfer the data from the engineering database to PDM to make information available to all parties. However, the engineering database has data for 13,000 sales orders, and the company requires 3D and 2D documentation of all variants before withdrawing the database. Furthermore, the new product data structure needs to facilitate the overview of the sub-system and, more importantly, its cost drivers. Hence, they are looking for a solution that can do the transformation to the new database within a reasonable time while meeting those needs.

We used a test scenario of one standardized HHT design as a representative population of the sub-system variants. The research focuses on developing a solution to transfer the data using the PDM and CAD systems in the company on the test population. ENO desire to have a clear overview of the existing variants and their cost drivers along with standardized processes for new variants when the data is transferred.

Current Situation. We conducted informal interview sessions with representatives from all in-house departments (see step 1) at ENO as well as the sub-supplier in India. We conducted informal interviews to understand individual involvement and current operational challenges. We highlighted the sub-processes the company wanted to improve, displayed with colors in Figure 3. This resulted in three main stakeholders; (i) Procurement – responsible for ordering the sub-system and manage logistical issues, (ii) Product Manager – responsible for the sub-system's technical documentation, and (iii) Sub-supplier – responsible for manufacturing, assembly, and test.

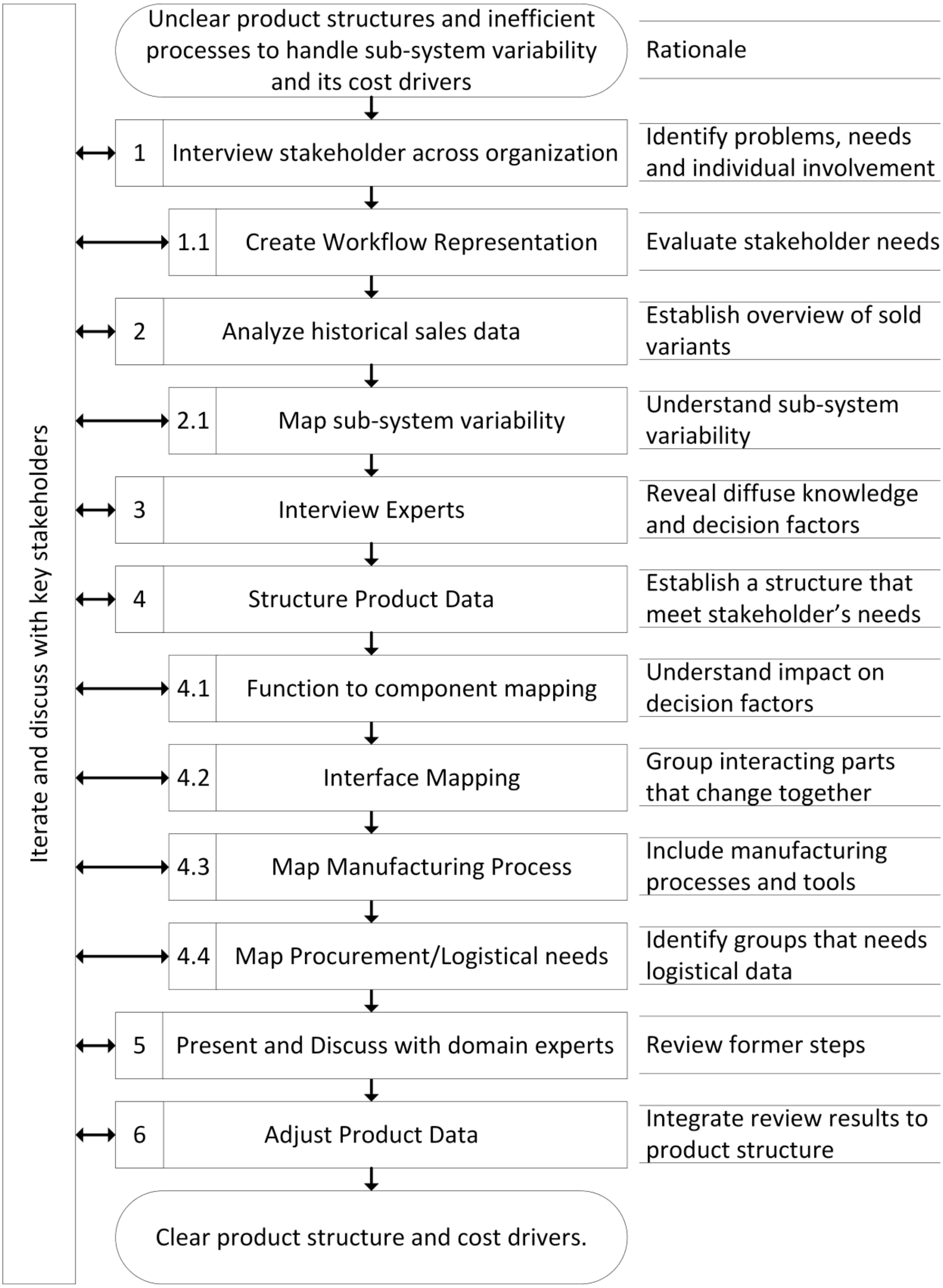


Figure 2 Description of the method used for product portfolio analysis

We analyzed historical sales data and quality reports, revealing cases with duplicated design efforts. We matched the product data from both PDM and the engineering databases and found mismatching properties. A few of these mismatched cases were reported as quality disturbances. The quality reports stated a mismatch between the requested product configuration and the delivered configuration. Further analysis revealed that manufacturing had two sets of mismatching requirements for producing the sub-system. One requirement had its origin from the engineering database, while the other had its origin from the PDM database. The sub-supplier stated that this was often the case and that their policy was to produce using the information in the purchase order that has its origin from PDM. However, the 2D drawings where manually shipped through mail to the supplier on request. Hence, the supplier did not achieve the technical 2D drawings for a specific variant. Today's solution involved a specification sheet with origin from the engineering database. The supplier uses previously generated 2D drawings from similar variants as a template for manufacturing and the specification sheet for variant adjustments.

Next, we analyzed the logistic data with a focus on manufacturing costs gathered from ENO's Enterprise Resource Planning (ERP) system. The HHT cost varied ±100% of the averaged sum. However, ENO has challenges in finding the cost drivers as sub-assembly costs are not included.

Research findings

During the informal interviews, we found several personal documents related to the sub-system. Internal stakeholders had different information that leads to diffuse person-dependent knowledge. ENO uses a copy-paste-adjust method for fitting the sub-system to new utilities. This increases the diffuse knowledge as new documentation is dependent on the person who created it in the past. We found the PDM product data to be inconsistent without a clear sub-system architecture that is necessary to understand the structural composition in sub-system variants. We found a need for a generic product structure (GPS), standardized at an abstract level, while the details remain configurable. The GPS had to facilitate a top-down work method to reuse modules and fabricated parts without the copy-paste method. Finally, we had to implement the GPS to supply the same information to all stakeholders.

Need analysis: Organizational layers affected by available information

We evaluated the workflow with key personnel from the company. Our results found that one challenge with the variability was the quality of documentation. ENO has information held by an employee that might be important to share between the departments. Interviewed personnel stressed that the challenges in the overview were a result of inconsistent/missing information between the variants. Hence, the stakeholders directed our attention to the impact of the product data and the related logistics data. We found three main stakeholders that use the information that challenges the overview. Table 1 shows the main stakeholders and the connection between the data. The data affected three layers of operational efforts; Configuration management, Product Logistics, and Manufacturing, represented by Product Manager, Procurement, and Supplier, respectively. We describe the stakeholder needs in the following subsections.

Procurement and product logistics. We observed a need to streamline the process of price negotiations with the sub-supplier in the procurement phase. The collaboration between these parties must be honest and fair to develop a process that requires minimum efforts from both sides. The process must be dynamic to address yearly changes in raw material cost and the like. Furthermore, we observed logistical needs for ordering and shipping sub-components in the product structure. This requires ENO to have logistical data in addition to product data on these components.

Product Manager and configuration. The product manager uses the product architecture to create new configurations of the sub-system. The product manager needs an overview of the product variability to reduce duplicated design efforts when aiding future projects. The product manager uses the product architecture to develop Bill-Of-Material (BOM) and technical 3D models with coherent 2D manufacturing drawings. We found a need to establish an architectural format in terms of product data development to achieve consistency. The company's 2D drawings must follow the architecture to achieve consistency used to display commonalities and differentiation in manufacturing planning. Furthermore, ENO needs standardized item attributes to search for existing variants in PDM.

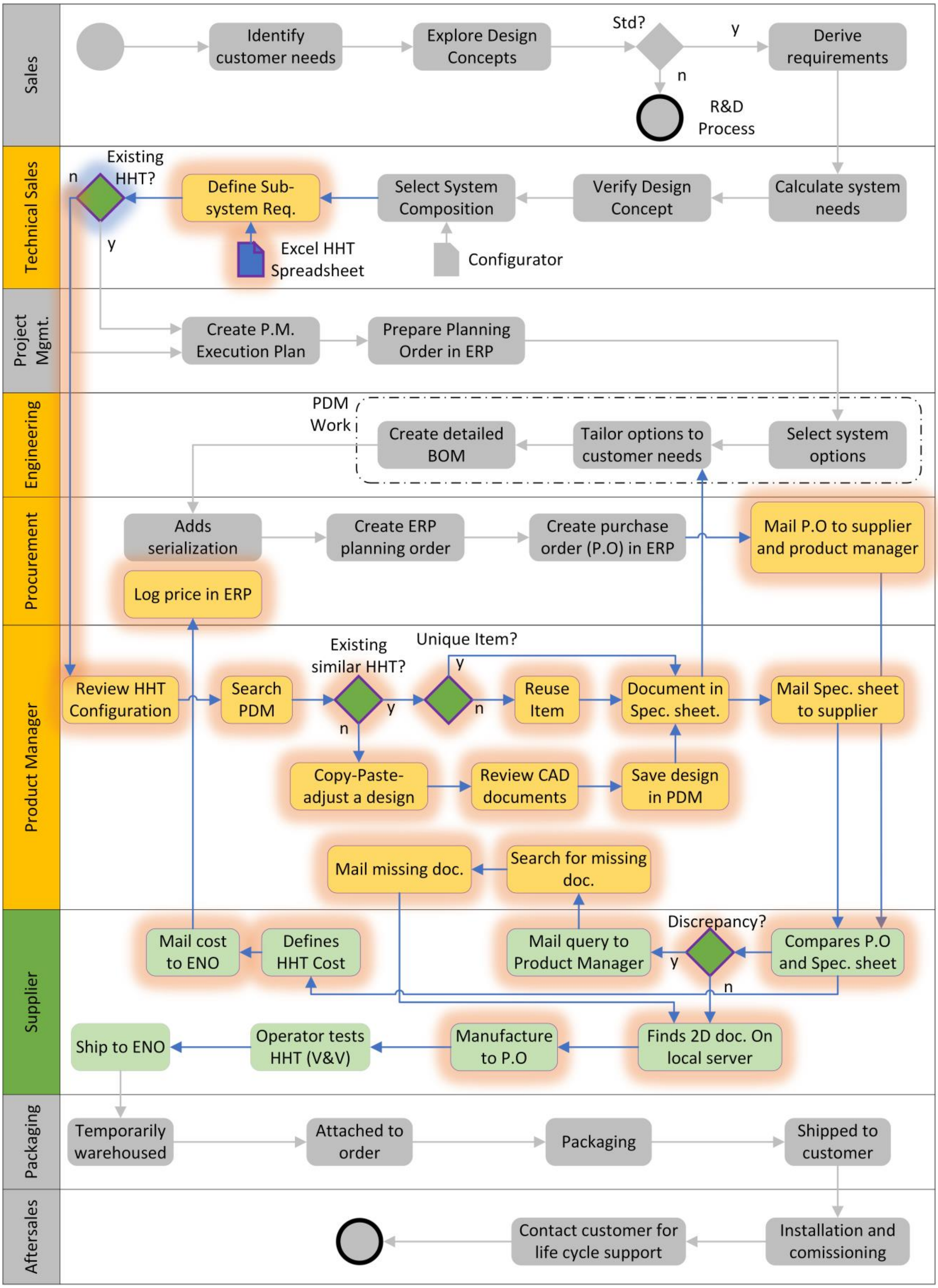


Figure 3 Workflow as a result of interviewing stakeholders and sub-supplier. Unchanged processes and swim lanes are grayed out.

Table 1 Data relation to main stakeholders

		Product Manager	Procurement	Supplier
Product Data	Product Architecture	x		
	BOM	x		x
	2D/3D documents	x		x
	Item attributes	x	x	
Logistics Data	Cost structure		x	x

Supplier and manufacturing. The company needs to cope with the variability and still stay competitive in delivery times and pricing. Planning manufacturing for variability is an important task to achieve that. The supplier can plan manufacturing based on either the 2D drawings + BOM or the entire product data depending on their relationship. Our observations revealed that taking advantage of commonalities and differentiation is essential to successfully plan manufacturing with variability. The product data needs to have consistency to achieve that overview. The supplier can then evaluate the shared elements in the sub-system to increase manufacturing efficiency.

Results

Developing a generic product structure

We used the product portfolio in Figure 1 for the sub-system product segmentation. The Sinac range is distributed in small "S," medium "M," and Large "L" systems. The selected HHT range constraints the configuration due to the sizing of mechanical parts and the requirement for the water circuit. We used this as a first grouping of the sub-system. Later, we used tools from Systems Architecture (Function to part allocation, Interface mapping, manufacturing, and Logistics mapping) to group the sub-assemblies and structure the fabricated parts. Figure 4 represents how we arranged the variability and the proposed GPS.

Function to part allocation. We found the sub-system to have three functions (f1, f2, f3). We used this information to group parts that are necessary for the function to work (P1, P2, P3, etc.). Experts provided information about the parameters and decision factors used to determine the magnitude of the functions. Hence, we had a structure that could reuse sub-assemblies based on the sub-system requirements.

Interface Mapping. We mapped the interfaces to evaluate the relationship between the parts and the functions, i.e., changing the function would change these parts through those interfaces. We used this information to separate sub-assemblies in the structure that targeted the specific function (SA1, SA2, SA3, etc.). The interface mapping helped to achieve alternative sub-assembly configurations that allow variability.

Manufacturing process mapping. The sub-supplier manufacture in one location. However, ENO's manufacturing facility is separated depending on the executed work. Hence, we had to include manufacturing steps depending on the used tools and processes (left side of Figure 4). We divided the manufacturing process into the following steps:

- **Machining:** All work related to turning, milling, cutting, drilling, etc.
- **Hot Work:** All work related to brazing, soldering, etc.

- **Basic Assembly:** All work where no special training is needed. Typical mounting.
- **Final Assembly:** Specially trained operators for the specific sub-system final assembly.

Logistics and procurement mapping. ENO needs to order a sub-assembly of the mechanical parts from the supplier. Meaning the GPS needs to treat the mechanical parts as a group (Mech. Parts Collected) to add to the logistics data (Logistics sub-assembly).

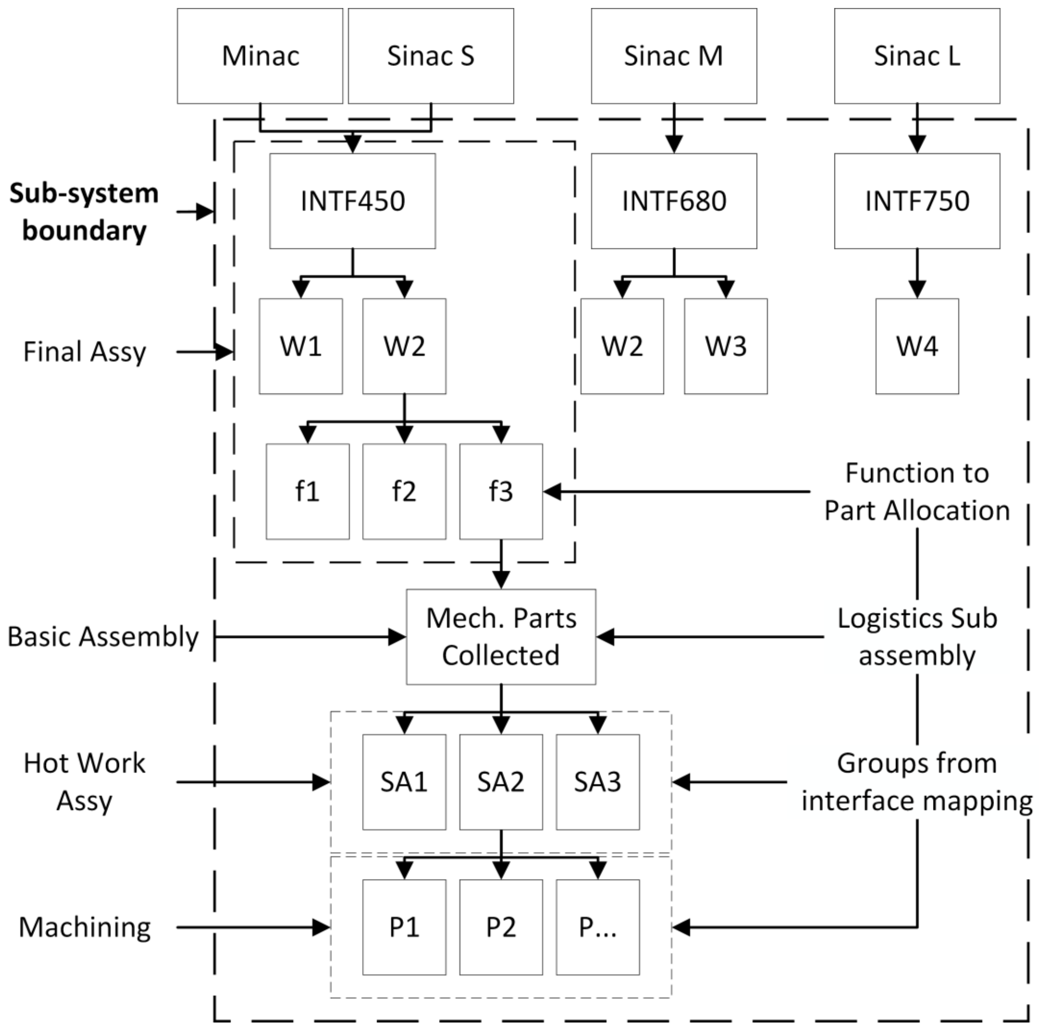


Figure 4 The proposed generic product structure as an abstract decomposition of the HHT. The names are specific for the sub-system, not the study. (INTF = interface, w = water circuit, f = function, SA = sub assembly, P = part)

Developing the initial cost model

The procurement team desired a cost model to estimate an HHT cost based on structural composition. The cost model had to follow the product structure and serve as an uncomplicated way to see the overview. Figure 5 represents the basic elements of the cost model. We used the generic product structure as the architecture for developing the cost model. ENO's ERP database holds all costs related to purchased parts and top-level items. We used the information from the historical sales analysis to store all variants of our selected variant population within the GPS. Then, we used the ERP data to connect parts and pricing.

We grouped costs using averaged costs, selected unit cost, and standardization to one unit to avoid creating a complex cost calculator. The selected unit cost involved parts that varied with two or more parameters; we chose one parameter to represent the cost of these parts. Due to incomplete ERP data for selected parts, we had to standardize the cost of one component. Meaning we chose one that represented all variants for that specific part. The discrepancy presented in Figure 5 is the selected cost value divided by the largest cost unit in one part variability. We estimated the cost model to be ±15% accurate on the top-level item due to the discrepancies and our evaluation of the cost data quality. We created the cost calculator using an Excel spreadsheet representation such that the information was available to all departments through PDM. The input from the experts was useful to make the spreadsheet dynamic depending on the decision factors. Hence, the personnel use only the decision factors to estimate the cost. Furthermore, we created the cost calculator to display the top-level item attributes that would help employees searching for the given configuration in the PDM system.

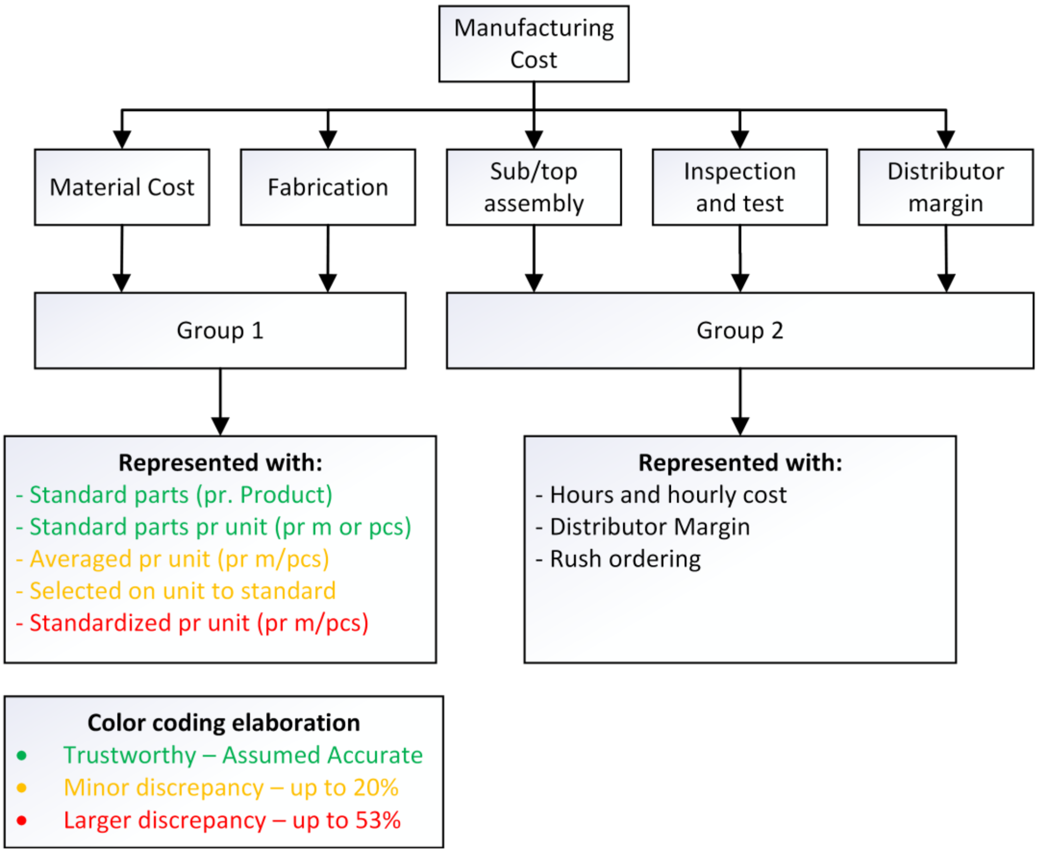


Figure 5 Elements of the cost model and their maximum discrepancy

Standardizing workflow processes: The "To-Be" scenario

Figure 6 represents the new "To-Be" scenario with the highlighted changes expressed with colors. We found two especially interesting processes that our work could affect. The first process is the configuration of new variants. The second process in the cost negotiation between ENO and the sub-supplier. Furthermore, our work could affect data availability across the organization for search-and-find purposes.

Sub-system configuration involves creating the 3D models, 2D drawings, BOM, and item attributes. In the past, the product manager used a copy-paste-adjust method that we wanted to change. We developed 3D models using parametrized CAD design for sub-assemblies and family tables for fabricated parts. The 3D models have associated parametrized 2D drawings. For every new variant, the product manager can use the GPS for loading the sub-assemblies, and the fabricated parts in the model to ensure consistency independent of a variant. The product data attributes attached in PDM must follow the same structure.

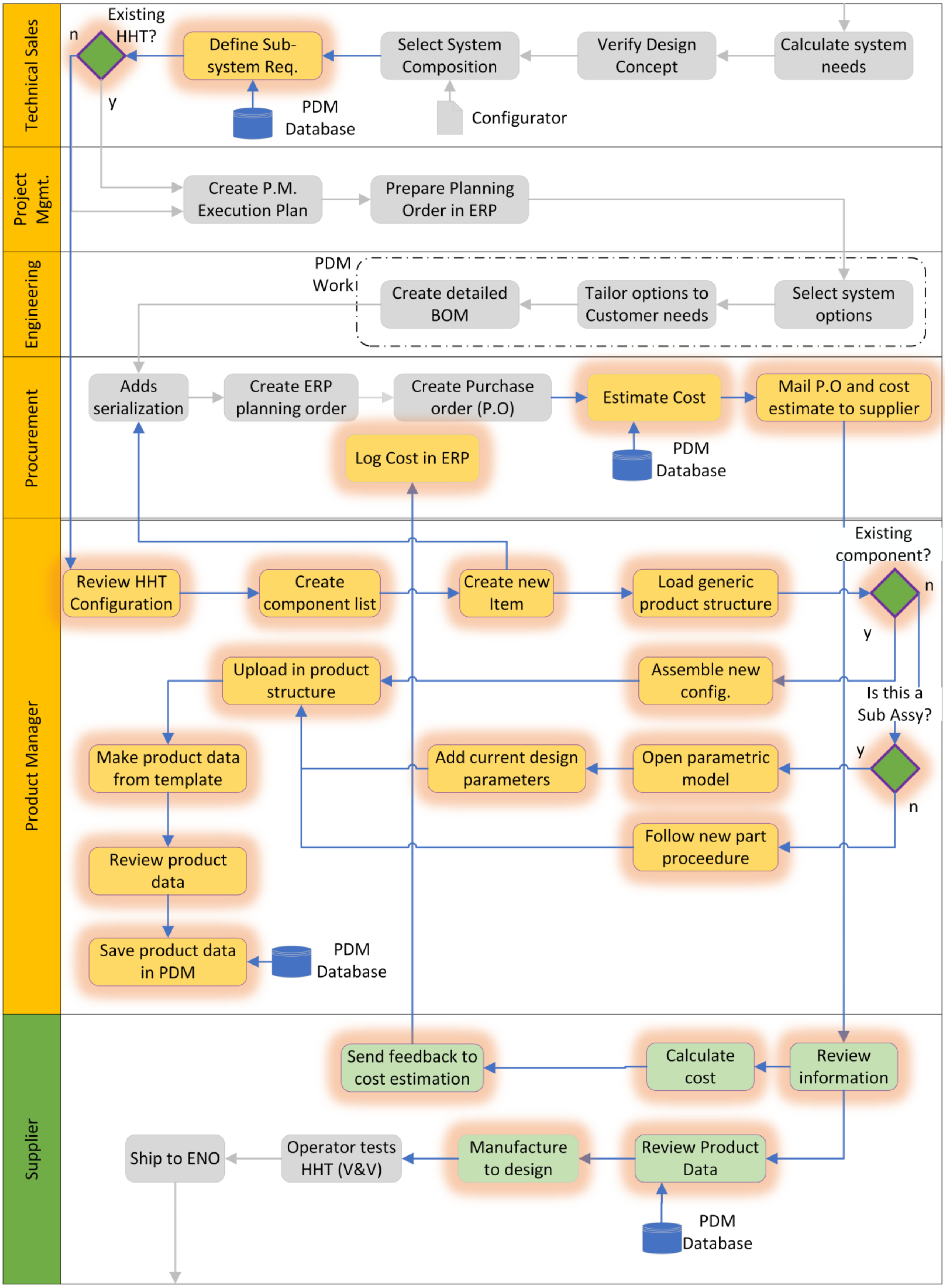


Figure 6 Proposed "To-Be" Workflow. Processes that are unchanged is grayed out and unchanged swim lanes removed.

Cost estimation in PDM can be done when the cost calculator is released. The procurement team will then be able to estimate the cost of a new variant and provide the result to the sub-supplier. The sub-supplier will review the cost and send feedback to the procurement team. The company use the feedback to adjust the cost calculator. Over time, the intention is a cost calculator that satisfies both the company and the sub-supplier. This will help both parties to standardize the cost process. The prospect is that the company and the supplier can negotiate the model that represents all variants instead of negotiating the cost on a project-to-project basis.

Evaluation

Configuration time. For the entire HHT400 series (our selected population), it would require 58 hours with one resource to transfer the old data using the new product structure. We used 29 minutes to move an HHT400 variant to the PDM system using the "To-Be" workflow, see Figure 6. We estimated to spend 12 minutes of those 29 minutes to find the old item, resulting in 16 minutes to configure a new variant of the standard design with complete product data.

Cost estimation accuracy. We tested the cost calculator by comparing the estimated cost versus the already logged ERP cost. In the worst-case scenario, the cost calculator accuracy was +48% and –40%. When we evaluated the sales volume over the past three years, the cost calculator performed a ±10% discrepancy on 65% of the sales volume, the total result can be seen in Figure 7. We found five components that made 80% of the sub-system cost. These were repeatable independent on variant, but their impact on the total cost depended on the HHT length.

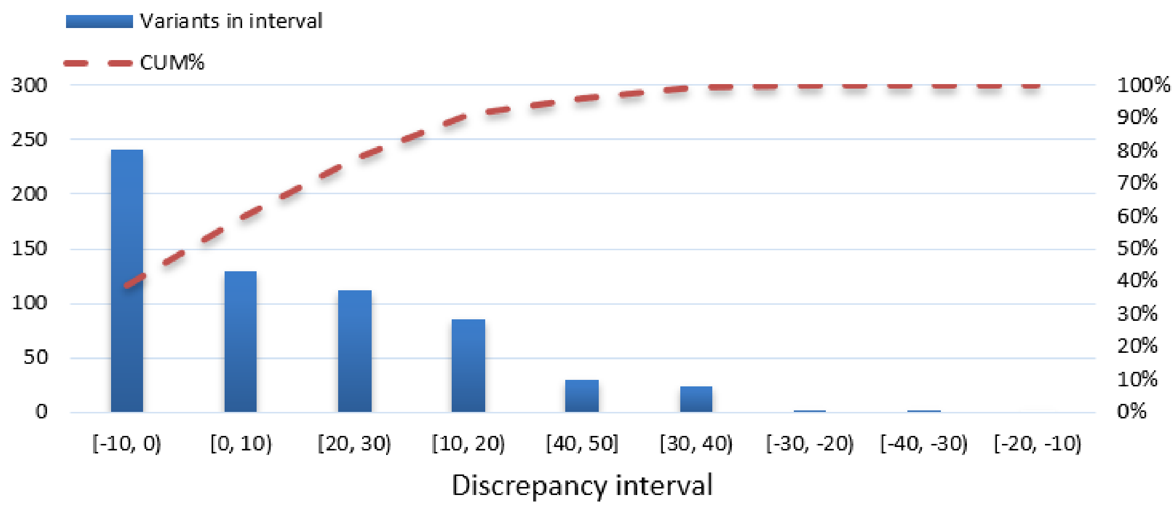


Figure 7 Pareto chart. Cost calculator results on 3y sold HHT400 items presenting the discrepancy between the estimated cost and the logged ERP cost.

Evaluation of proposed workflow. We had the Engineering Manager (EM) and the Industrialization Manager (IM) as stakeholders to evaluate the proposed solution. We gave them predefined questions one week in advance of the evaluation. The stakeholders had answered the questions in advance of the meeting by putting their role initials (EM/IM) in the worse-neutral-better (-, =, +) scorecard. We arranged a virtual meeting for the evaluation. The stakeholders gave their assessment beginning with discussing the predefined questions, the problem statement, and the research questions. Then, we discussed their answers going through the questions one by one in detail.

Discussion

This research used product portfolio mapping to restructure a sub-system's product data. We added interface mapping, the manufacturing view, and the logistic view to a product portfolio analysis from a similar study conducted in 2014. The company evaluated our work as an overall improvement. However, to confirm our findings it requires further studies in similar industries. We collected and evaluated the data as objective as possible. However, it can still hold biases, especially due to the number of evaluators. Nevertheless, we found results that point in a positive direction. We recommend the reader to evaluate Ulonska & Welo 2014 before executing similar projects.

Table 2 presents the evaluation results of the proposed solution, while Table 3 presents the proposed product portfolio analysis.

Table 2 Evaluation of the company solution using their PDM, CAD and ERP systems

	Does the proposed solution…	-	=	+	Comment
1	… ease the overall uncertainty in product variability and cost?			EM IM	Yes. We are unsure about the ERP cost quality, and if all variants are included.
2	… fit the needs in manufacturing?			EM IM	It seems better. We need to involve the supplier to evaluate To-Be efficiency.
3	… increase efficiency in product configuration			EM IM	“As-Is spec.sheet” is faster but is done for all sales. Overall, To-Be it is better.
4	… increase data quality and consistency?			EM IM	Yes. Operational efficiency will likely increase.
5	…update existing documentation effectively?			EM IM	Time usage can increase for more complex HHT's.
6	… meet the needs for estimating product cost?			EM IM	The calculator works, see question 1

Table 3 Evaluation of the proposed product portfolio analysis

	Does the proposed method…	-	=	+	Comment
1	… involve the necessary steps?			EM IM	Yes. The steps gave valuable information.
2	… involve some unnecessary steps?	EM	IM		It depends on the technique used, effort, and output quality.
3	… meets the effectiveness in time usage for the company?			EM IM	It depends on the technique. It must be a cost-quality ratio with a result of increased quality.
4	… generalize to apply for other products/sub-systems?	EM		IM	Works on existing mature variation but will not work for planning new constructions.
5	… result in revealing tacit/diffuse knowledge?			EM IM	The employees will trust the documentation instead of tacit comments and understanding.

What causes unpredictable product cost and uncertainty in product development for the organization? Following the literature search, we found that increased variability affected operational efforts from product design to production, inventory, selling, and service. The company used the product data to share information between the departments. We found it challenging to obtain an overview of the variants due to inconsistency in the product data structure. Company stakeholders had created personal documents to keep track of the variability. However, none of these documents included all the information nor all the variants. Our observations found the personal documents and the inadequate quality of the product data to increase tacit knowledge that affected operational efficiency in both cost predictions and product development efforts.

What are the needs in the company for a solution that handles product variance? Our observations revealed the need to standardize the product data in the enabling systems (ERP and PDM). We discovered that standardizing the product data could result in standardized processes that increase documentation quality and availability. In our evaluation, we found that the employees must trust the product data to decrease tacit knowledge and remove personal documents. To include all necessary information in the product data, we had to consider the product range, the architectures, manufacturing, and the supply chain, including the enabling systems. We argue that this is important to manage variability without compromising cost, quality, or delivery.

How can Systems Engineering methods help to reduce the experienced uncertainty inside the organization? Following the literature, we found a need to think holistically when coping with variability as it affects several operational efforts. We had to structure a mature sub-system with high variability. For that, we choose Systems Architecture tools to explore solutions. However, we argue that the thinking and logic behind our work (Step 1 – Step 6) is more important than the selected tools itself. We experienced SE to facilitate holistic thinking that captured the stakeholders and their interests. Systems Architecture tools helped us concretize these needs to design a solution.

How can a product structure that follows architectural principles improve operational processes in the workflow? Literature emphasizes architectures are essential in planning for variability. We found the function-to-part allocation as an efficient way to group parts on the functional level, and more importantly, we found the similarities between the variants based on the functional requirements. Along with the interface mapping, we had an overview of how the sub-systems physical architecture changed based on the functional architecture. We included manufacturing and logistics in our planning as the company stressed its vital role in operational efficiency. In our evaluation, the key stakeholders found these tools efficient with adequate quality output. However, the inputs came from steps 1-3, where we found the efficiency dependent on the technique used.

How can product portfolio analysis help organizations to increase efficiency in managing product variability? This research focused on restructuring product variants by assessing them against each other and the operational efforts within the company. Primarily, we evaluated the study to target existing products with high variability and not new product development. We need to test the findings in other domains/systems to assess if the generalization can help other organizations. We recognized that our analysis requires a problem that has a potential gain in the cost-quality ratio. Therefore, we argue that it is necessary to discuss the quality-cost ratio before starting the analysis and recommend new evaluation after step 1. We urge others to plan and clarify the techniques used in each step to understand the needed effort for such work.

Conclusion

This research analyzed 13,000 sales orders to investigate a mature sub-system range with large variability. We used product portfolio analysis and tested our results on a population of the sub-system range utilizing the company's enabling systems (ERP, PDM, CAD). We performed sub-system-to-product segmentation, function-to-part allocation, interface mapping, manufacturing mapping, and logistics mapping to develop a generic product structure that allows variability. We found mismatching manufacturing requirements, duplicated design efforts, inadequate documentation quality, and large cost variations (±100%) as main factors for the experienced challenges. Furthermore, we found personal documents that increased the level of tacit knowledge. We used the GPS as an architecture to standardize the configuration workflow in the company. We used 29 minutes to move old data from the engineering database to PDM and 16 minutes to configure a new one in PDM. We estimated 58 hours to move the entire HHT400 series to PDM, which means the company can withdraw the engineering database in the future. This will improve the consistency and quality of the product data in the long term. We developed a cost calculator to simplify the workflow in procurement by negotiating all variants compared to project-to-project based. The cost calculator is dynamic and dependent on the decision factors in design. Firstly, the cost calculator estimates variation cost and presents a Pareto chart with its cost drivers. Secondly, the cost calculator gives the item attributes on a standardized form for search and find purposes in PDM. We observed that the cost calculator to be ±10% accurate on 65% of the sales volume, comparing the estimated cost with the already logged ERP costs. We found five components made 80% of the cost for all variants. The company evaluated the

"To-Be" as an overall improvement that reduces the experienced uncertainty both in cost predictions and product management.

This paper presents a modified product portfolio analysis. Our modifications include interface mapping, the manufacturing view, and the logistical view that are essential to create product data in handling variability. We found it necessary to evaluate the cost-quality potential before the investigation starts and after step 1. The study identifies the need for these decision factors, so the people executing the work, and the company have realistic output expectations. We conclude our analysis as a good fit for a mature product with large variability and not for new product development. Furthermore, we conclude that it is necessary to understand the organizational workflow, the technology, and the constraints in the enabling systems to restructure the mature systems with high variability.

Future research

This paper suggests and applied additions to a product portfolio analysis found in Ulonska & Welo (2014). Our findings require further research to confirm if they are applicable in other similar industries and companies. We managed to apply the solution using a population of the sales volume but not to cover the full implementation. The researchers recommend future research to investigate the implementation phase of similar work. We found many loose ends discussing the implementation phase with the company. Mainly we discussed the risk of withdrawing the "As-Is" documentation and the risks connected to changing the company workflow. We recommend researching how to execute the implementation phase with a focus on risk measures. Furthermore, we recommend research on how to select the proper technique for each step as we found it dependent on the information available and the company size.

Acknowledgments

We thank the company for all their support in aiding this research. We especially thank the ENO’s industrialization manager, engineering manager, and product manager as well as the sub-supplier for the valuable input and support throughout this work.

References

Elmaraghy, H et al., 2013. Product variety management. CIRP Annals - Manufacturing Technology, 62(2), pp.629–652.

Levandowski, C.E. et al., 2013. An integrated approach to technology platform and product platform development. Concurrent Engineering, 21(1), pp.65–83.

Ulonska, S. & Welo, T., 2014. Product portfolio map: a visual tool for supporting product variant discovery and structuring. Advances in manufacturing, 2(2), pp.179–191.

Anon, 2012. Abstracts from the Society for Clinical Trials Annual Meeting, Miami, May 21-23, 2012. Clinical Trials, 9(4), pp.450–554.

Jiao, J. & Tseng, M., 1999. A methodology of developing product family architecture for mass customization. Journal of Intelligent Manufacturing, 10(1), pp.3–20.

Nepal, B., Monplaisir, L. & Famuyiwa, O., 2012. Matching product architecture with supply chain design. European Journal of Operational Research, 216(2), pp.312–325.

Sundet, A.O. & Mansouri, M., 2020. Systems thinking applied to find underlying problem in enterprise management of induction heating transformers. INCOSE International Symposium, 30(1), pp.1657–1669.

SEBoK Editorial Board. 2019. The Guide to the Systems Engineering Body of Knowledge (SEBoK), v. 2.1, R.J. Cloutier (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed February 10, 2020. www.sebokwiki.org. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Computer Society.

Biography

Arne Odin Sundet received in 2014 a certificate of craftsmanship in welding working 2 years for the offshore construction industry. In 2017 he graduated from the University of South-Eastern Norway in Porsgrunn with a B.E in Mechanical Engineering. From fall 2017, he has worked in EFD Induction Norway as an industrialization engineer while taking his MSc in Systems Engineering at the University of South-Eastern Norway Kongsberg. He received his MSc in the spring 2020 and continued working as a design optimization engineer for EFD Induction Norway until 2021. He is currently working with data insights using machine learning as a jr. Functional Developer at Grasp Labs, Skien.

Gerrit Muller, originally from the Netherlands, received his master's degree in physics from the University of Amsterdam in 1979. He worked from 1980 until 1997 at Philips Medical Systems as a system architect, followed by two years at ASML as manager systems engineering, returning to Philips (Research) in 1999. Since 2003, he has worked as a senior research fellow at the Embedded Systems Institute in Eindhoven, focusing on developing system architecture methods and the education of new system architects, receiving his doctorate in 2004. In January 2008, he became a full professor of systems engineering at University of South-Eastern Norway in Kongsberg (USN), Norway. He continues to work as a senior research fellow at the Embedded Systems Innovations by TNO in Eindhoven in a part-time position. Since 2020, he is INCOSE fellow and Excellent Educator at USN.

Satyanarayana Kokkula. received his Master's degree in Applied Mechanics from IIT Delhi (Indian Institute of Technology, Delhi) in 2000. He worked for one year as an Assistant Systems Engineer at TATA Consultancy Services, India. In 2005, he received his PhD from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. After finishing PhD, he joined FMC Kongsberg Subsea AS as a Specialist Engineer in Structural Analysis from 2006 to 2016. At present, he works as an Associate Professor of Systems Engineering at the University of South-Eastern Norway.

Dr. Kokkula is a Certified Systems Engineering Professional (CSEP) by the International Council on Systems Engineering, and a Senior Member of the Institute of Electrical and Electronics Engineers.

Elisabet Syverud received her MSc in Aerospace Engineering from the University of Kansas, US, and her Dr.Ing in Thermal Energy from the Norwegian University of Science and Technology in Trondheim, Norway. She started her industrial career in 1993, and has worked in multiple roles in the oil&gas and defense industries for almost 20 years. Since 2019, she is Associate Professor of Systems Engineering at University of South-Eastern Norway in Kongsberg, Norway.