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Degree Programme in Mechatronic System Design

Milla Vehviläinen

3D MODELING OF A LARGE ELECTRIC MACHINE FOR SALES PURPOSES

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Examiners: Professor Aki Mikkola
D. Sc. (Tech.) Kimmo Kerkkänen

TIIVISTELMÄ

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Tässä diplomityössä selvitetään, mikä olisi paras ABB:n nykyresursseilla toteutettavissa oleva tapa mallintaa yksinkertaistettuja myyntivaiheen 3D–malleja laivateollisuuden asiakkaille. Tutkielma tehtiin ABB:n yksikölle, joka suunnittelee ja valmistaa suuria sähkökoneita. Asiakkaat haluavat 3D–malleja usein jo myyntiprosessin alkupuolella, jotta he voivat integroida ne osaksi omia tilanjärjestelymallejaan. Toimittajat luonnollisesti haluavat toimittaa malleja helposti ja nopeasti.

Aluksi perehdyttiin ABB:n nykyisiin myyntivaiheen 3D–mallinnusmenetelmiin sekä siihen, mitä ominaisuuksia asiakkaat tuotemalleilta vaativat ja milloin he niitä tarvitsevat. Tämä tehtiin toteuttamalla 14 puolistrukturoitua haastattelua. Haastateltavana oli sekä ABB:n insinöörejä että asiakkaita laivateollisuudesta. Haastattelujen pohjalta suoritettiin temaattinen sisällönanalyysi, jotta saatiin selville, mikä nykyisistä menetelmistä vastaa parhaiten kriittisiksi koettuja tarpeita.

Todettiin, että nykyisissä olosuhteissa paras tapa tuottaa yksinkertaistettuja asiakasmalleja on tehdä ne detaljimallien pohjalta. Jos detaljimalli on 3D–mallinnettu, NX:n *Linked Exterior* –työkalua tulisi käyttää ensisijaisena ratkaisuna. Jos ainoastaan 2D–detaljimalli on saatavilla, suositellaan mallinnustyön ulkoistamista. Molemmissa tapauksissa 3D–asiakasmalli voidaan tarjota yhdessä työpäivässä.

Ehdotettu menetelmä ei kuitenkaan tyydytä kaikkia asiakastarpeita. Asiakkaat haluavat mahdollisimman kevyitä mallitiedostoja, joiden maksimikoon pitäisi olla selvästi nykyistä pienempi. Lisäksi huoltotilojen sisällyttämistä malleihin pidettiin tärkeänä. Vaikka tämä on toteutettavissa *Linked Exterior* –työkalulla, manuaalista lisätyötä vaaditaan sekä suunnittelijalta että asiakkaalta.

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
School of Energy Systems
Mechanical Engineering

Milla Vehviläinen

3D Modeling of a Large Electric Machine for Sales Purposes

Master's Thesis

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86 pages, 27 figures, 3 tables and 2 appendices

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D. Sc. (Tech.) Kimmo Kerkkänen

Keywords: 3D, spatial design, industrial layouts, conceptual modeling, marine, customer needs

In this master's thesis, I propose a best practice for providing reduced 3D models to marine customers at sales stage at ABB, a company designing and manufacturing large electric machines. Marine customers often request 3D models early in the sales process to integrate them into their own spatial layouts. The suppliers naturally want to be able to provide models easily and swiftly.

To examine what kind of product models customers want and when, and to map ABB's current sales phase 3D modeling practices, I conducted 14 semi–structured interviews. There were both ABB engineers and marine customers among the interviewees. Using these interviews, I exploited thematic content analysis to find out which of the current methods suit for the needs considered critical.

I find that the best practice is to extract the reduced customer model from detailed product designs. If the detail design is 3D modeled, NX tool *Linked Exterior* should be the primary solution. If, however, only a 2D detailed model is available, I recommend outsourcing. In both cases, a 3D customer model can be provided within one workday.

The best practice, however, does not satisfy all customer needs. Customers desire as light model files as possible, and the maximum file size should be much lower than it currently is. Moreover, the inclusion of maintenance and service spaces in the models was widely requested. Although that can be done using *Linked Exterior* tool, manual extra work from both ABB designers and customers is needed.

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Milla Vehviläinen

Milla Vehviläinen
Vantaa, 24.05.2020

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LIST OF ABBREVIATIONS

2D	two–dimensional
3D	three–dimensional
ANSYS	analysis of system, an engineering simulation software
BIM	building information modeling
BOM	bill of materials
CAD	computer aided design
FEA	finite element analysis
FEM	finite element method
FLP	facility layout problem
GT	gross tonnage, a measure of overall internal volume of a ship
GTSS	Global Technical Sales Support, ABB's sales support department
HV	high voltage
IGES	initial graphics exchange specification, a neutral 3D CAD file format
MCCU	Multiphysics Cascaded Computing Unit, ABB's internal online tool for dynamic calculations of electric machines
PDM	product data management
PDQ	product data quality
QIF	quality information framework, a neutral 3D CAD file format
STEP	standard for the exchange of product model data, a neutral 3D CAD file format
STL	stereo lithography, a neutral 3D CAD file format
VBA	visual basic for applications, a programming language developed by Microsoft

1 INTRODUCTION

This master's thesis examines what kind of solution satisfies marine customers when offering them reduced three–dimensional (3D) models during a quotation order using conceptual computer aided design (CAD) techniques. The study is conducted in collaboration with the Motors and Generators unit in ABB Oy.

1.1 Background and Motivation

Spatial layout of facilities plays a significant role in marine industry. Facility equipment are ordered from several different supplier companies that design and deliver products from their own specific areas. Ship building is a long–term project where space management of a ship is crucial due to high number of equipment and limited room capacity. Therefore the customers, namely shipyards, often request conceptual 3D models from their suppliers for space reservation purposes in order to arrange layouts virtually in advance. Suppliers should be able to integrate their conceptual models into customers' spatial layouts. In order to know what kind of models to provide, one must be aware what customers actually need.

Conceptual 3D models should be modeled to include as few details as possible. Firstly, suppliers do not want to share sensitive design information outside the company. Secondly, customers want light product models to reduce complexity of their layout assemblies. However, obtaining conceptual 3D models is not a trivial task for supplier companies whose main expertise is in designing detailed product models.

ABB Marine delivers annually around a few hundred electrical high voltage (HV) motors and generators to a few dozen ships (Figure 1). The challenge in quote–order–deliveries has been the lack of capability to provide customers adequate 3D models at the right time point. So far, more or less improper models have been provided according to what has been available. In other words, customers have settled for what they have got. Information on what exactly do the customers want or need and when is yet unclear.

Figure 1. Commercial rendered 3D model of ABB azipod propulsion unit (ABB 7.5.2020).

1.2 Objective

The purpose of this master's thesis is to offer a qualitative pre–study on marine customer needs and propose a best practice for a solution that ideally enables conceptual modeling of 3D product models in one workday and thereby improves efficiency in marine sales orders. With these aims, the following aspects are considered:

- What are the most critical marine customer needs regarding the 3D models?
- How can the critical needs be satisfied in quotation orders using 3D CAD tools?
- What is the appropriate time point when the customer models should be provided?

To examine what kind of product models customers want and when, and to map ABB's current sales phase 3D modeling practices, I use semi–structured interviews. Thematic content analysis is then exploited to find out which of the current methods suit for the needs considered critical.

2 THEORETICAL BACKGROUND AND METHODS

In this literature review, I firstly clarify the nature of customer–driven industry, after which I define industrial layouts and marine design concepts. Subsequently, the idea of conceptual modeling is familiarized with a short presentation of configurators as a common subtype. In one subsection, I discuss model quality and delivery time with respect to customer satisfaction. The last two subsections review the the qualitative empirical methods I use, namely semi–structured interviews and thematic content analysis.

2.1 Customer–Driven Industry

Each company is running a business with a purpose to serve its customers. Competitive position of the company on a global market platform is defined by how well customer needs are addressed compared to other companies providing the same type of benefit. Nowadays, international competition is intensive due to increased economic globalization (Welfens et al. 1999). The winner is the one who offers the best contribution and the "best" is defined by customers. Hence, customer satisfaction is the first priority in customer–driven industry.

Customers can be roughly divided into two main categories, consumer customers and industrial customers. Industrial customers differ from consumer customers in many ways. They participate actively from the conceptual design phase to the final purchase order, and sometimes even after that in the aftersales stage. According to Kärkkäinen et al. (2001), a major difference is that industrial customers often purchase intermediate products to produce their own products. Furthermore, the authors note that industrial customers are usually professionals who require plenty of information of the product to be able to evaluate multiple options carefully. Requirements in industry are more specific and in some cases extra time and patience are needed to achieve mutual agreements. Griffin (1997) notes that industrial products have relatively complex structures and longer production times. This leads to the situation where the products are sold less frequently but with higher prices than everyday goods.

Usually industrial companies concentrate on their core business where they excel. Other tasks are often outsourced, including design work and manufacturing, to their partner plants (Zheng et al. 2012). Industrial companies can form long business chains which contain those parties that provide components, machines or services for the final product (Kärkkäinen et al. 2001). The parties can be different vendor, supplier or customer companies and also their stakeholders. Importance of communication between these organizations highlight the role of concurrent engineering.

Industrial companies prefer to stand out from others, but it is not always self–evident how to do this. As Kärkkäinen et al. (2001) express, companies should avoid passive attitude and instead seek for possibilities to refine their products towards the customers' needs. Inspecting customer needs is a careful and systematic process which requires profound orientation and consideration from the supplying company. Awareness of customer needs is tightly connected to capability to respond to those needs. It takes time to collect the respective information. Since the whole range of customers cannot be pleased, the company should possess a clear strategy to clarify those critical needs that could and should be contemplated.

Critical requirements originate, for example, from the current market trends, national and international regulations, mechanical and electrical specifications or time and money resources. The list is endless. Sometimes even customers themselves might not know exactly what have been requested. Liu et al. (2011) remind that an optimal product design is selected, not only for the customers but with them. Thus, companies need to help their customers to clarify what can be selected and what impact it has on other parts of the product development.

Liu et al. (2011) remark that the two important aspects which must be taken into account when designing a product are the voice of customers and the voice of engineers. The voice of customers is used as an input criterion that is fed into the design process driven by the voice of engineers. Customer requirements and wishes affect significantly the design stage of the product. It would be against the common sense to design products that nobody wants. There is no reason to offer "too fine" either, unless the extra effort is somehow compensated. Correspondingly, design engineers have a direct influence on customer satisfaction through the successful product design. Opinions and individual needs from each part of the business chain guide the product development and thereby organizational strategies of the companies.

Due to complexity of industrial markets, where concurrent engineering projects involve collaboration between several participants and where customer needs are increasingly sophisticated, customer satisfaction is more and more difficult to achieve. Kärkkäinen et al. (2001) report that despite the importance of the customer needs, the definition process is often implemented in an unorganized and unsystematic fashion. This might stem from the lack of proper process–level procedures or from the wrong interpretation of the needs. Companies must possess clear methods to gather knowledge from the customer interface and to help customers to communicate with them. Regular feedback policies or enquiries are concrete examples. Assessment of customer needs should go hand in hand with product development. In this manner, there should be a low threshold for communication.

In addition to customer needs evaluation, importance of scheduling the assessment process should also be acknowledged. For example, Kärkkäinen et al. (2001) suggest that a proper synthesis between technology and customer needs could be established by a clear customer need assessment phase in the innovation management process. Customer need clarification actions should be implemented rather in the early stage of the design work so that future changes and revisions could be kept in minimum. This ensures that from the very beginning of the product development project the whole organization works towards the same goal according to the same identified customer needs.

Proper evaluation of customer needs results in a better competitive status and promoted co–operation between the companies and their customers. Incorporation of constant communication offers an opportunity to stay ahead in the competition. Altogether, communication helps companies to focus their efforts particularly on the processes where the attention is needed the most. The process starts by collecting customer needs and sorting the most critical requirements. Then, the quality of implementation must be ensured so that the critical needs are properly addressed.

Simultaneously, time, costs and input demand are reduced while faster and leaner customer projects can be accomplished.

2.2 Industrial Layouts

Layout design is an essential stage that has a notable impact on the design requirements of facility equipment. Industrial customers, such as plants, need to be aware that the items are compatible with each other within the same layout before the actual assembling and installation begins. Therefore, companies should not only have optimal planning and operational practices but also a well–designed facility layout (Pillai et al. 2011). Designing process of an optimal layout is a complicated practice due to competitive environments, increasing customer demands and integration issues (Liu et al. 2011; Pillai et al. 2011; Bénabès et al. 2013). The current industrial product development consists of distributed design environments (Xue and Yang 2004), which means that separate components are modeled by different business chain participants in various locations.

Perceiving complete overview of an industrial layout environment is often problematic. The challenge related to spatial locations of equipment and items is called facility layout problem (FLP) (Singh and Sharma 2006). The facility layout means a physical arrangement of facility equipment in a given layout within limited space and boundary conditions, and FLP covers cases where constraints of different items are conflicting. Bénabès et al. (2013) consider layout related problems as multidisciplinary optimization issues, requiring both technical and economic expertise. There are many literature reviews studying the industrial FLP (see, for example, Meller and Gau 1996; Barbosa-Póvoa et al. 2002*a*; Raman et al. 2009; Hosseini-Nasab et al. 2018)).

Multiple solutions to various industrial layout optimization challenges have been suggested. Cagan et al. (2002) provide a survey of computational approaches to 3D layout problems highlighting the relation of spatial models with complex features and time–consuming computation. Similarly, Hassan et al. (2017) state that the number of objective functions increase the processing time of spatial layout design in an exponential manner.

Some papers present mathematical models, algorithms and theories behind the layout arrangement, and most of these are two–dimensional (2D) solutions which do not take the third spatial coordinate (often height) into account. For instance, Luo et al. (2015) optimize a facility layout design of a ship cabin using a mathematical model. For simplification, they utilized a 2D layout, but then concluded that in order to increase accuracy of the system, a 3D design will be needed in the future. The difference between 2D and 3D models can be seen in Figure 2.

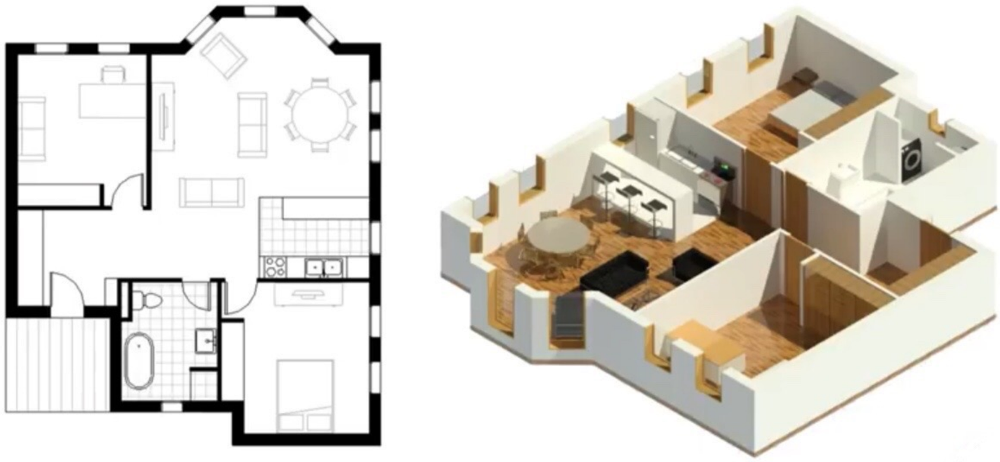

Figure 2. The 2D layout compared to the 3D layout of the room (Balkan Architect 2019).

3D layouts have become more preferred due to their clear visuality and the possibility of including vertical constraints. However, the increased number of constraints also requires more power from computers.

Even if the number of different items to be located is not large, numerous constraints are still needed to specify spatial relationships. Every constraint increases geometric complexity of non–uniform 3D components, which is a challenge for the mechanical layout synthesis. In spite of this, geometric representation spatially is often necessary in order to assure clarity and to avoid conflicts between the items. (Cagan et al. 2002.)

In an ideal situation, the customer company maintains its own layout design using software that support the arrangement of spatial elements. The customer receives 3D models for the items that are going to be purchased. At this stage, the customer may or may not know whether to eventually purchase the items. The model is for the evaluation whether the item item could potentially serve its purpose within the layout.

When designing industrial layouts, multiple boundary conditions must be considered. For example, Barbosa-Póvoa et al. (2002*a*; *b*) list topological characteristics, distance restrictions, space availability, item orientations, equipment connectivity inputs and outputs, irregular shapes and safety and operability areas as important factors. Luo et al. (2015), on the other hand, selected operating space, distance requirements, amount of hoisting, balance of cabin and personnel movement distance as critical parameters. Both Barbosa-Póvoa et al. (2002*a*) and Luo et al. (2015) address the relevance of illustrating maintenance and service spaces in industrial layouts. Maintenance areas are regulated for scheduled actions, such as for oil change, regularly done to make sure that facility equipment stays in form. Service areas in turn, are needed for special tunings or reparations outside of the ordinary maintenance schedule.

Layout characteristics play a significant role in the background when designing layout facilities. For that reason, the design of facility items and the layout should be proceeded simultaneously. (Barbosa-Póvoa et al. 2002*b*). Bad layout designs decrease productivity and increase the time spent on work–in–process (Jain et al. 2013; Pillai et al. 2011). Good layout designs, on the contrary, increase productivity and overall clarity (Raman et al. 2009).

2.3 Marine Design

Marine industry is associated with ship building business and the peripheral processes such as shipyards and their equipment. Marine industry includes the design and production of heavy and large machines and devices that are traditionally manufactured applying a built–to–order strategy, a common strategy for highly customized and low volume products. Ship building in marine industry is a complex continuous planning and development process. Systematic approach is needed so that the design aspects are considered with the aim to meet the requirements of the complex nature of marine business (Tupper 2013).

Ship building is a long–term project that takes years to complete (Bremdal and Kristiansen 1986). Ships are expected to operate efficiently for long periods of time (Tupper 2013). As individual systems, ships are produced carefully from the beginning without preliminary prototypes. Thus, they are assumed to be commercially applicable from the date of acceptance (Tupper 2013). Vessel are sort of comparable to small independent villages with their own integrated infrastructure.

Historically, novel design work of marine structures was adventurous and risky, and due to the lack of knowledge on hydrodynamics, mechanical structures and reliable analysis methods, an evolutionary approach was used (Tupper 2013). Ships were mostly designed based on the existing designs with only a few occasional minor innovations. Little by little, marine design developed through more or less deliberate experimental insights from accidents and incidents (Vossen et al. 2013).

Practical experience is no longer the principal method to obtain feasible solutions for ship design alternatives. Nowadays, the accumulated knowledge and computer science can be exploited. More accurate and at least suggestive results can be obtained with the help of modern computer calculation and simulation programs without idle consequences.

Marine industry is continuously required to meet new customer requirements, new regulations and new needs on the market (Vossen et al. 2013). Accordingly, new strategies and innovations are necessitated to be able to meet the increased expectations. Several market players such as ship owner, charterer and ship broker have impact on a ship design (Vossen et al. 2013). These parties have their own aspects and requirements that need to be taken into account when approaching the shipyard. For example, Vossen et al. (2013) list the most critical design related aspects and requirements under four categories which are commercial aspects, operational requirements, external requirements and available technology (Figure 3).

Commercial aspects include current market situation. National and international oil prices are the driving supply and demand of the vessels. Availability of materials such as steel is another factor that determines cost and time boundaries for the building process. Commercial aspects put even more weight on the competitive position between vessel operators who continuously require more and more cost–effective ships. (Vossen et al. 2013.)

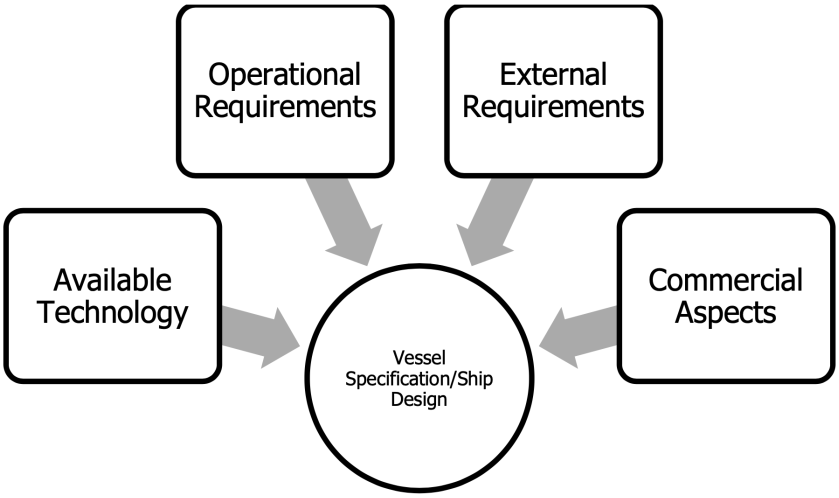

Figure 3. Four categories of requirements for marine design by Vossen et al. (2013).

Operational requirements relate to parameters that must be considered when designing the ship geometry. For instance, main dimensions, deck area, tank capacities and special equipment are important operational parameters, each of which must serve a specific purpose (Tupper 2013). Compared to the other industrial layouts, the relevance of a careful design is highlighted with ship layouts because of compactness requirements and space limitations, which is in line with Luo et al. (2015). Also, environmental conditions such as water depth, wave heights and humidity are operational requirements that control the designing process of the ship (Vossen et al. 2013).

External requirements aim to ensure safety and security anticipation. These requirements are derived from national and international rules and regulations which have become more rigorous due to increased attention to environmental issues and safety aspects (Vossen et al. 2013). New rules and regulations are constantly reclaimed when major failures occur. Safety and security aspects should be learned by heart so that they become a part of ordinary routines.

Available technology requirements are connected to design tools which are essentially modeling, calculation and simulation software systems. Proper integration between these systems is necessary because designing process incorporates multiple software specific tasks between which sufficient information flow is needed. Bremdal and Kristiansen (1986) note that understanding and utilizing both human and computer capabilities is important.

Development of technology resources and automation is constantly entailing new benefit to industrial processes, which can be noticed as increased efficiency and reduced waste. Despite the continuous improvement, in 2020, many processes are still implemented manually, which indicates that the manpower must not be underplayed. Processes from engineering work, system management and product development areas are combined to develop a large ship consisting of sophisticated hardware and software equipment. Collaboration between different disciplines is inevitable so that the fully functioning vessel can be delivered to the end–customer. Diverse skills are expected in large–scale industrial projects like in marine field. For example, integration and adaption are competitive abilities that can offer fundamental advantages to a company.

As an example, system integration of a ship using 3D environment by Vossen et al. (2013) is illustrated in Figure 4. Respectively, piping routings, electrical connections and heat, ventilation and air conditioning equipment and other accessories on board must be located in a way that overlaps between the systems are avoided.

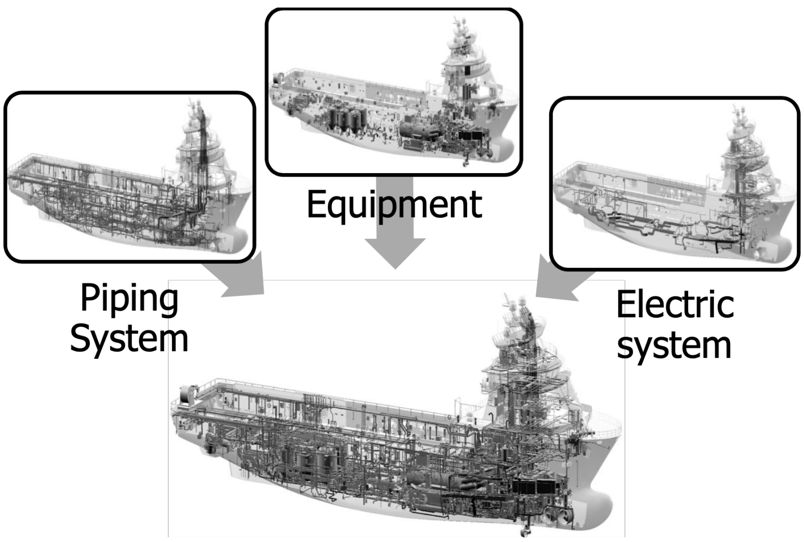

Figure 4. System integration of a ship is the most convenient using 3D tools (Vossen et al. 2013).

Integrating the subsystems into one ship, the main system, sufficient information flow between a ship builder and its suppliers is necessary. Much like Vossen et al. (2013) address, successful integration requires the right type of information from suppliers and sub–suppliers at the right time. The information may include for instance data sheets of machines or components, 2D or 3D drawings of the systems and other specific documentation. The information should be available but not every participant need access to the details. Additionally, information needs to be communicated to the right recipients in a correct form so that, despite different interfaces, integration of software systems is possible. Ship building is sequential process where the timing is also critical. A lack in design information from one supplier might cause many posterior phases to be delayed.

Ship design process consists of varying sub–stages. Amount of work depends on the type, size and novelty–degree of the ship (Tupper 2013). However, conceptual stage is the one that is unavoidable in ship design. Trincas et al. (2018) asserts that the concept level is the most important stage of ship design process by having the greatest impact to the overall cost of the ship.

2.4 Conceptual Modeling

Designers have rarely a full overview of the design requirements at conceptual design stage (Khan and Tunçer 2019). Nevertheless, some kind of depiction is needed to be able to convey a design idea, whether a partly existing or fully novel one, from designer's mind to successive processes. Conceptual modeling denotes an activity where a preliminary presentation of a system is created. It is a product development point between requirement analysis and further design phases (Bozlu and Demirörs 2008) and includes flexible and spontaneous innovation along the process (Khan and Tunçer 2019). The conceptual model is not a representation of the real world but a simplified cognitive abstraction of how we conceive the model (Robinson et al. 2015). It combines the overall initial structure of both geometric and non–geometric design information (Komoto and Tomiyama 2012). The former is the visual appearance and the latter involve invisible metadata that designates material specification, weight, part identifications and such.

Conceptual design work appears in many levels. However, it always relates with the fact that some or the most of detail information need to be more or less restrictively displayed. For that, there are at least two important scenarios in the design stage when conceptual models are vital. In the first scenario, details are hidden because of their nonexistence (Robinson et al. 2015). This usually takes place in early phases of design process when exact system parameters are still under consideration and negotiation. This way the concept must be built on specification that is available at the particular moment. On the contrary, the other scenario is using concept models at the end of design process when the details are already acknowledged but there is unwillingness to share them forward. It has become more and more necessary to limit visible information (Vossen et al. 2013). For instance, if a company provides its customer a product model it does not want to give out any sensitive information that could be copied or otherwise misused. In this situation, there should be a way to extract a concept model from a detailed one in an “undressed” manner.

CAD modeling is often used as a part of the conceptual design for geometric exploration of forms and shapes of the system (Khan and Tunçer 2019). In software engineering, CAD sub–segment accounts for the largest market share in 2020–2026 (Market Watch 2020). 3D tools consider spatial degrees better than 2D systems with respect to visuality and aesthetics. For this reason, they are often used for layout design planning and space reservations.

There are numerous design tools out there that support 3D CAD modeling. Help of CAD software are needed in the phases of design work but not only some of them are suitable for conceptual drafting (Jaiswal et al. 2016). Different design stages ask for different abilities from the software. One system lacks ease of modification afterwards and the other lacks a proper metadata inclusion. One is better for more complex features or accuracy and the other is better to reduce data waste. Specific details to be modeled should not be limited by available software but they should direct the selection of one (Robinson et al. 2015).

The resolution facet adds up variation to the quality of design work. Conceptual models are not accurate, but it is hard to determine how far from the precise they should be to reach the optimal. Depending on particular function of the model, the level of details should be something between the simplest sketch and the most detailed design. Figure 5 illustrates the contrast between levels 0 – 3 of details of a building. Lower resolution saves computational resources but shows as compromised accuracy and reduced data. Then again, higher resolution takes more power from software and hardware but holds more both geometric and non–geometric data.

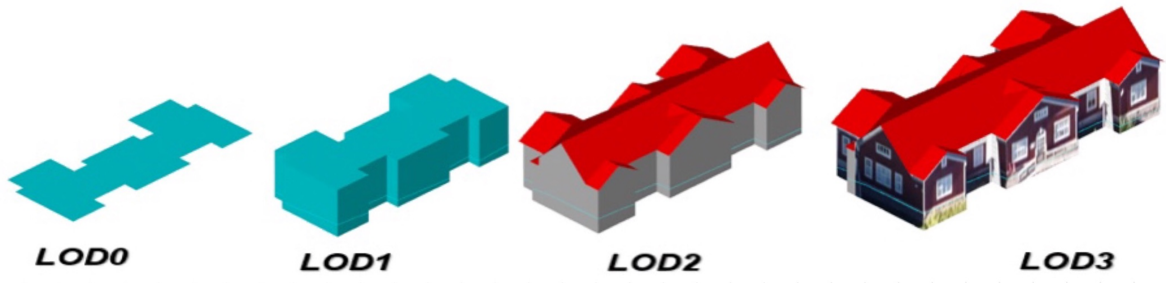

Figure 5. Difference between LOD 0 – LOD 3 (Espoon kaupunki 2018). LOD referring to level of details.

Nowadays, CAD software use their own native file formats as a primary input (Eigner et al. 2010). Since conceptual models are often necessary to communicate to different external and internal parties, the sharing format should serve even them who do not use professional CAD tools (Ball et al. 2007). In these cases, the company may want to offer customers some neutral standard file formats (Hartman 2009) which are used for migrating the full–featured CAD models into lightweight designs (Ball et al. 2007). Hartman (2009) brings out that choosing the most compatible, say lightweight, file format is critical to the communication and collaboration with the customers. The most common neutral CAD formats are among others quality information framework (QIF), initial graphics exchange specification (IGES), Parasolid, standard for the exchange of product model data (STEP) and stereo lithography (STL).

Conceptual models are a serious part of product design operations. They enchant common understanding and communications between product developers, customers and other stakeholders (Bozlu and Demirörs 2008; De Troyer et al. 2009; Komoto and Tomiyama 2012) and are used for large systems that incorporate the overall overview of multiple system objects. Building layouts, plant constructions, manufacturing facilities and ship designs are essential examples to be mentioned. Conceptual models can also be used as demonstration props for commercial purposes.

In pursuant to De Troyer et al. (2009), conceptual models reduce complexity in development processes and they also offer an abstraction layer to suppress details that may appear irrelevant, inaccurate or distracting in initial design work. Despite the simplicity of conceptual approach, multiple subsystems can easily form a complicated combination.

Modern products have become more convoluted and refined which shows as number of subsystems and components have increased (Komoto and Tomiyama 2012). Jaiswal et al. (2016) predicts that the role of CAD tools in engineering design will likely continue growing in capacity, scale and complexity to correspond those modern product needs. Moreover, Trincas et al. (2018) point out that regardless of product complexity, the concept design stage requires only limited amount of information which however is significant. For this reason, careful selection of the details to be represented in the conceptual form is important.

Jaiswal et al. (2016) names two major drawbacks associated with the conceptual design. The first one is inability to take advantage of existing models as preference and the second one is that a designer is expected to know geometric details and parameters to be able to define a model.

There are also several studies that seek new levels of conceptual 3D modeling. For example, Khan and Tunçer (2019) conducted a study related to 3D CAD modeling using gesture and speech commands. Yet this technique is not advanced enough for wider use in industry due to personality dependent variation.

Jaiswal et al. (2016) proposed 3D modeling for conceptual assemblies using probabilistic factor graph based on encoding of the geometric and semantic relationships between assembly models and their components. The idea was to overcome a concept level situation where designers do not yet know exact and fully defined user input parameters.

Also, conceptual simulation space models have gained some attention from research field (Bozlu and Demirörs 2008). For instance, De Troyer et al. (2009) define semantics of conceptual 3D modeling in virtual reality but find a lack of proper constraint types an issue when simulating moving parts with more complicated connections such as a gear wheel pair.

One more technique that is used when large number of conceptual models are needed, especially in plant and building layout planning, is building information modeling (BIM). Sulankivi et al. (2009) demonstrated BIM–based site layout planning to support occupational safety in construction projects. Wang et al. (2015) proposed an automated tower crane layout planning system, also utilizing BIM technology.

2.5 Product Configurators

In conditions of the current product proliferation, required product feature multiplications result in exponentially growing amount of information that need to be communicated between the sales organization and the customers (Forza and Salvador 2002*b*). Variation of industrial machines often involves large volumes and multilevel data which is heavy for a human mind to be processed (Zhang 2014). Acquisition of customer needs and their fulfillment ask for explicit orientation from companies that sell industrial products in concurrent engineering environment.

Sales experts use product configurators as tools for interacting in the customer interface, which is supported by information and communication technology (Hansen et al. 2003). Product configuration is an intermediate design between fixed mass produced and totally customized products. It has become an obvious part of conceptual modeling (Zhang 2014) since it provides the functionality to represent 3D models with varying features. In other words, configurators help to combine and determine product attributes within limited options (Hansen et al. 2003).

The basis of 3D configuring process is a basic product model frame that will be modified further according to customer preferences. Actually, configuration systems are high product variety environments (Forza and Salvador 2002*b*) where optional design choices are derived from the basic model by suggesting different predefined sets of components.

Configurators also follow predefined constraint rules along the components. Constraints can be either global or local (Wielinga and Schreiber 1997). Global constraints, such as weight and main dimensions, are results of the whole assembly, whereas a change in one local constraint, a bolt length for example, have effect on that one respective parameter or component only.

Hansen et al. (2003) depict the basic functionality of product configuration process in Figure 6. The configurator system offers default option values to be selected by the customer. Option values can be either scalable parameters as a part of a parametric function or they can be simple true–false inputs. Value selections are then stored in the customer–specific product model.

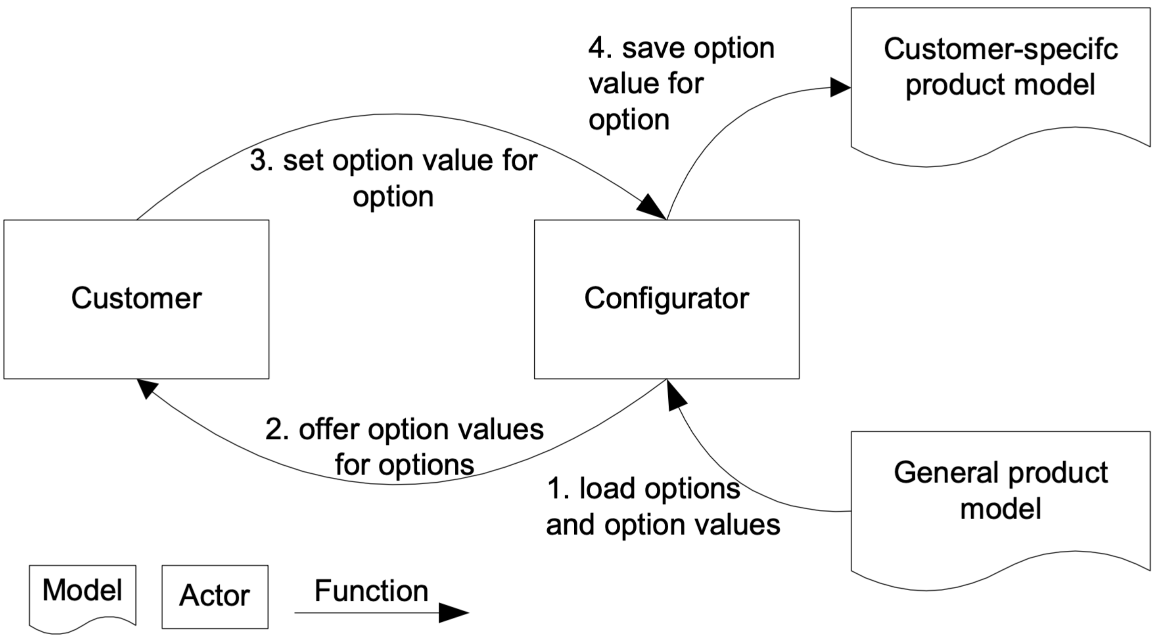

Figure 6. Basic functionality of a product configuration process (Hansen et al. 2003).

In addition, product configurations include other activities that are related to the modeling of customized compositions (Zhang 2014). Another primary task in configuration projects is to structure and represent the knowledge associated with the model to be configured. Yu and MacCallum (1996) emphasis that the life cycle of product development is not only about configuration design but also configuration management. Similarly, Aldanondo et al. (2000) names two types of knowledge that are needed for smooth configuring processes. The first is design expert knowledge possessed by the user and the second is programming knowledge mastered by (software) developers. Sales configurations help to automate product specification documents, for instance, quotation, sales price, bill of materials (BOM) and CAD (Hvam et al. 2008).

The role of the customer is significant since the configuration variation is maintained based on customer needs. Hansen et al. (2003) call customers prosumers who are capable themselves to determine the specification of the initial product frame within prescribed options and option values. Even though the configuration event is located in the sales interface, so that the process can nearly be proceeded by the customer, there are always situations when the customers do not know exactly what options to select. Hence, Hansen et al. (2003) see an external consultation interface useful.

Due to limited number of variants, some optimality criterion may sometimes be given (Wielinga and Schreiber 1997). This means that if customer requirements for certain product cannot be satisfied exactly, a variant with the closest characteristics is then offered instead. The phenomenon is typical in configuration design where a minimal number of sub–blocks are managed.

Numerous advantages can be obtained when using a product configurator at sales phase. Configurations serve best their purpose when the products are at least partly similar or they are otherwise assembled according to generalized boundary conditions. Errors from manual modeling tasks are reduced to almost zero (Forza and Salvador 2002*b*) when routine tasks are automatically configured. Configurators increase technical productivity with both geometrical design and non–geometrical documentation activities (Forza and Salvador 2002*b*), which helps to organise and control product variety (Forza and Salvador 2002*a*). At the same time, high quality can be maintained. Total time spent on quotations is minimized, which frees more work hours for greater contributions (Forza and Salvador 2002*b*). This way the whole sales delivery process could be shortened (Haug et al. 2011). Mutual sales platform with customers enchant collaboration and inter–firm coordination in companies (Forza and Salvador 2002*a*). The communication interface allows the parties have access to the certain knowledge that they need.

However, configurators also bring some difficulties along. In the beginning of product configurator development, serious changes in design practices and high investments in terms of man–hours are required (Forza and Salvador 2002*b*). Configuring systems require plenty of maintenance and besides, they are somewhat stiff for sudden structural changes, even for subtle ones. New patterns might cause friction when companies try to establish a uniform consensus (Forza and Salvador 2002*b*). Thus, it affects departmentalization level in the company as well (Forza and Salvador 2002*b*). Also, personal roles are in transition when parts of the traditional modeling work are handled with the product configurators (Forza and Salvador 2002*b*). Therefore, it is reasonable to carefully consider whether manual modeling would offer more short–term benefit.

Usage of configuration systems have a positive impact on the product quality, which however decreases when the complexity of requirements determination increases (Trentin et al. 2012). Configuring the most complex machines is no longer productive when sales volumes for a certain types of products do not pay back the investment (Forza and Salvador 2002*b*). Accordingly, Zhang (2014) admits the fact that most of the product configuration activities are applicable in a single company. That is why each company should carefully consider its long–term goals before adopting a product configurator.

2.6 What Is Quality and How Long Does It Take?

White and Cundiff (1978) mention that it is difficult to discuss industrial processes without taking the product quality aspect into account. Universal definition for the quality does not yet exist, in fact, the definition varies widely according to from whom it is asked. For example, Trentin et al. (2012) explain that the quality is a multifaceted concept consisting of different definitional perspectives. In spite of the tricky nature of the concept, quality is, nevertheless, one of the key characteristics that play an important role in industrial business.

Juran, J. M., and Godfrey, A. B. (1999) states that successful companies achieve higher quality standards by allowing the customer satisfaction to become their principal operating target. This strengthens the idea that a major part of the quality definition comes from the customers, which leads discussion back to the topic of, how salient it is to acknowledge what exactly satisfies the customer. Hennig-Thurau and Klee (1997) consider customer satisfaction as an "antecedent of the customer's quality perception".

Quality for the customer is receiving what was expected. In conceptual modeling this means obtaining 3D models that serve their purposes. To recall, the function of conceptual 3D CAD models for marine customers are space reservation purposes in big spatial ship layouts.

Nowadays, digital product data management (PDM) systems and CAD tools help engineers to provide industrial products with higher quality and in less time (Contero et al. 2002). CAD models are an essential part of the product data and thereby the product data quality (PDQ) as well (Son et al. 2011). Conflicts arise from integration of different product data systems. In particular, Contero et al. (2002) remark the link between the PDQ and the data exchange problem. This means that bad quality appears as data exchange issues and poor integration between downstream applications during the design stages. In terms of PDQ it is important that the exact information is directed to the right recipients at the right time (SASIG 2005).

This brings in another major concept, namely the time. Once real customer needs are determined the consideration of how to respond those needs and whether it is reasonable to respond the needs is to be evaluated. The process needs to be implemented so that time is spent as little as possible and simultaneously quality is kept as high as possible. The time should be spent on those particular factors that add the most quality to the customers. Time is saved when it is not used for the unnecessary actions that do not add quality to the customers. The same actions reduce data exchange problems, which again, saves more time.

So, there are two important factors to be considered when delivering the conceptual models for the customers. One is the quality which can be increased by responding customer needs accurately. The other is the time spent on modeling tasks which can be reduced by applying CAD tools and such in a way that helps to respond the needs efficiently and, above all, swiftly.

Overall, there are two main disciplines, the supplier and the customer, that both desire high quality and minimized process times. These factors can be distinguished into smaller areas, each of which is derived from organizational protocols. Clear instructions for both internal and external co–workers help engineers to work in a uniform manner. Additionally, routines accelerate the common practices. Skills are a part of one's personal contribution, which means better and faster problem solving. Tools, namely software and the integration between them plays also a key role. These facets not only increase quality and decrease time consumption of the modeling work, but also improve other areas of designing.

2.7 Semi–Structured Interviews

The empirical part of the study is implemented through interviews, a common tool in qualitative research. As Gubrium and Holstein (2001, p. 83) point out, the idea in qualitative interviewing is not to generate accurate rules or laws but to carry out interpretations. Tuomi and Sarajärvi (2009, pp. 85–86) explain this further by adding that the interpretations are made in order to understand something wider, for instance, a system or a phenomenon.

In order to obtain valid interview data a few practices need to be clarified first. Once the interview type is settled a sampling plan need to be developed to find the people who have the most relevant expertise and experience. Also, data collection must be planned so that the empirical methods are suitable for the particular environment and follow common rules of individual and organizational privacy.

Semi–structured interviews, which Berg (2004, pp. 79–81) also calls semi–standardized interviews, are only partly structured with a few unfixed questions as the name implies. The advantage is flexibility. Questions are not fully determined beforehand and their order may change depending on each case. They can be repeated in several different ways, whatever is appropriate to a respondent, and answers can be clarified with additional questions if needed. Berg (2004, p. 81) also emphasizes the role of the interviewer who is not only allowed but even expected to digress beyond the original pre–defined patterns. Therefore, the interviewer should be familiar with the interview topics.

The intention is to collect as much information of certain topics as possible. According to Seidler-de Alwis and Hartmann (2008) semi–structured interviews are the most prominent way to investigate the structure in the organization and bring out tacit knowledge. Furthermore, they note that tacit knowledge forms the foundation of the company's competitiveness and innovation management. The term is also known as *silent knowledge* due to its nonverbal existence. Moreover, Kikoski and Kikoski (2004, p. 66) describe unwritten and unexpressed information of the personnel as "a reservoir of tacit knowledge". It accumulates based on individual characteristics involving one's background, preferences, opinions, experiences and talent. As Nonaka and Takeuchi (1995, p. 238) declare, due to personal form of the knowledge, it is hard to be communicated forward. For example, a cognitive skill that has been learned by continuous repetitions might be difficult to transcribe into written rules.

Interviewees

Participants are selected to be interviewed based on their professional background and experience in particular fields. The aim is to receive as much knowledge as possible, one person at a time. It is not reasonable to interview all people from the same field of profession as the saturation can be achieved by interviewing only a few with similar backgrounds. Also, it is unnecessary for this study to get the same information from multiple resources. Therefore, a smaller sample group can be exploited, and thus, more variation and depth can still be achieved.

In research projects with interviews, sampling is often an iterative but necessary process to locate the best possible respondents who have the experience and knowledge relevant for the research (Flick 2018, pp. 29–30, 80). For this reason, the selection of informants should not be random but carefully considered and purposeful (Tuomi and Sarajärvi 2009, pp. 85–86). In the beginning, it might be challenging to know which parts of the process responsibilities belong to whom if desired respondents are people in different positions. This is why the so–called snowball sampling is executed.

Snowball sampling is a non–probability sampling strategy that is the best way to subjectively identify people who could contribute specific knowledge from a certain area of expertise (Etikan et al. 2016). Berg (2004, p. 36) describes *snowballing* as interviewing several people with the research related attributes. These initial contacts eventually lead to new contacts through their social networks; the snowball grows. Patton (1990) also refers this strategy as chain sampling as information collection occurs from person to person.

Selected interviewees are experts in the fields of sales operations, CAD modeling and marine industry. Sales engineers are interviewed in order to receive more knowledge of the quotation sales processes. Deeper knowledge from available CAD software is determined through design engineer interviews. Marine customer interviews are conducted with the aim to elaborate the notion of the customer interface and establish a more uniform understanding of critical customer needs.

Data Collection

Semi–structured interviews have many subtypes and one of them is the focused interview which was introduced for example by Merton et al. (1956). The focused interview is likewise known as the theme–centered interview and it is currently the most common subtype of semi–structural interviews (Tuomi and Sarajärvi 2009). In some cases, semi–structured and theme–centered interviews are thought to be close to synonyms as they are usually applied together.

The principal idea is that the knowledge from interviews are operational into pre-constructed themes, on which the conversational discussion is built. Themes are derived from initial research statements and they can be either predefined or constructed while the research proceeds. Depending on the expertise area of an informant, the themes can be emphasized differently. Besides, Eskola et al. (2018, p. 41) remark that not every theme fits naturally in all interviews. Interview structures are typically categorized further in terms of subthemes and their sublevels. Utilizing more than one theme structure helps to delve more extensively into the study.

In content analysis, themes represent the highest level of abstraction (Erlingsson and Brysiewicz 2017). Overly descriptive nature of themes may result in lack of cohesion between the data analysis method and final conclusions (Vaismoradi et al. 2016). On the other hand, excessive freedom within the theme structure can cause trouble to draw out clear interpretations.

After the first contacts are collected using snowball sampling a brief, either oral or written, explanation of the aims and purpose of the study is communicated. Each person who volunteers to participate receives an email invitation. After approval, sixty–minute time slot is arranged. The interview may take more or less than one hour, but the initial idea is that interviews are tried to perform as full sessions without breaks.

Most of the interviews are executed privately face–to–face within company's facilities, in silent meeting rooms, which is the most convenient for both, the interviewer and interviewee. This way the target group is best available (Berg 2004, p. 32). Some exceptions are allowed if the contact person is not able to visit the office, for instance, due to participation from another country. The location is not crucial for the research and therefore, other locations or Skype video calls can be considered as well. The language during the interviews is either Finnish or English, whichever is more fluent for the interviewee.

The interview session starts with a short recap of the topic and filling in the following information: location, date, start time, interviewee's name, job title and contact information. Consequently, the respondent is asked whether it is appropriate to record the session. In case of denial, only written notes are taken. If the interviewee accepts, voice recording is turned on and the consent is once more confirmed onto a tape. The informant can begin with a free narrative of one's position and tasks in the company. It is likely that the conversation naturally flows towards one or several related themes. If not, then the interviewer guides the situation with additional questions so that eventually, the relevant themes are discussed. At an appropriate point, the recording is stopped. If necessary, and above all possible, snowball sampling is continued by asking advice for the next contacts.

Data Handling and Confidentiality

Confidential background material, identified by names and job titles of each case, include transcribed interviews and voice recordings. Full names of the individuals are irrelevant for this study and hence they remain anonymous. The interviewees are hereby denoted with capital letters. However, the interviewees have given either written or recorded agreement to assign one's name, transcribed interview and possible recording forward for scientific purposes. If you have questions on these interviews, contact the author.

In order to obtain data that can be analyzed comprehensively, some handling procedures are needed first. For this, voice–recorded interviews are transcribed manually into textual form. Transcripts include simplified spoken questions and answers from voice recordings. Also, the interviews where the participant has not allowed the session to be recorded are documented based on written notes taken during the interview. The purpose is to interpret the content, not any emotional or behavioral features so oral components such as small utterances, repetitions and breaks in speech can be ignored.

Transcribed interviews need to be reduced and transformed in a way that makes the data more accessible, understandable and manageable (Berg 2004, p. 39). Initial reduction is implemented in an iterative manner so that the sections not directly related to the themes are removed. At this point, reduced transcripts should include only the most relevant parts of the interviews to be analyzed.

2.8 Thematic Content Analysis

Once most of the unnecessary interview data is reduced, the actual analysis part may kick off. There are many ways to proceed the thematic content analysis in qualitative studies. Selection of the method depends on the nature of the research. In this case, analyzing the content consists of two central activities, structuring and interpreting the data. Optimally, the former is implemented before the latter but practically the analysis is often jumping back and forth those two schemes.

The text from the reduced transcripts are transferred into a large table where the phrases are categorized under associative themes. Erlingsson and Brysiewicz (2017) call the phrases *meaning units* which are close to word–to–word sentences. The meaning units are simplified more by generating *condensed meaning units*, which means shortening the text while still retaining the core idea (Erlingsson and Brysiewicz 2017).

The next action is the coding of the content. The condensed meaning units are categorized according to codes which are labeled under the original themes. In qualitative context, codes are the smallest particles of the analysis representing the most exact description of the particular condensed meaning unit (Erlingsson and Brysiewicz 2017). The codes help to organize and simplify the data so that the thematic content analysis can be properly utilized. Main steps of the data structuring activities are depicted on the left side of Figure 7.

After the data is structured in a way that seem logical and rational, some interpretations can be initialized. Relationships, connection and patterns between the codes are identified, after which some tentative estimations can be drawn according to the condensed meaning units. Returning to the reduced transcripts once in a while is necessary in order to reflect initial interpretations to the meaning units.

Organizing and evaluating the results so far, with respect to the sub–themes, raises the level of abstraction. Finally, wider generalizations and conclusions can be accomplished by returning back to the starting point, the main themes. The data interpreting activities are illustrated on the right side of Figure 7.

The current 3D modeling practices and processes in ABB are evaluated and compared to each other in order to investigate if any of existing solutions could be revised or used as they are. The selection of the final proposal is based on the critical factors derived from the thematic content analysis.

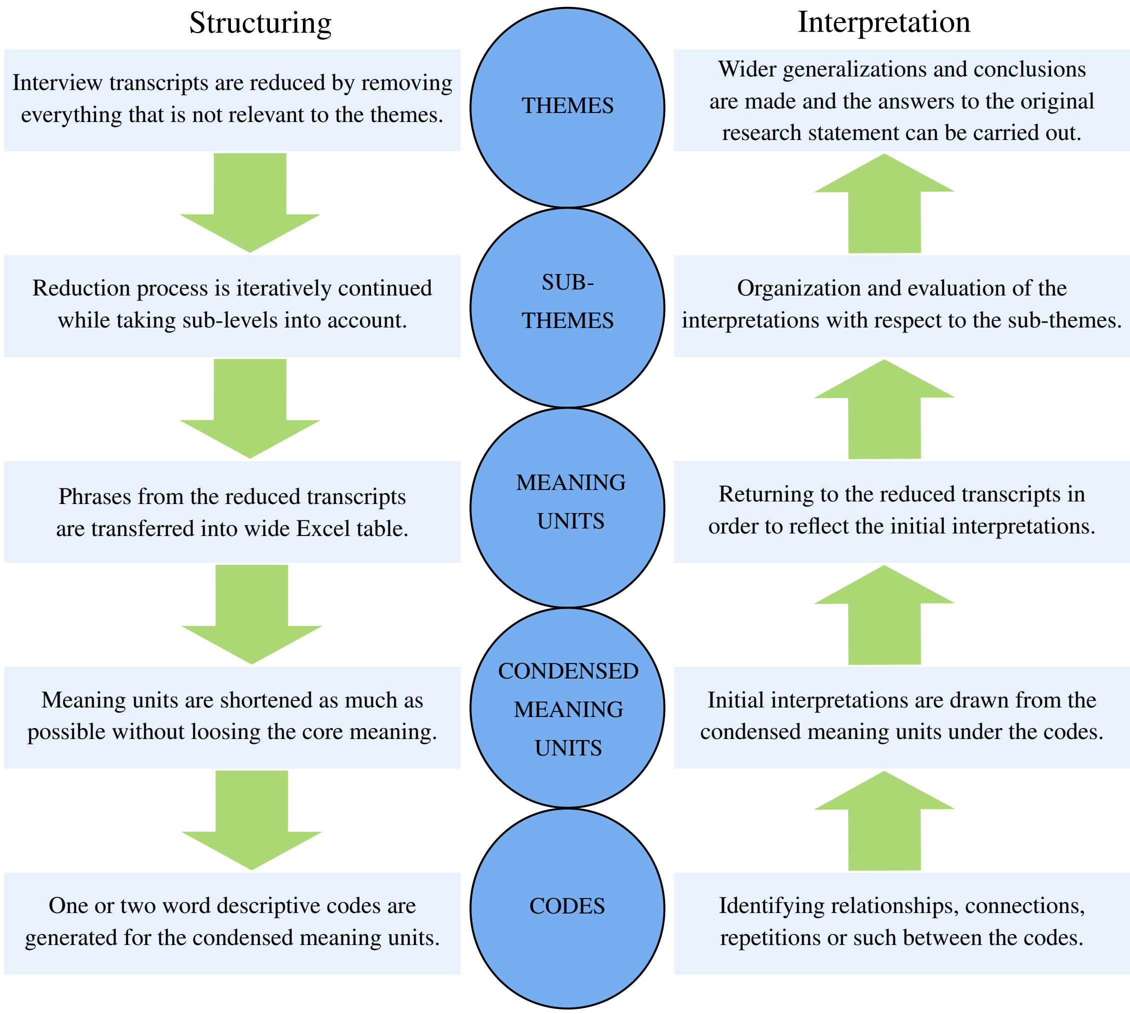

Figure 7. Structuring and interpretation processes in qualitative content analysis.

3 RESULTS AND ANALYSIS

I conducted 14 interviews in early 2020. Four informants participated from the sales operations. Six interviewees were mechanical designers. The rest of the respondents represented marine. Several participants possessed also previous experience from more than one particular field. Interview sessions took 30–90 minutes per case. Two of the sessions were arranged using Skype video calls, one was held in the customer's facilities and the others were executed face–to–face in ABB's premises. The interviewees are denoted by capital letter codes from A to N. Their job titles and other public background data are listed in Appendix I.

In the present section, I provide an overview of the current sales order process in ABB, introduce a few of the most potential conceptional modeling methods for reduced 3D models and propose a best practice method. Implementation of the final solution proposal is excluded as the focus remains only on the qualitative pre–study.

3.1 Themes

I constructed two separate three–level theme structures for the semi–structural interviews with the following idea. The first level (dark grey) represents the main theme, a topic to be discussed. The second level (light grey) includes clarifying categories that split the main theme into smaller sub–issues. The focus of each theme depended on personal contribution of the case. The last level of the theme structure (white) suggests directive questions, related to previous levels.

The first theme structure (Figure 8) aimed particularly to unfold the current 3D CAD modeling methods. It was primarily meant for internal ABB engineers who are the most aware of the process level procedures and modeling practices in the organization.

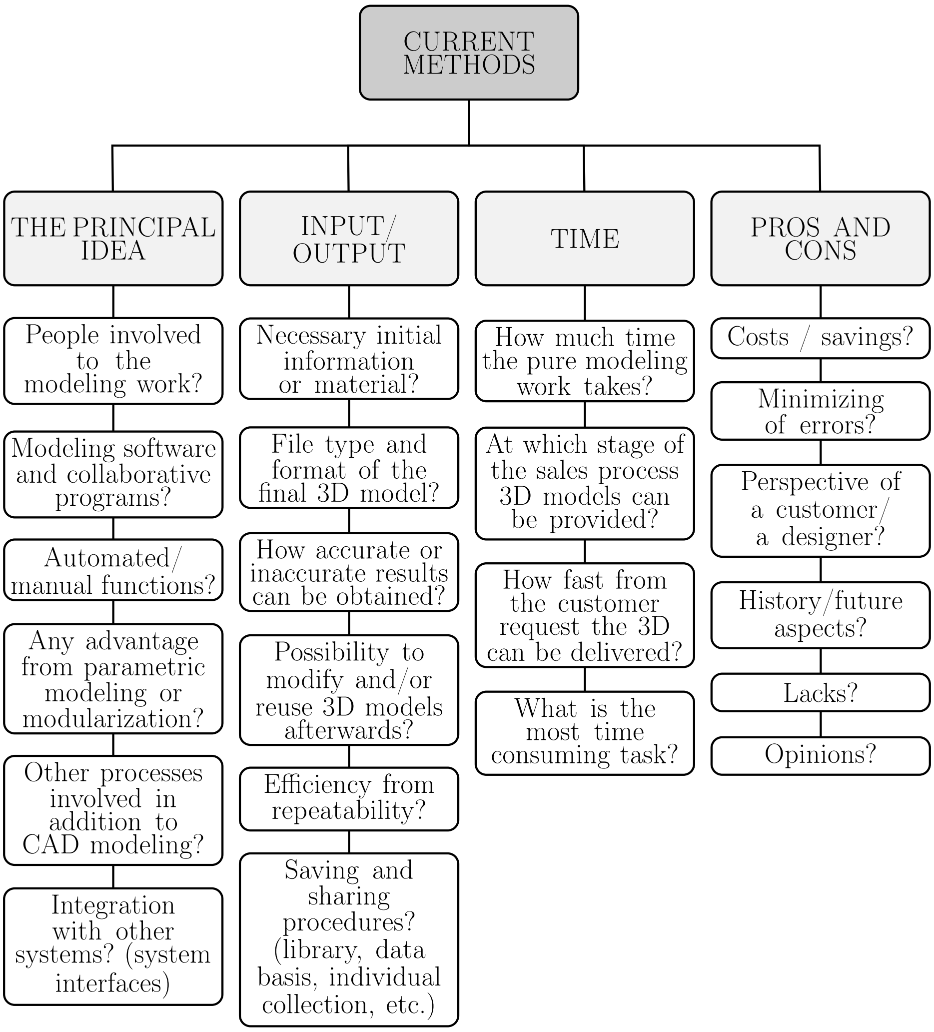

Figure 8. The three–level theme structure associated with the current conceptual 3D modeling methods in ABB.

Figure 9 is a corresponding representation of the second theme structure that was used to clarify marine customer needs. Unlike in the first theme structure, these questions probed for less in–depth answers. Logically, this structure was the most relevant with the marine expert interviews, but experimental assessments from the other participants were also taken into account.

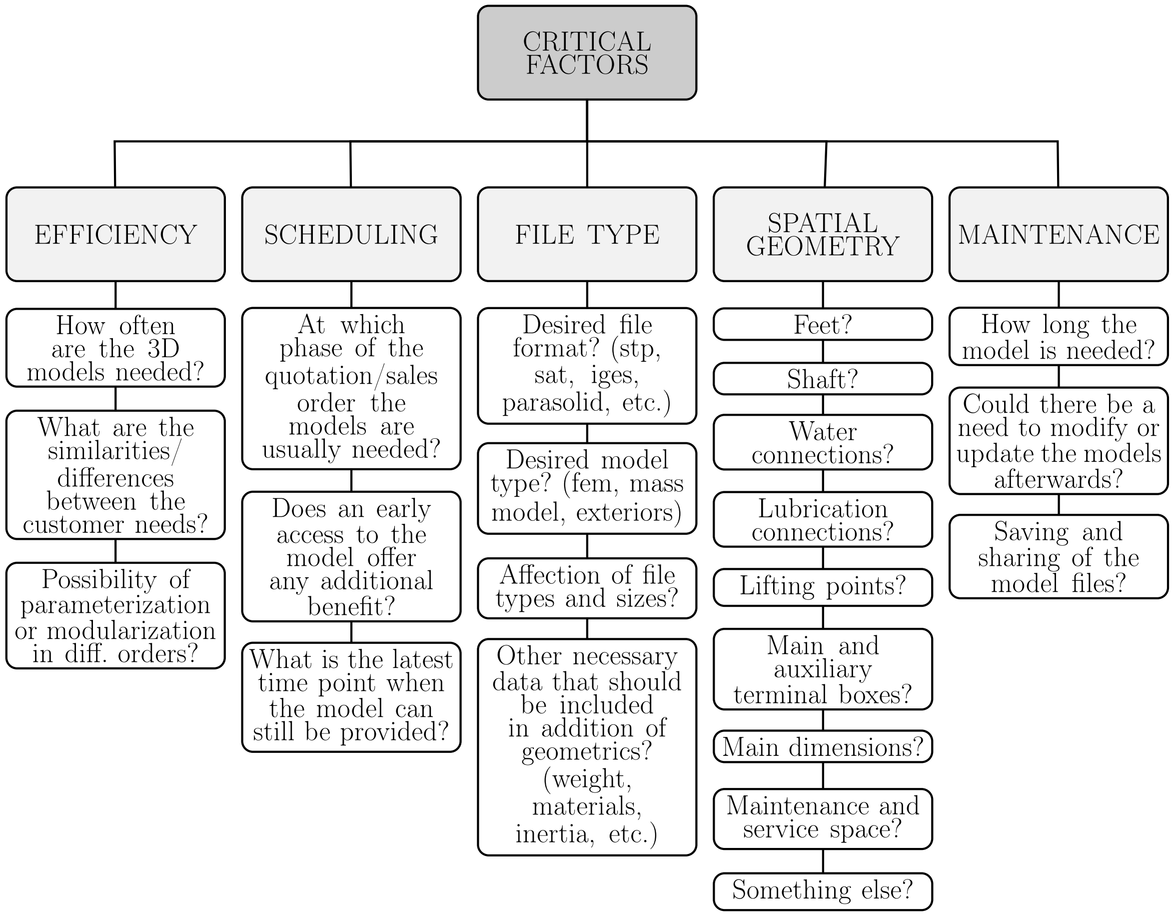

Figure 9. The three–level theme structure associated with marine customer requirements.

3.2 Sales Processes in ABB Oy

ABB Motors and Generators unit designs two types of HV products, induction and synchronous machines in a megawatt–class. Characteristics of sales processes for those are different in nature, which appears as varying CAD modeling methods of the products. Induction machines are mass produced with high volumes and limited number of variants. They are smaller in size and less expensive than synchronous machines that in turn, are more tailored to meet more specific customer preferences.

The starting point of the sales procedure is that a customer needs an electrical motor or generator. Usually the customer contacts a salesman who works in a vendor company and requests a quotation. Another option is that the customer contacts ABB directly. In both cases, the beginning of the sales process is following.

In standard situations, the salesman is able to offer the quotation based on ABB's product catalog. For example, in induction machine cases vendors can often create quotations using ABB's sales configurator called Cuusamo which is presented more in a moment. After the quotation is confirmed by the customer, the order moves on to the order engineering phase where a mechanical designer checks the structure and prepares the detail design. After this, manufacturing of the machine shall begin. This was the first, more straightforward scenario.

Another scenario is for the special orders when standard options do not offer the optimal solution. In these cases the vendor contacts a sales engineer in ABB's Global Technical Sales Support (GTSS) department. GTSS is a group of sales specialists who work closely with vendors. They pursue to find a solution for customer demands and to create a customized quotation within ABB's capabilities. GTSS offers several different special services, including finite element analysis (FEA) and electric calculations, to help customers to know what kind of product characteristics can be requested. More challenging cases may need, for instance, calculations of acoustic noise, resonance or shock loads or minimization of masses. Then the GTSS engineer sends the quotation back to the customer to be confirmed. If the quotation is accepted the order flows to the order engineering and continues to the detail design phase as in the first scenario. The beginning of the sales process in ABB is illustrated with the flowchart in Figure 10.

3D model requests may occur at any given time point from the quotation to the detail structure finalization. Connectors A–C in Figure 10 represent the time points when the models have been requested the most. Time point A appears as the most complex because the overall design is often in progress at the time. Usually the model is prepared by a mechanical designer in the order engineering team. If the order flows through GTSS department, in time point B, the geometry is prepared either by the sales specialist or if that is not possible, again, the model is asked from the designer at time point C.

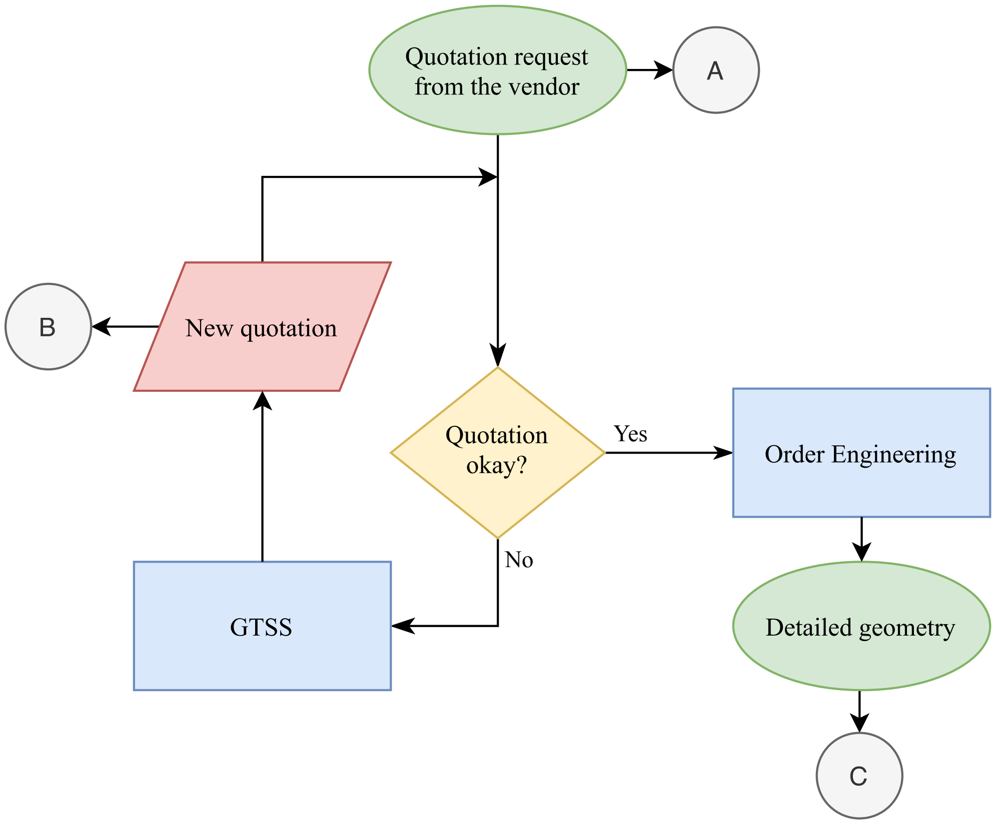

Figure 10. The flowchart represents the beginning of the sales process in ABB.

The basic structure of induction machines is designed before selling of the product begins. Therefore, there is a theoretical possibility to offer customers conceptual models at early stage of quoting. Mainly 2D drawings from AutoCAD software are used for customer documentation and for mechanical designing so in this light, however, their preconditions to offer customers 3D models are not optimal. In contrast, the situation is the opposite with more customized synchronous machines. With these, reduced models cannot be obtained before the mechanical structure is fully designed, but the full design is 3D modeled from the beginning.

3.3 Current Modeling Methods in ABB Oy

ABB is a large organization using a wide range of different CAD tools for modeling electrical machines. It is not reasonable to declare every possible 3D modeling method in these circumstances. Therefore, I chose only the most potential options to be introduced. I ranked potentiality of modeling methods according to following criteria:

- The method is currently or has previously been in active use.
- The method supports exportation of neutral 3D models.
- The concept of the method is applicable for marine products.

External Subcontractor

Four of the interviewees (A, B, G, K) mentioned a possibility to adopt external work for conceptual models. Recently, in most cases when customers have asked for 3D models, and only 2D detail design existed, modeling work have been ordered from an external subcontractor. The models are frequently asked especially for space reservation purposes.

ABB uses its own internal data base system for requesting the models from the subcontractor. A sales engineer creates a new case to the system and fills in some detail information including a shaft height, installation type, cooling specification, bearing properties and such. Also, the 2D document of the main dimensions is attached to the case. The request creation takes approximately from five to ten minutes if the initial product parameters are known. The subcontractor models the 3D model based on the 2D drawing, in one day and for relatively low price.

When the model is ready, the sales engineer receives an email notification, after which the 3D model can be downloaded as a STEP file. The model includes the main exterior features only, not any details or inner structures. Before the model can be forwarded to the customer it must be carefully checked by the designer. In case mistakes have transpired or if a need for changes come along, a new 3D model is requested from the subcontractor. Despite the double work, a new request is still cheaper than investing time for modifying the defective model. Figure 11 shows an example of an electrical induction motor that was modeled by an external subcontractor.

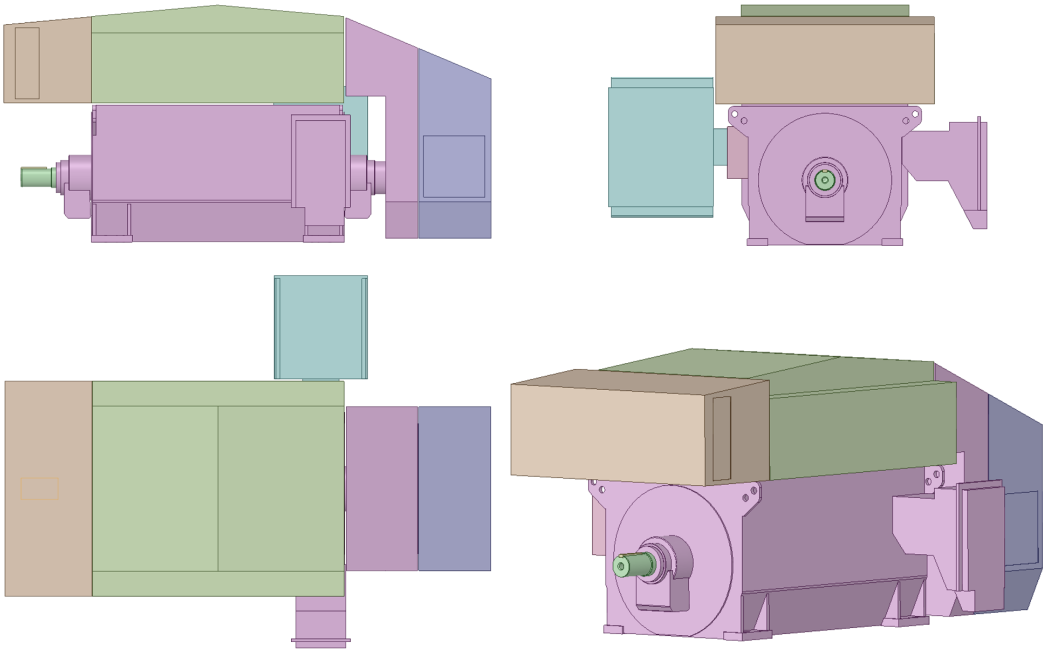

Figure 11. 3D STEP model of an electrical induction motor modeled by an external subcontractor (ABB 23.3.2020).

Using an external subcontractor is more common in induction than synchronous machine orders. The reason is the difference between the machine types and also the way they are modeled. Mass produced induction machines have a long history with 2D drawings which have served their purposes well enough. As a consequence, induction machine designers have not yet a comprehensive 3D library of which to take advantage. However, they have a wide range of 2D drawings which is, after all, necessitated before sending a new request to the subcontractor.

So far, customers have been satisfied with 3D models they have got from the subcontractor. The models are relatively accurate and they can be delivered at a short notice. All in all, the procedure is efficient and relatively cheap compared to many other methods, at least in the short–term. Nonetheless, implementation of any additional requests is less forthright. The designer cannot directly contact the subcontractor and ask, for example, to diverge the standard modeling protocols. The communication is handled through a bureaucratic system, which is not ideal for individual exceptional cases.

Oikku Blocks

2D CAD designing of induction machines is implemented mostly in Oikku which is ABB's internal extension of AutoCAD software. Participant F offered a general overview of this application which is a detail design tool determined for product development projects. Because of the consistent expectations towards 3D modeling, the need was tried to be satisfied by creating a 3D configuration function to Oikku.

The idea is that different predefined configurable items such as terminal boxes and frames are modeled as 3D blocks, which are then conditionally combined to build a full model. Lightness and the number of details can be adjusted by the resolution of the Oikku blocks. At the moment, approximately a dozen blocks are needed for one product model with one shaft height and one machine type.

The outcome is a solid 3D model that represents only visible outer parts and surfaces (Figure 12). In addition to the 3D model, the 2D drawing of the main dimensions is derived, but the blocks are not linked to the drawing. To clarify, a revision of the 3D structure does not update the 2D geometry and other way around. The best exportation file format has been STEP, although Oikku supports several other CAD software specific formats too.

Oikku's role in configuring customer models have recently received little attention. Configuring itself does not take much time, a few minutes, but the modeling of the 3D blocks is gradual. The method is fully applicable in theory, but slightly clumsy in practice. One core explanation is that sales engineers do not have a sufficient access to Oikku because they do not use AutoCAD on a daily basis. Also, the need for continuing its development turned out to be less necessary than originally expected so the method was set aside.

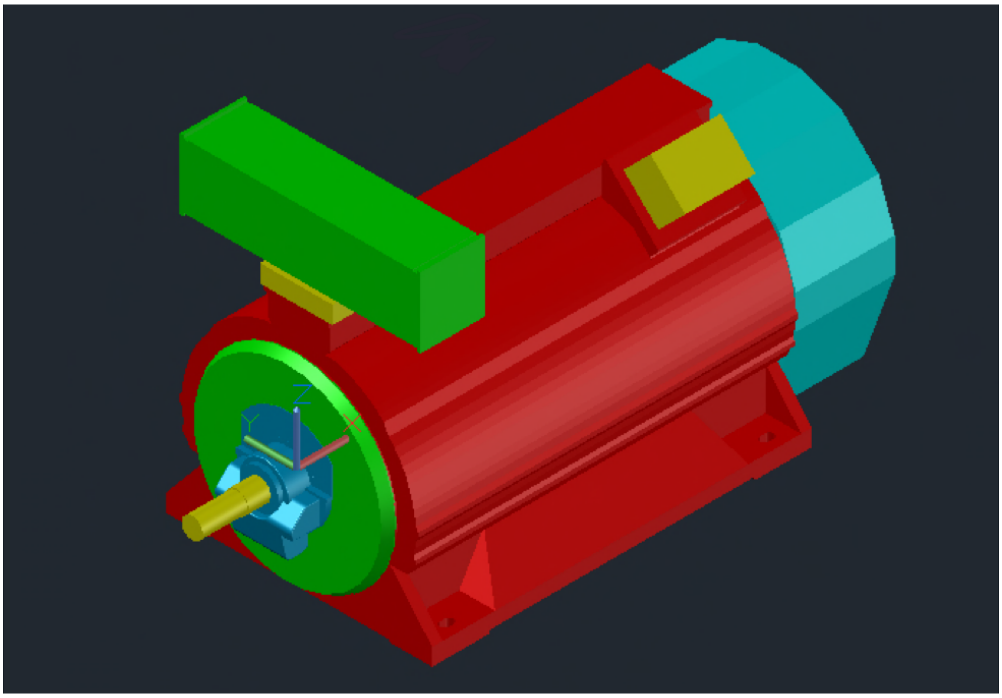

Figure 12. An induction motor build from the 3D Oikku blocks (ABB 29.1.2020).

Sales Configurator Cuusamo

Interviewee H introduced the sales configurator called Cuusamo that was originally developed for supporting automated configuring of large induction machines. The purpose was to bring the product configuring feature closer to the sales phase and the customer interface. The configurator has worldwide users, including salespersons in different vendor companies and in ABB's sales organization, sales engineers from GTSS and also occasionally designers from the order engineering and product management. Cuusamo is a client software that runs on Windows platform. Its core capability is to concurrently configure sales order documentation and product models. This configurator is mostly used for induction motors, but also for induction generators. Additionally, it includes a limited support for synchronous motors, for which the support is intended to be enlarged in future.

The genesis of the sales order configuration is that there is a need for the electric motor or generator. The customer approaches the salesperson and requests a quotation with tentative boundary conditions. The salesperson creates a new project in Cuusamo environment and adds metadata, such as contact information, to the project. Subsequently, the salesperson starts to define the electrical design for the machine according to the request, after which a new product position is created to the project. The electrical design consists of a group of specifications, for instance frequency, voltage, shaft height and number of poles with a corresponding speed. Each of the parameters modifies a specific electrical performance of the machine. Then, Cuusamo offers some combinations that match with the electrical design. The user can select the one that is the closest to the customer's optimal. Based on the selection, equipment items can be configurated to the position. The equipment in Cuusamo means an object that can be sold. It can be a physical feature, such as a terminal box or a bearing type. Equipment can also be something less concrete, as an example, a standard for a painting class. Configuration is implemented by adding, removing or replacing equipment within the product position.

After the configuration of the product position is finished, the drawing of the main dimensions and the customer model can forthwith be downloaded. The drawing is a PDF document with 2D representation, and the customer model is 3D geometry of the motor, comprised of the configured physical equipment. Configuration of the visual elements is based on customized logic of aggregating different pre–modeled and simplified 3D components. The logic comes from Cuusamo server where, for example, one 3D component is associated with another in particular spatial point within particular spatial rotations. This technique allows only the most relevant connection points and primary shapes to be modeled which is why the 3D models from Cuusamo are very rough and therefore light representations of the products. Due to the lightness of the geometries, the models take hardly 2 MB. As the result, automated configuring is also fast. The time is mainly needed for preparing the quotation. If the salesperson is experienced to deal with the electrical specifications, the quotation is prepared and the 3D STEP model is exported in less than half an hour. An example of two configurations of an induction motor with different bearing types can be seen in Figure 13. Despite the pruned geometry, the visual outlook of Cuusamo models is still convincing.

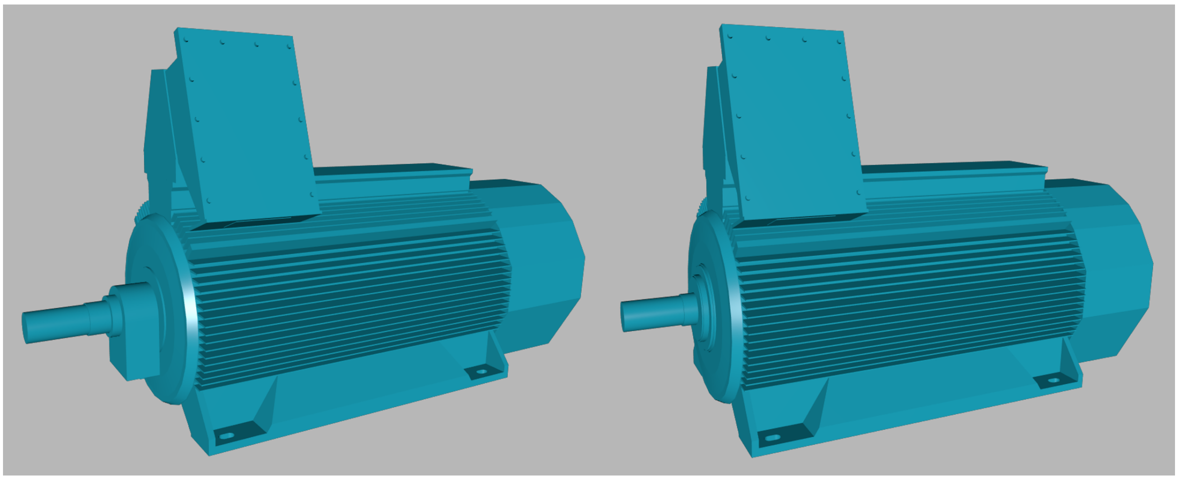

Figure 13. An induction motor from Cuusamo with two different bearing configurations (ABB 14.1.2020).

Moreover, the pricing of products for the end–customer is controlled from Cuusamo. The configurator offers a price based on default pricing. The price can be adjusted by the salesperson so that the sales organization gets an acceptable sales margin. After the pricing, a quotation document is printed out and sent to the customer to be confirmed.

Cuusamo also takes care of revision management in case if the customer gets a second thought of some features. If so, the order is modified and the quotation is updated and then sent back to the customer. When the customer accepts the deal, the process is moved from the sales to the project management and to the order engineering phase to be fully designed.

Cuusamo is built with a great variation of additional functional abilities, such as cost accounting, electrical calculations and user authentication. Therefore, the amount of information is enormous in the beginning of the sales order process. This also means that maintenance tasks are accounted as a full–day job.

Because the modeling logic is based on Cuusamo server, likewise the other internal functionalities, 3D models are not directly linked with external modeling software. This means that revisions or modifications that affects to the geometry are updated manually, not through information flow from another CAD or PDM system.

Sales configurator Cuusamo has a steady role in induction machine orders. However, extending the support for new products or defining new equipment is a large undertaking project.

FEM Models

Among other practices, GTSS team runs finite element method (FEM) analyses for electrical machines. FEM models need to be simplified as much as possible in order to avoid immensely complex calculation mesh that would decrease computational capacity. Calculation models, utilized by FEM specialists, are often derived by exploiting original 3D structures. Unnecessary roundings, bolt holes and other features are removed before the model is applicable for FEM calculations. One potential option is to consider whether the same models could be used for conceptual models as well.

Sometimes volumetric 3D models are requested directly from the structural analyst for space reservation purposes. These requests are rare, but they signify that there is a possibility to obtain conceptual models using the same CAD tools, such as analysis of system (ANSYS) or ABAQUS, than it is used for strength calculations. After all, the primary idea in the beginning is similar to what is desired with customer models; as little details as possible, as long as the certain details remain.

Participant C explained that the geometries for FEM calculations are traditionally prepared manually by reducing features from detailed 3D models. For this reason, FEM models are obtained several weeks after the quotation process initialization, at the point when the detailed design already exists. Modeling of the geometry takes days rather than hours, but it is proceeded for FEM calculations regardless of the need for the reduced version.

The file format of volumetric models depend strongly on software and the customer preferences. Mostly Parasolid, STEP and STL files are exported and suggested to the customers unless they specifically request other formats. Besides, designer C slightly shuns STEP format because it is more prone to corrupt than the other listed, of which the STL takes the least storage while still holding properly exterior information.

In addition to the manual modeling, ANSYS functions can be programmed using for example, Python scripts. There is indeed some automation development related to parameterization of 3D geometries for FEM analyses with which respondent A have worked on. The goal is to automatically assemble a 3D model of an electric machine from a shaft, rotor, stator, bearings and frame components in ANSYS SpaceClaim software.

Python scripts are used for searching parameter values from different software interfaces. First, a 2D drawing from Oikku is executed, and the output is a transfer data file that is saved into designer's local temporary folder under a specific project number. The file includes a list of frame parameters of the machine.

Interviewee D introduced Multiphysics Cascaded Computing Unit (MCCU) which is an internal open–source online tool, originally developed for dynamic calculations of rotors and sleeve bearings. One of its extensions is Rotor.zm which is meant for creating a 2D cross–section of a shaft (Figure 14). Rotor.zm uses the data file from Oikku as an input. Then, ANSYS SpaceClaim takes 2D information from Rotor.zm as an input and turns the 2D geometry into a solid 3D model with a revolve feature (Figure 15). The rotor, stator and bearings could be modeled around the shaft in ANSYS with another data file from Adept, an electrical calculation software.

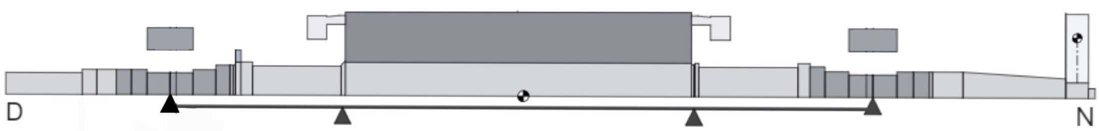

Figure 14. MCCU generates a 2D cross–section of a shaft based on an input file from Oikku (ABB 20.3.2020).

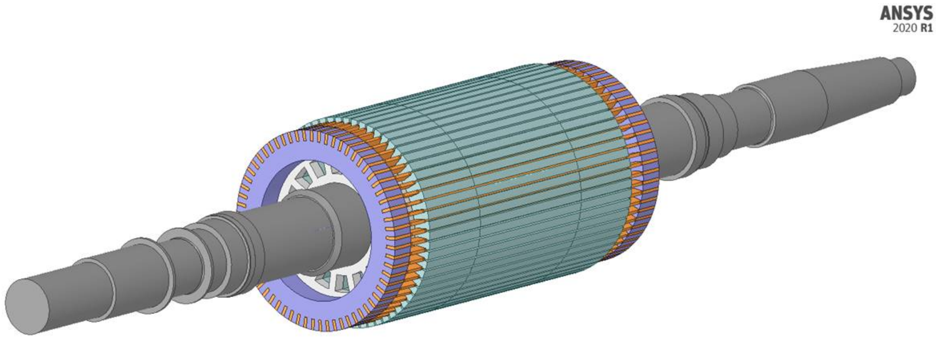

Figure 15. At this point, inner parts of an electrical machine can be parameterized in ANSYS SpaceClaim exploiting Python scripts which read parameters from Oikku, MCCU and Adept interfaces (ABB 20.3.2020).

Additional realizable functions in progress are related to 3D modeling of the rest of the machine. The frame shape of induction machines is mainly constant. Only some dimensions are varying, which would be easily parameterized with Python scripts as well. Bearing shields are still a bit of an issue since they cannot yet be automatically parameterized. At this point, the whole procedure takes only a few minutes compared to manual modeling that may require two days, even when the other tasks and possible typing errors are excluded.

ANSYS Space Claim platform seems to offer an efficient and fast way to obtain simplified 3D models. Definition of how accurate or inaccurate assembly is wanted can be easily adjusted by the scripts. The method, however, involves many different software interfaces, which requires more of know–how from designers. On the other hand, it is a nice example of how open–source programming makes it easier to transfer information between multiple system interfaces.

Using FEM models for conceptual purposes is possible if a clear way of sharing the geometry model can be defined. The models need to be saved somewhere where sales engineers have the access, and the saving need to be done at the time point when both the volumetric and the calculation model can still be worked on. Internal components such as the rotor, stator and bearings are crucial for calculation models. They are irrelevant for customer models, but then again terminal boxes are important unlike they are for calculation models. However, the components can be easily removed from the machine structure when needed.

Teamcenter and NX

The institutional 3D CAD modeling software in ABB is NX which is linked to the PDM system called Teamcenter, both developed by Siemens PLM Software. CAD expert K considers NX as a versatile modeling software which offers varying subfunctions through easy–access programming interfaces. Meaning that the functions are feasible and available even for those engineers without extreme coding skills. New subfunctions can be invented according to what is needed among mechanical designers. For instance, the support for visual basic for applications (VBA) and Python scripts encompasses a great benefit for automated parameterization and modularization of 2D and 3D models. In addition to uniform scripts, NX and Teamcenter incorporate many software specific tools for 3D modeling. Designer J, for example, have exploited these attributes while programming two product configurators for synchronous machines.

The first configurator was originally created in 2014 for obtaining simultaneously a simplified 3D model and its 2D main dimension drawing for the customer at a short notice. The system supports particularly large synchronous generators. The idea is that the product model is configured with user inputs using *Options and Variants* tool in Teamcenter. Input variables are either integer values within a certain range or options from predefined drop–down menu. There are approximately twenty input values given, including frame length, feet height, shaft key dimensions and specifications for accessories. Variations for the inputs are programmed separately with conditional if–else statements. Error elimination is also noted by restricting wrong types of input values when the input is given either outside of the range or when it causes conflicts with other parameters. After user inputs, Teamcenter checks whether identical structures already exist. If not, a new item code is created for the 3D exterior model that can be opened in NX (Figure 16). Otherwise the user is suggested to use the existing model as a reference. The model can be exported as a proper file format, after which a sales expert or a project manager will forward the file to the customer. In case the necessary initial input parameters are acknowledged, the whole process takes from five to ten minutes. Designer J estimated that practically the 3D model can be delivered to the customer in half an hour from the moment of request if the requested product type is supported by the configurator.

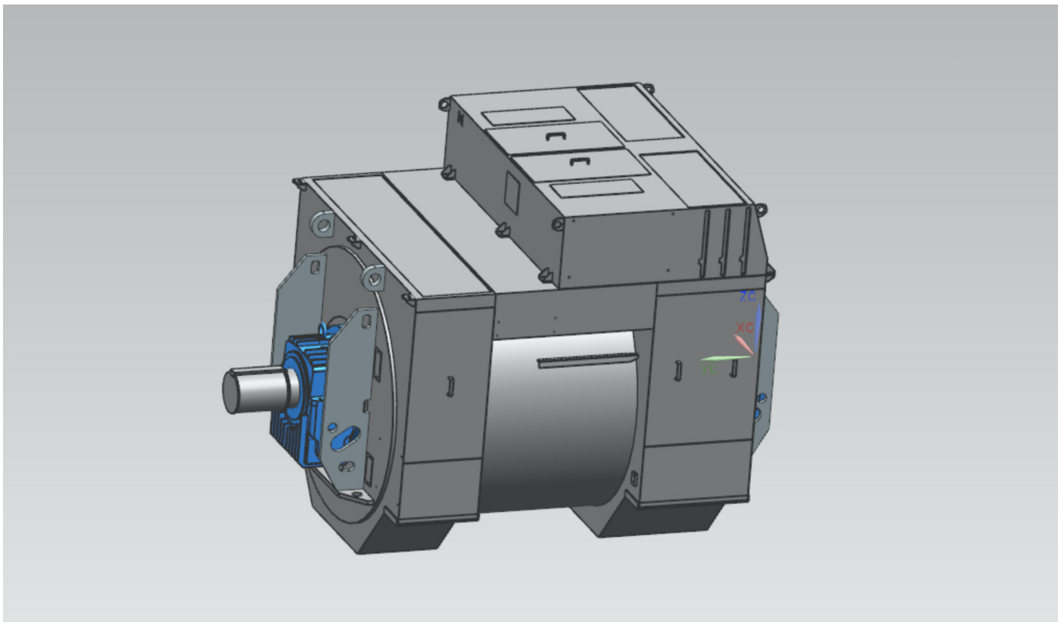

Figure 16. 3D NX model of a synchronous generator configured using Teamcenter *Options and Variants* tool (ABB 17.2.2020).

The configurator was actively in use after it was created, but recently, due to new Teamcenter and NX software updates, it has become a little complicated to use. The creation process of this kind of configurator for a new product is complicated and time consuming. Additionally, maintenance tasks cause trouble, which is why *Options and Variants* tool has recently been left out of focus.

The second configurator is for modeling welded frame structures of synchronous motors. Configuration is implemented using *Expressions* tool in NX. The method is based on parameterization of 2D planes that move along 3D coordination. The most significant parameters are then constrained to the planes. This way, modification of thickness, holes or other features of the steel plates do not break constraint links between the other plates. Additionally, code inside the model stays cleaner and easier to handle. Figure 17 is a close–up illustration of two components from the welded structure where the 2D plane is left visible.

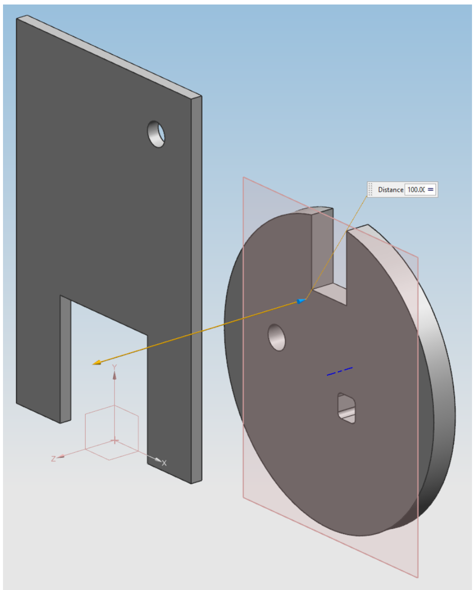

Figure 17. Steel components of a welded frame structure are parameterized using NX *Expressions* tool to locate 2D planes (ABB 4.5.2020).

Relative functions and parameters are named logically in *Expressions* tool where the user can modify the input values. Furthermore, some structures, such as a frame type, are conditionally selected from several options with *Arrangements* setting that suppresses unnecessary frame variants. Similarly to the previous method, running the configuration takes only a few minutes after the basic structure of the model have been modeled. The workload in the beginning is determined by how much details are involved. Despite the fact that the programming work with this particular welded structure is currently still in progress, the method is already in regular use.

Benefit of configuring products with NX *Expressions* and Teamcenter *Options and Variants* methods is that there is no limits whatsoever when it comes to any product type. Configurators can be created for either detailed or simplified products, but the geometric specification need to be acknowledged well in advance. Additional advantage is the real–time connection between the 2D drawing and the 3D model. The model is a master file from which the geometrical revisions are updated to the drawing.

Interviewees E and K told that when the customer asks a 3D model for the customized machines, one way to extract the simplified geometry out of the finished detail design is to use NX specific functions. The customer model can be extracted for example, using

Linked Bodies with which a group of single components are combined and united into solid entities (Figure 18). This action fades outlines between the linked components that cannot be separated afterwards. The model can then be exported in a proper format after which the file is sent to the customer.

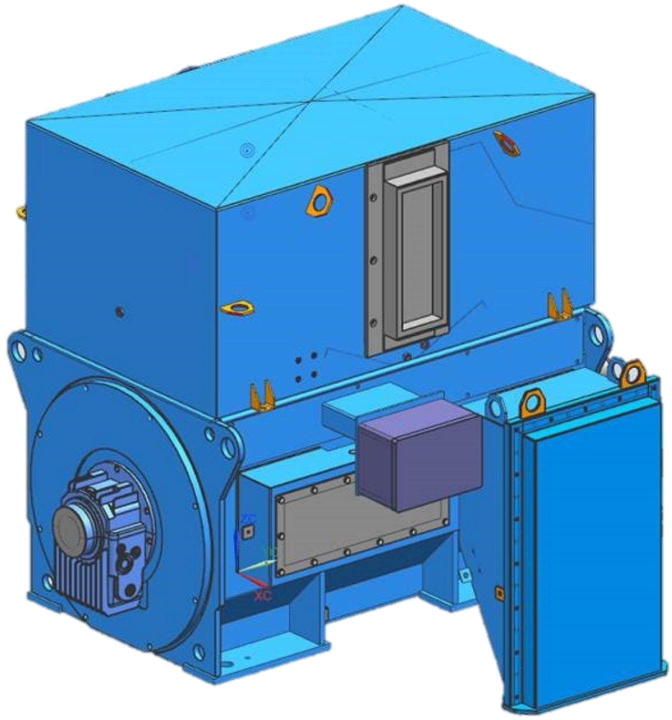

Figure 18. External 3D features can be combined as unite solids with *Linked Bodies* tool in NX (ABB 16.1.2020).

Visibility of the details reposes on the number of components that are united at once. To simplify, the more components are linked into one solid body, the more details are disposed. Selection of the bodies to be linked together requires manual attention from the designer, but then again, the more details are desired to be hidden the more entities can be selected at once, and thereby, the less time it takes. Preparing the conceptual model using *Linked Bodies* takes from half an hour to one hour.

Linked Exterior is another NX tool, especially meant for extracting exterior features from detailed structures. The tool was indicated by respondent K who told that some tests were recently run for different surface modeling tools, but *Linked Exterior* was ranked as the smoothest while still retaining the most sufficient quality. Even for a big assembly, the 3D model of exteriors can be obtained in a few minutes.

The idea is that a detailed 3D model is scanned from user–defined number of perspectives. At least the cardinal and intercardinal directions can be chosen. Then the exterior feature is combined from surfaces that are visible from the selected views. The outcome is a 3D surface body which represents only outer features of the original model (Figure 19). Lastly, the model can be exported from NX as desired file format.

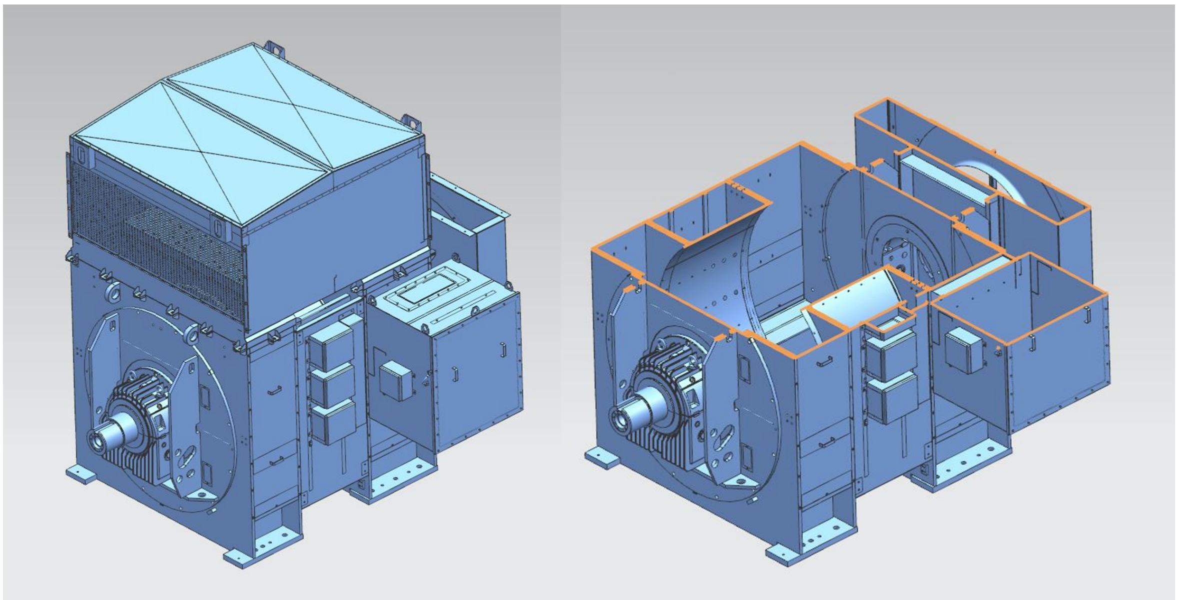

Figure 19. A full and cross–sectional exterior model, extracted using *Linked Exterior* tool in NX (ABB 31.3.2020).

Closer capture of the same exterior model (Figure 20) reveals that there seems to be some random floating surfaces on the bearing housing once in a while. Sometimes the surface is missing from small areas due to complex geometry and lack of proper view perspectives. So far, it has not turned out to be an issue when taking the original function of the model into account.

NX works with the basic file formats such as STEP and IGES. Moreover, K explained that it is also possible to prepare so called installation files that define the features to be included to the exportation file. For example, it can be determined that a STEP file includes either surfaces or solids with certain coordinate points.

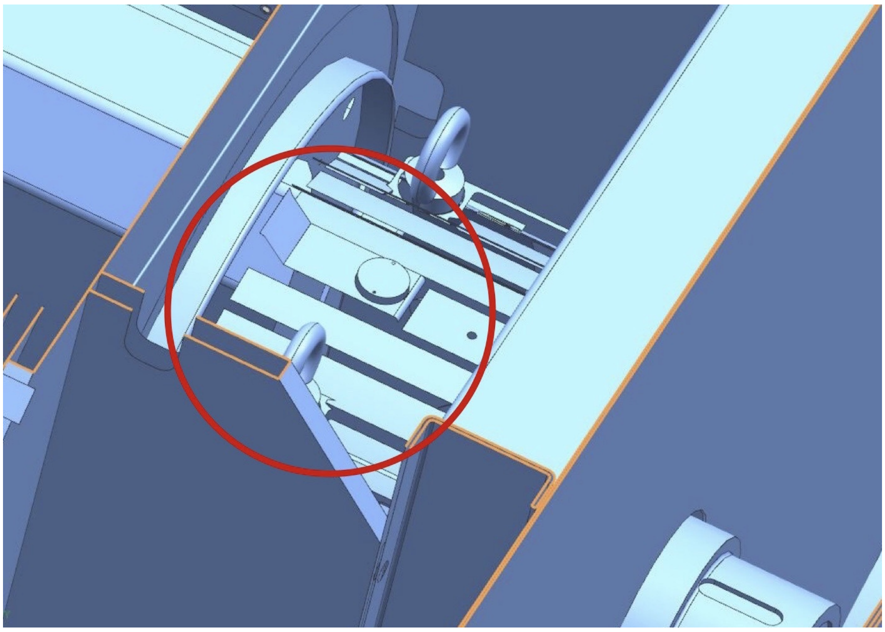

Figure 20. Sometimes more complex shapes are scanned improperly resulting in missing surfaces (ABB 31.3.2020).

3.4 Marine Customer Needs and Critical Factors

Composition of the critical factors was made using the categories from the second theme structure (Figure 9). The factors are introduced along the topics and not in a specific order according to their criticality.

Efficiency

It turned out that a need for 3D customer models is seasonal rather than equally spread throughout the year. Interviewees G, L, M, and N, who are the most experienced in the marine field, evaluated that an annual need for ABB items would be in 10–20 projects. Each of the projects is associated with one type of vessel and for each vessel, there might be a requisition for several different types of motors or generators. Respondents L, M, and N advocate an automatic generation of the models because in marine, the products are considered as unique items. In other words, even though the number of annual marine projects seems to be low, a need for marine product models can rapidly increase during certain months. To the same extent, there might be some months when hardly any new marine orders occur.

Efficiency, in this kind of situation comes from the ability to obtain conceptual customer models swiftly without interrupting other parts of the design process. Also, it should be considered by whom the models are prepared. The modeling solution to be proposed should be easy and quick to implement so that it is ideally possible to be maintained as a routine task by a single person. Therefore, *easy and fast* is selected as the first critical factor.

Oikku, Cuusamo, NX and Teamcenter configurators are fast 3D modeling tools once the configurable variants are carefully prepared in advance. From these three, Cuusamo is probably the user–friendliest because it can be used by vendors, GTSS engineers and order engineers. FEM models are not the fastest, but as it was mentioned earlier the waiting time would come mostly from waiting for the model for strength calculation purposes, which would offer double benefit when the customer model is obtained simultaneously. However, it is not self–evident that marine products automatically need FEM calculations. *Linked Bodies* and *Linked Exterior* tools require NX software which is not so common among sales engineers, but otherwise both methods are easy and fast to implement. When ordering the modeling work from an external subcontractor obtaining the full model takes one day, but as it is with the FEM models the time can be meanwhile used for other relevant procedures.

Due to unique characteristics of marine orders, a flexible tool that is applicable with different types of products should be pursued. Thus, the second critical factor is *flexibility*.

Only some of the methods are capable to deal with a great product variation, which makes them less flexible in terms of customized products. The range of variation must be acknowledged before Oikku and Cuusamo type of configurators can be applied and still, preparing readiness to comply with new variants is tricky. Teamcenter and NX configurators are slightly more flexible because the models can be modified afterwards, although it requires manual work, which again, is time consuming. With the FEM models, their flexibility controls also the flexibility of the customer models. Hence, pre–work is still necessitated. Increasing the common consensus of what is needed from the FEM models for the conceptual geometries is important if this particular option is utilized. In case of the subcontractor the 3D geometry is manually modeled by a person, so the flexibility expectation is already met. It is only matter of how well the 2D drawings, based on which the 3D model is modeled, are prepared. By the same token, *Linked bodies* and *Linked Exterior* tool can be applied to all product types because the models are kind of copied from existing detail designs.

Scheduling

When it comes to scheduling the findings varied noticeably. Definition of the time point when the models are the most requested is not straightforward to construe. It depends strongly on the nature of the project. New customers may request models earlier, in the beginning of the quotation, while more experienced customers already know what they are going to receive and therefore they do not mind receiving the models later in the process. Additionally, novelty of the project drives the need of getting 3D models as early as possible for careful space reservation planning. Interviewees C and D have remarked that different nationalities also tend to bring variation to the scheduling from customer's side. Some customers request the models more often during the quotation whereas the others do not necessitate the models until the quotation has been confirmed.

Most of the respondents (B, C, G, L, M, N) commented that providing models at early stage of the quotation would be an additional benefit, but not an absolute prerequisite. It was mentioned that the capability to visualize the products would have a clear effect on customers' thoughts from commercial perspective. Occasionally shipyards might do some designing even prior to signing the contract. Although this is not typical, the ability to arrange facility layouts before the purchasing decision could definitely add value to the customer experience.

Disorientation about the optimal time point may be caused by a lack of information. If customers are not sure when exactly the models can be requested it is only natural to ask rather earlier than later. In the meantime, engineers are not sure whose responsibility it is to generate the models.

Despite the actual benefit, offering the models as early as possible may not be the best way to go after all. According to the interviews, it is difficult to clarify the particular time point for the "as early as possible". However, the mutual consensus of the latest time point when the 3D model should be provided while still satisfying the needs is easier to determine. The time point should be the same when the main dimensions drawing is confirmed (L, M, N). This is when the contract has been signed, the purchase order has been issued and the final detail design has been completed (connector C in Figure 10).

From ABB's perspective as a supplier, it would be reasonable to set a constant time point when the 3D model is provided in order to avoid confusion about customer models that are delivered only "when requested". Besides, the customers have approached with a clear wish to automatically receive the models. The time point should be appropriate for as many types of projects as possible so, with this in mind, the model could be provided at the same time with the main dimensions drawing, after the detail design is finished. Herewith the next critical factor is *concurrency of the 2D and 3D documents*. This way the task can be assigned to particular people as a part of their conventional responsibilities, which also increases the efficiency in designing processes.

In theory, it is possible to provide the 2D drawing of the main dimensions concurrently with the 3D model using any of the method candidates, but some differences in timings when to do so exist. The 3D model from the subcontractor comes one day later than the 2D drawing could be provided. With Oikku, the drawing needs to be prepared manually either before or after the 3D model is finished because there is no link between the model and the drawing. Using NX and Teamcenter configurators the drawing is updated automatically after the configuration is executed. In terms of the manually reduced FEM models there is a remarkable delay from the 2D drawing to the conceptual model. The same thing with the parameterized FEM model, *Linked Body* tool and *Linked Exterior* tool, but the delay is much shorter because the 3D model can be obtained faster with these methods. In turn, Cuusamo provides both the model and the drawing at the same time.

File types

A few things need to be mentioned about the file type and format of customer models. Firstly, the file size stood out prior to the file format and secondly, there was notable fluctuation between 3D file preferences of different customers.

For space reservations, customers often ask for surface or exterior models. These kinds of models are conceptual geometries without any visible internal parts. Suppressing details as much as possible is beneficial, not only for the customer but also for the supplier. The customer wants to have as light model as it can be, and the supplier prefers to hold back sensitive information from outsiders.

Sometimes ABB designers have been obligated, due to tight schedule and sudden requests, suppress the details by hiding and deleting components from the original detail structure. This is not the most convenient way to do so because hiding a feature from the model does not mean that it would no longer take space from the file. Participant L explained that for this reason, customers often complain about 3D models being over detailed and large for their purposes.

It is difficult to define a limitation for the file size of a customer model because of the fluctuation among the requests. For example, interviewee M does not see any limitation for the file size as long as it is under 15 MB, but furthermore notes that of course smaller files are always easier to handle. Interviewee L stated by the same token that the simpler the model the smaller the file size, and therefore the better for customers.

Surprising contrast in customers' practices in assembling their spatial layouts was noticed. Protocols of two different shipyards were investigated more specifically, and there appeared to be a significant correlation between the file size of a single component and time losses due to total size of the whole layout.

It is known that shipyard 1 is willing to use reduced 3D models for the spatial layout whenever it is feasible. They usually request light 3D models from suppliers and if possible, in STEP format. Shipyard 1 might either directly use the model they receive or if the file it is extremely detailed, they manually reduce details from the structure, after which the model can be applied. The definition of what is light enough have been a bit unclear.

Shipyard 2 have decided to operate very differently from the shipyard 1. Interesting fact about their modeling concept is that 3D models are regularly requested from suppliers, but they are not directly used in spatial ship layouts. The model files from their suppliers have constantly been heavy to be utilized so ten years ago the shipyard decided to begin to remodel their facility equipment using primitive programming to ensure proper integration and decent file sizes of the models.

Primitives are the simplest representations of 3D geometries. The syntax is software specific, but the method itself is not. For example, a cylinder can be coded as a circle with a certain radius with one of the points on the circle being multiplied by a direction vector which gives the thickness for the geometry. Similarly, the next primitive can be created and located by adjusting local coordinate systems of each primitive within the global coordinates. CAD software runs the code as TXT file and the result is a “cleaned–up” solid 3D model consisting of intelligent primitives. The experience was that the primitive models are not even extremely simplified. They actually look amazingly alike the corresponding detailed models. Figure 21 is an example of 3D CAD, remodeled by primitives.

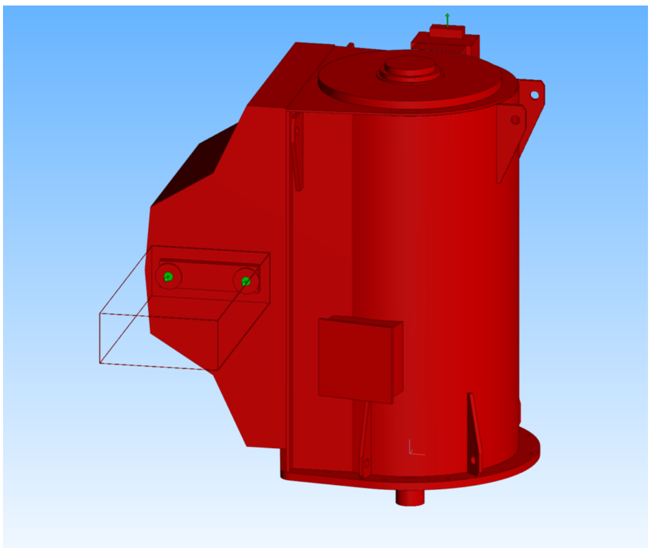

Figure 21. A primitive model of an induction motor (Shipyard 2 27.2.2020).

The contact person from shipyard 2 emphasized that the simpler is a formula for one primitive the shorter is its geometric equation, and the smoother it can be computed. The modeling is straightforward as long as it deals with the primitives. Shipyard 2 exploits an external subcontractor from the same time zone for the modeling work. A few designers at the subcontractor company are specifically trained to create primitive models based on 2D main dimension drawings, received from equipment suppliers.

Reasonings for using the primitives are derived from accumulation of issues when dealing with large assembly files. Number of the components in a ship assembly may be millions and each component with extra bytes makes the layout model heavier to be processed. Participant N described the capacity required from the computer processor as geometric cost which can be measured by the time loss due to slow performance of the assembly.

The following example of two cruise ship projects, built by shipyards 1 and 2, demonstrates the importance of keeping the file sizes of 3D components in the minimum. Geometric cost data of the projects was offered by shipyard 2. Shipyard 1 is working on project X with 135 000 GB gross tonnage (GT) which describes the internal volume of the ship. Project Y is built by shipyard 2 and its GT is 200 000 GB. Based on the data, I drew the following diagram in Figure 22 that represents sums and averages of the largest files in both projects. The horizontal axis denotes the number of the largest components in the sample. Blue pillars are the average component file sizes in MB in project X, and respectively, green pillars in project Y. With the same colors, the lines represent the sum of the assemblies in KB.

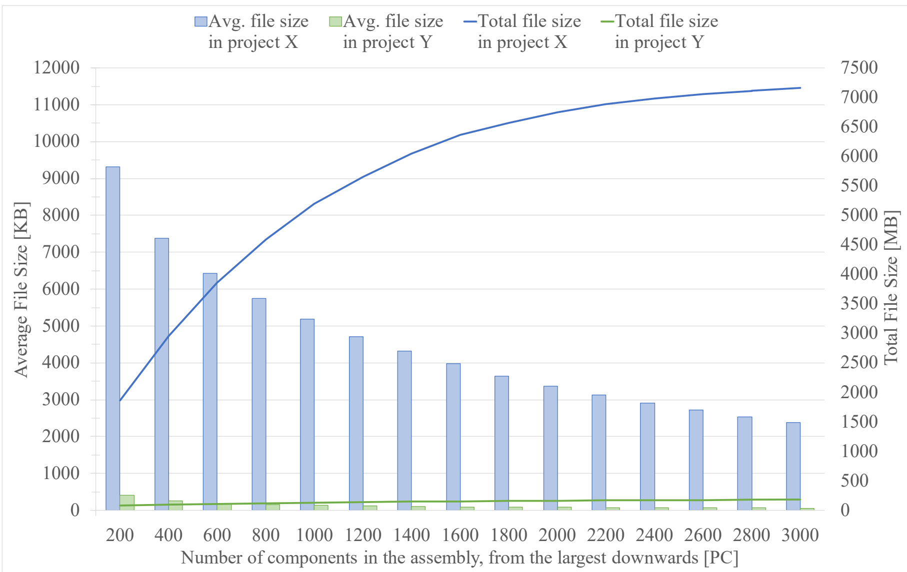

Figure 22. Comparison of accumulated geometric costs between projects X and Y. The data for the diagram was given by shipyard 2.

Together, the total size of the 3000 largest component files in project X is 7.2 GB, whereas the corresponding value in project Y is 182.2 MB (Table 1). According to contact person N, there are no other ways than primitive modeling if the file sizes are desired to be kept this low. It must be noted that even though a few gigabytes file might not sound like a large one, in 3D modeling that is already a significant challenge for a computer processor.

Table 1. Point values from Figure 22 with the 1000, 2000 and 3000 largest components.

	Avg. file size in project X	Avg. file size in project Y	Total file size in project X	Total file size in project Y
1000 PC	5.2 MB	130.8 KB	5.2 GB	130.8 MB
2000 PC	3.4 MB	80.6 KB	6.7 GB	161.1 MB
3000 PC	2.4 MB	61.1 KB	7.2 GB	182.2 MB

An additional minor experiment was executed so that shipyard 2 remodeled four customer models, received from ABB. File sizes of the original STEP models were decreased from 8–12 MB to 50 KB by cleaned–up primitive models. Regardless, the visual resolution suffered surprisingly little, which can be seen from Figure 23.

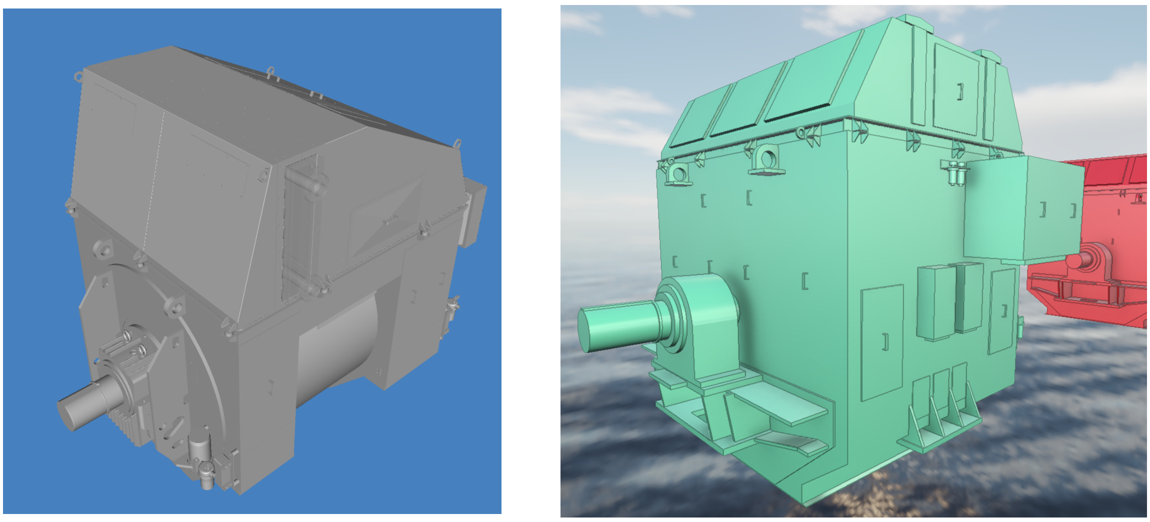

Figure 23. One of the original STEP models from ABB on the left and one of the remodeled versions on the right side (Shipyard 2 16.4.2020). Backgrounds of the figures were hidden for sensitivity reasons.

Respondents A, C, D and G explained that sometimes customers themselves might not know what kind of file they need. On the contrary, the requirement the customer might be over detailed with respect to what can be contributed. Interviewee G showed additional sets of file format related requirements from two different shipyards (Table 2). A clear disparity can be noticed. Shipyard 3 would comply with file size of 20 MB whereas shipyard 4 asks to stick with one tenth, 2 MB.

Table 2. Example comparison between specifications, related to 3D model file formats, required by two different shipyards (ABB, 2020).

Shipyard 3	Shipyard 4
Max 20 MB WRML 2.0 or SAT 7.0	Max 2MB STP or IGES Dimensions in mm Main dimensions (including terminal boxes)

The file size seemed to be by far one of the most constraining factors for the customer models. Considering the limitation, it is salient that within the current circumstances, offering KB level 3D CAD models is yet unattainable. Nevertheless, it would be rational to continue with the idea of pursuing as light models as possible. The target size for the models must be set so that it no longer grows into a bottle neck. That is, following the mainstream wishes from the interviewees, which also automatically covers the need to be forwarded as an email attachment. Hereby, the corresponding critical factor suggests to keep the *exported file size under 10 MB*. According to the interviews, excluding the contact N from shipyard 2, this is at least sufficient a file size for.

Configurators turned out to be relatively efficient in exporting compact CAD files. Average Cuusamo models were under 2MB and Oikku models even less, around 1MB. Also, 3D model files from the subcontractor were under 1MB. Reduction of the FEM models have a massive impact on the size of the model files. However, it was reported that it is possible to easily get models with under 10 MB if the details are sufficiently reduced. NX methods produced slightly heavier 3D models with 5–20 MB depending on the physical size of the machine. It can be assumed that when paying more attention to the amount of details, NX models could also meet the 10 MB.

Metadata attributes were also under discussion, but not any crucial factors were detected. Those engineers (A, B, E, I, J) who have been responsible of the mechanical design of the machines informed that they have not added any additional metadata to customer models. From specific requests, some data such center of gravity, overall mass, bearing specifications and such have been marked to 2D drawings instead. Interviewee M thought that it is enough to see center of gravity from the 2D drawings and nothing else than the physical main dimensions are needed in the 3D model. Customer N preferred at least weight as an essential factor and thinks that center of gravity is not that crucial when it comes to motors and generators that are relatively small components compared to a big ship. Furthermore, additional strength and acoustic calculation values were mentioned to be beneficial extra parameters, but they neither were required.

Moving on to the file formats. Respondent L said that STEP is the most heard file format among customer requests. IGES, STEP and SAT were listed as proper file formats for the models by interviewee M. Participant N told that they comply with STEP, but IFC would be even better since it holds more metadata than STEP. Respondent H assumed that STEP is popular because it is open, not software specific format.

So, another file type related critical factor includes advocation to manage the *exported file as STEP format* as it is the most universal and also, the most requested. The support for optional file formats is desired but not necessitated. It may appear as additional flexibility from the supplier's side if other than STEP models could be obtained as well. Of course, it would then require a separate request from the customer. That is why the STEP should be an initial default setting to keep things fluent as long as no other clear requirements occur. Moreover, as a neural file format STEP offers the best compromise considering the file size as well.

Each of the methods also meet the principal expectation of obtaining STEP models. Actually, STEP is the default format when using the subcontractor or Cuusamo configurator. Other tools support also plenty of other formats such as STL and IGES. In addition, it is also possible to create specific exportation format functions in NX assuming that STEP format does not come into question.

Spatial Geometries

Demonstrating overall main dimensions of the horizontal and vertical directions is the principal meaning of the 2D main dimensions drawing. Especially respondents G and L emphasized during the interviews that the drawing is the minimum requirement for a new order, which is in line with interviewees M and N who even considered the document as self–evident. As it is easier to use the model over the drawing for layout arrangements, the same *main dimensions* should be measurable from the 3D model as well, and thus it is carried out as the next critical factor. That is to say, those components that add up need for space reservation should be included to the customer model.

Interviewee B explained that when the customer models are ordered from the external subcontractor, the main dimensions are accurate as the 3D is modeled according to the 2D drawing. With the rest of the methods, the accuracy can be set to whichever resolution is desired. The main concern is more about what components, with respect to the space reservations, should be added to the model. None of the modeling methods seems to be better or worse to handle the assemblies.

Most of the opinions preferred modeling of terminal boxes and heat exchangers. Without exception, the components require plenty of space, which need to be taken into account – at least sizes and locations of the boxes. Terminal boxes and heat exchangers are illustrated not only for space reservations but also for locating some *connection points* which is the forthcoming critical factor.

At least electrical and auxiliary connection points in the terminal boxes were mutually considered relevant, but the corresponding cablings not so much. The heat exchanger comes often with water piping and it is important that at least the flanges are properly located in the 3D model. Answer to whether to model the pipes as well, was less conspicuous. Although the geometric shape does not reveal any sensitive information, it certainly increases geometric complexity.

It was brought up that everything related to connections or installation points from the customer side should also be illustrated in the 3D model. The customer can have for example, an external lubrication unit for bearings. According to informants A and M, it could be beneficial to model the connection points in case. Then again, some respondents (C, N) saw small components, including external lubrication units, as void for space reservations.

The respondents agreed that the most dominant parameters of product models are the location of the drive–end of the shaft, and the distance from this point to the feet. These connection points must be nothing but accurate in both, the 2D drawing and the 3D model. The location of the shaft determines the attachment point of the coupling and the feet placement defines mounting points of the entire machine, both of which are primary constraint areas in the customer interface.

Apparently lifting points of a machine are not critical information. Only participants M and L said that they could be included to dimensional information if it does not require extra effort and the others were not concerned about the lifting lugs at all.

With the connection points, the question is about whether the certain 3D features are modeled or not. The external subcontractor models connection points according to mutually agreed constant resolution. From fully configured methods Oikku and Cuusamo, the connection point locations are generated automatically according to predefined configurations. NX and Teamcenter configurators and parameterized FEM modeling follow the same idea, except it is slightly easier to do minor manual modifications afterwards. Then again, using *Linked Exterior*, *Linked Bodies* and reduced FEM models the connect points are replicated directly from the detail structure.

The most challenging requirement related to the illustration of areas for maintenance, service or other functional operations. Limitations regarding the surrounding space of the machine depend on the application and performance of its components. For example, installation of the rotor, hot air from the cooling unit and opening of the cooling window require extra space to be reserved around the machine.

Designer interviewees from ABB told that customers have been able to check the extra space specifications from the manual of the machine which is always provided among the other customer documents. Sometimes these dimensions have also been manually marked to the 2D drawing when requested, but so far, they have not been included to the 3D model. Though, some designers (A, C, G) admitted that modeling of additional spaces would be helpful if a convenient way to do so can be found.

According to customer N, a need for maintenance and service space information is certain. The person showed examples from their own layout model, used in shipyard 2, where space reservation areas were illustrated with either 2D sketches or translucent solids. The former is represented in Figure 24 where the cooling windows of ABB generator are depicted in open position with 2D sketch planes. Figure 25 demonstrates the latter with the situation where many generators need to be located close to each other while respecting the space boundaries.

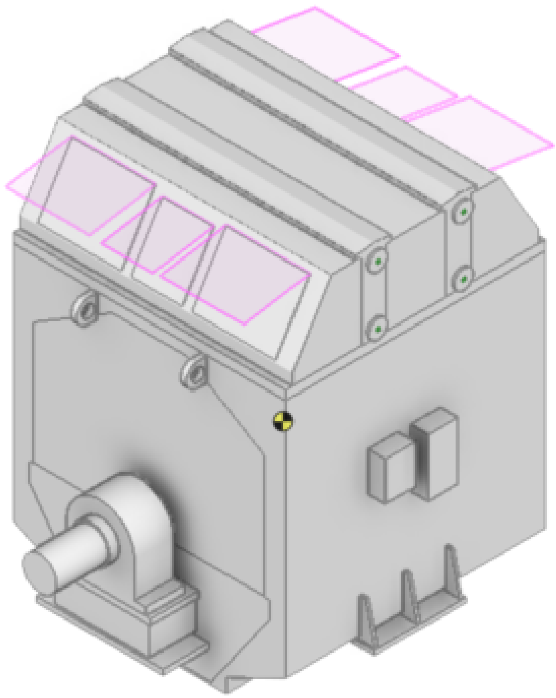

Figure 24. 2D sketches represent the open position of cooling windows (Shipyard 2 27.2.2020).

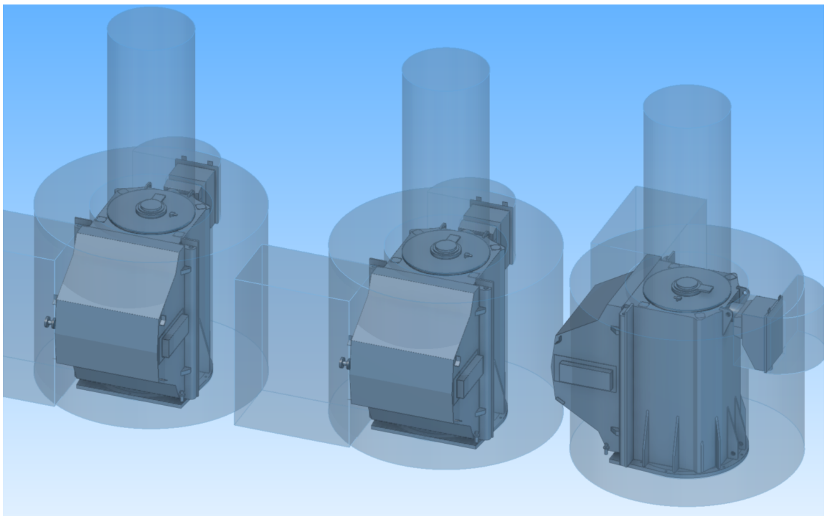

Figure 25. Translucent features illustrate space reservation areas and help to locate multiple generators so that they are not too close to each other (Shipyard 2 27.2.2020).

Space reservations are exclusively essential in ship layouts, and as respondent L puts it, maintenance and service tasks are usually proceeded in place since facility equipment is rarely moved elsewhere from the ship for the particular procedures. Visual maintenance and service spaces were the most requested feature which, however, have not yet been accomplished to fulfill. This requirement was not obligated, but it would forthwith provide increased customer satisfaction. Consequently, the visibility of *maintenance and service areas* is worth to be considered as one of the critical factors.

Assuming that maintenance and service spaces need to be consistently modeled, their respective features should be conditionally prepared in Cuusamo and Oikku configurators beforehand. In order to include the areas to the models that are ordered from the external subcontractor, communication and negotiation through a bureaucratic information system is needed because the features are not modeled by default. With the rest of the methods, depiction of the space reservations as translucent solids could be modeled manually before the final exportation. The latter would be the one to pursue since it allows more flexibility with the sudden but irregular marine orders. The only question mark is the syntax definition of CAD software from which the model is exported and to which the file is imported. Both CAD translators should support similarly different features, such as the translucency level. Otherwise the misrepresented information may result in disturbing obstacle rather than an additional benefit.

The case was examined with a minor experiment by modeling a random box, to represent maintenance and service spaces, around a conceptual product model. The conceptual model in the experiment was extracted using *Linked Exterior* tool in NX, and the surrounding box was modeled as a yellow translucent solid feature with 50% of translucency (the right side of Figure 26). Both, the conceptual product model and the translucent box can be either in the same part file or in different part files but in the same assembly file. The combination was exported as STEP file using version AP214.

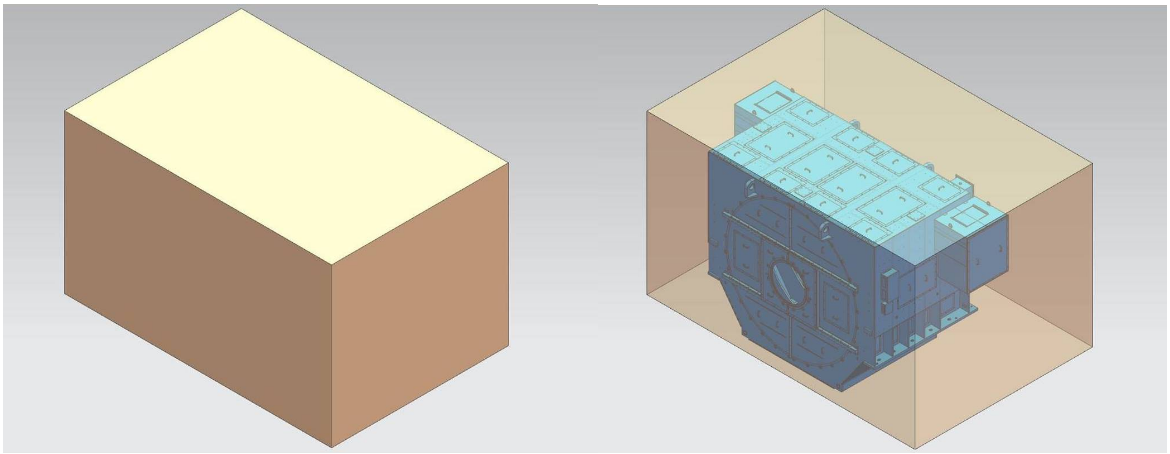

Figure 26. Demonstration of STEP exportation when additional space reservation was manually modeled as a translucent box and combined with a conceptual product model (ABB 8.5.2020).

As the result from the exportation, *Linked Exterior* feature does not show anything else but the solid box with the constant color (the left side of Figure 26). As expected, the STEP version conveys colors but not the transparency information. Nevertheless, the exterior feature still exists inside the box. When the STEP model is opened in any modern CAD software, the yellow box is relatively easy to change back into translucent, which was confirmed by informant K. The technique is valid in theory, but the customer needs to have the right kind of CAD tools to manually modify the model.

One critical factor, related to the exterior geometry, was condensed to stress the importance of the *visual outlook*. The factor seemed to be no brainer with any of the presented methods, but in space reservations it is among the most dominant ones. With NX, TC, Cuusamo and Oikku configurators the accuracy of the outlook can be adjusted by modifying the pre–configured features. The same applies to the parametric FEM model. With *Linked Exterior*, *Linked Bodies* and manually reduced FEM models, the accuracy decreases according to how heavy is the reduction of 3D detail features. Outlook of the models that are modeled by the subcontractor is not adjustable, but so far, the level has been satisfying without a need to require visual modifications.

Maintenance

According to attributes of conceptual 3D models, they should not include any sensitive details, and therefore it has been safe to send the models to customers by email. On the other hand, emails set some boundaries to the maximum size of the files because many mail servers limit the total size of attachments to 20–25 MB.

Since email services provide probably the most flexible sharing platform, 20 MB should be considered as the definitive maximum, unless more constraining requirements for a smaller file take place. Different tools for splitting, zipping and sharing the models exist, but due to idea of as small file size as possible is generally upheld, this limitation helps to keep things more forthright. Besides, when taking the previous critical factor of 3D models being under 10 MB into account, email attachment size restriction will not take over.

Contacts G, L and M told that vendors rarely need to save 3D models for later purposes. They do not use models themselves but send them forward to the customers, namely shipyards. Conceptual 3D models are not widely used in detail designing, so they do not have any absolute value for the main design either. The models should be modeled so that there is no need to modify them afterwards. Hence, the linkage from the models to the PDM system is not demanded. For this reason, the next critical factor suggests that the *customer models are saved apart from the detail design*. Meaning that both reduced and detail designs can be stored in the same place, but any revision action made to the detail structure do not have effect whatsoever on the conceptual one. If some revisions are needed afterwards, then it must be reconsidered whether to deliver the new model based on the previous conceptual model or based on the current detailed model.

Critical Factors

As the result from the interviews, I carried out ten critical factors (Table 3). An important aspect to consider is the information to be included to the customer documents, whether it is in 2D or 3D form. Factors *1* and *2* pursue to rank the modeling methods based on their usability in the current sales order processes. The time point matter is determined with factor *3*. Guidelines for output resolution and posterior handling of the models are given by factors *4*, *5* and *10* which are set to offer a temporal solution, but which will need more refining in the future. Since it has been a basic assumption that most of the information is offered via the 2D drawing, the visual space reservation appears to be the most significant contribution of the 3D models. Accordingly, the remainder factors (*6—9*) relate to the geometrical appearance of the model.

Table 3. The critical factors for the best practise proposal.

Critical Factor	**Definition**
1. Easy and fast	The method is easy and fast to implement consistently as a routine task by a single person.
2. Flexibility	The method is applicable to different kinds of components or assemblies despite the product type.
3. Concurrency of the 2D and 3D documents	The 3D model and the 2D main dimensions drawing are provided to the customer at once.
4. Exported file size under 10 MB	The maximum file size for 3D models is 10 MB.
5. Exported file as STEP format	3D models are exported in STEP format by default. Other uniform formats can be provided as an additional benefit.
6. Main dimensions	At least geometrical information of the frame, heat exchanger and terminal boxes should be included.
7. Connection points	Attachment points of the feet and shaft, water flanges and pipes, electrical and auxiliary connection points should be carefully depicted.
8. Maintenance and service areas	Space reservation areas are modelled as transparent solids according to the product manual, in case the customer is able to read the information.
9. Visual outlook	The outcome model should have recognisable level of details and all inner parts should be suppressed.
10. Customer models saved apart from the detail design.	The 3D model is separately saved after it has been forwarded to the customer.

It must be noted that some of the factors are somewhat exclusionary. For example, increasing visual outlook is ideal, but it also increases the size of the models, which is against the desired notion of light models. Also, it can be said that the most constraining factors for the methods that were investigated during this study ended up being the file size, with which was settled to produce as light models as possible, and the maintenance and service areas, with which the problem was not fully solved.

The critical factors are one more time listed in Appendix II with respect to the previously introduced modeling methods. The methods in the table contain values from zero to two, zero meaning incapable to satisfy the corresponding critical factor. Number one implies that the method is feasible in theory if the preliminary work is properly managed. Those methods that are able to directly satisfy the given factor received value two. Additionally, the rows in the table (Appendix II) are ranked according to the sum of the values on each method. However, the best values do not necessarily equal the best practice, but some conclusions can be drawn.

As it can be noticed, ABB uses many different kinds of product configurators for both detailed and conceptual geometries to automate 3D modeling tasks. Configurators have clearly offered the most lightweight models. Even though the electrical machines that ABB delivers to marine customers are highly customized, it can be assumed that at least some of the components are identical. In other words, not every single component is customized within millimeter scale so some constant parts with some varying dimensions may exist. With this in mind, there actually is a hypothetical possibility to build a configurator for the particular constant part of the machines. However, the need to predefine the configurable variants is lamentably a pivotal drawback, especially when more detailed knowledge of the machine types is not available. Considering the contribution conceptual modeling provides to the whole design stage, the benefit from a configurator is still relatively small. Due to unequal and comparably low annual need of the marine products, the time investment on partial parameterization or configuration of the customer models would not necessarily pay back. The high level of variation within the products also fades the benefit. Manual modeling of individual parts after the configuring would be necessary anyway so no matter how fast the configurator would be, but a combination of many different tools for one model may easily escalate and appear as a complex and confusing task. Occasional need for the models creates a situation where one is not willing to invest a lot for background maintenance and configuring work. When it comes to the flexibility, configurations are not the most helpful. With marine machines, something more appropriate for unique designs should be applied. Thereby, configurators are not considered as an option for conceptual modeling of marine products.

The main concern with the FEM models is delegation of the modeling tasks. Synthesizing the customer models with the calculation models requires diverse adapting and integration from several different areas of the product design. When the structural analyst is preparing the plain geometry, whether in parameterized or in reduced way, the order engineer needs to take care of the rest of the modeling as the model is not yet feasible as it is. This means that at least two people are involved to the one main task. Because it is not certain that the FEM model is automatically needed with the orders, conceptual modeling should be an independent process so that in case FEM processes are excluded the conceptual modeling remains straightforward. Similarly to the configurators, FEM models also lack some flexibility. FEM models, modeled by structural analysts and modified by order engineers, should rather be a standby option than the primary practice.

Ordering the 3D models from the subcontractor turned out to be a considerably potential option despite the waiting time of one full workday. The method is efficient especially in projects where the whole detail modeling is implemented using only 2D tools. In contrast, the benefit is no longer overwhelming when the 3D structure already exists. In these situations, it would be waste of time to derive the main dimension drawing from the detailed 3D model in order to obtain a new 3D model. Because of the inability to manually modify the models afterwards due to the STEP format, the method is not the first one to be recommended.

Then there are two NX tools, *Linked Bodies* and *Linked Exterior*, both of which have a lot of similar characteristics as they practically allow conceptual modeling of any type of product. However, *Linked Exterior* is slightly faster and it produces a smaller file size by saving only the visible surface of the machine whereas *Linked Bodies* generates wide solids, combined from number of components resulting as higher total volume of the exported model. Therefore, *Linked Exterior* is preferred over *Linked Bodies*.

3.5 Best Practice Proposal

Conceptual 3D modeling seems to be tightly depended on the detail design of the products. It is possible to model the detail design apart from the customer model but not the other way around. The customer model is a temporary product, produced with the short–term aim. It does not necessarily have effect on the end–product, but it is a central component of the customer experience. In this light, the concept modeling for customers should be assimilated as a part of the current principal CAD practices. However, ABB has already developed a great set of tools and protocols for the main level product designing which should not be bothered in general. At this point, based on these reasonings, it is not rational to propose a new or radical solution.

The time point when the best practice method is proposed to be implemented is decided to be the one marked with connector C in the prior Figure 10. The proposal is depicted as a new part of the current process in the beginning of the sales order (Figure 27). The idea is that the previous process is not disturbed and the new sub process for modeling the customer models is herewith attached.

Linked Exterior tool is proposed as the best practice solution for modeling the conceptual 3D CAD models for marine sales purposes. This is the main protocol in cases where the detail structure is fully designed using 3D. Whenever the 3D design of the detail structure is finished so that the components according to the critical factors have been modeled, and the 2D main dimensions drawing can be prepared, the conceptual reduced model can be carried out. The task belongs primarily to the order engineer team from which the designer of the project checks the detail design as usual and makes sure that the whole assembly looks appropriate and that there are not any sensitive or irrelevant outer parts that need to be hidden or removed. Lastly, *Linked Exterior* tool in NX is utilized in order to obtain the 3D exterior feature.

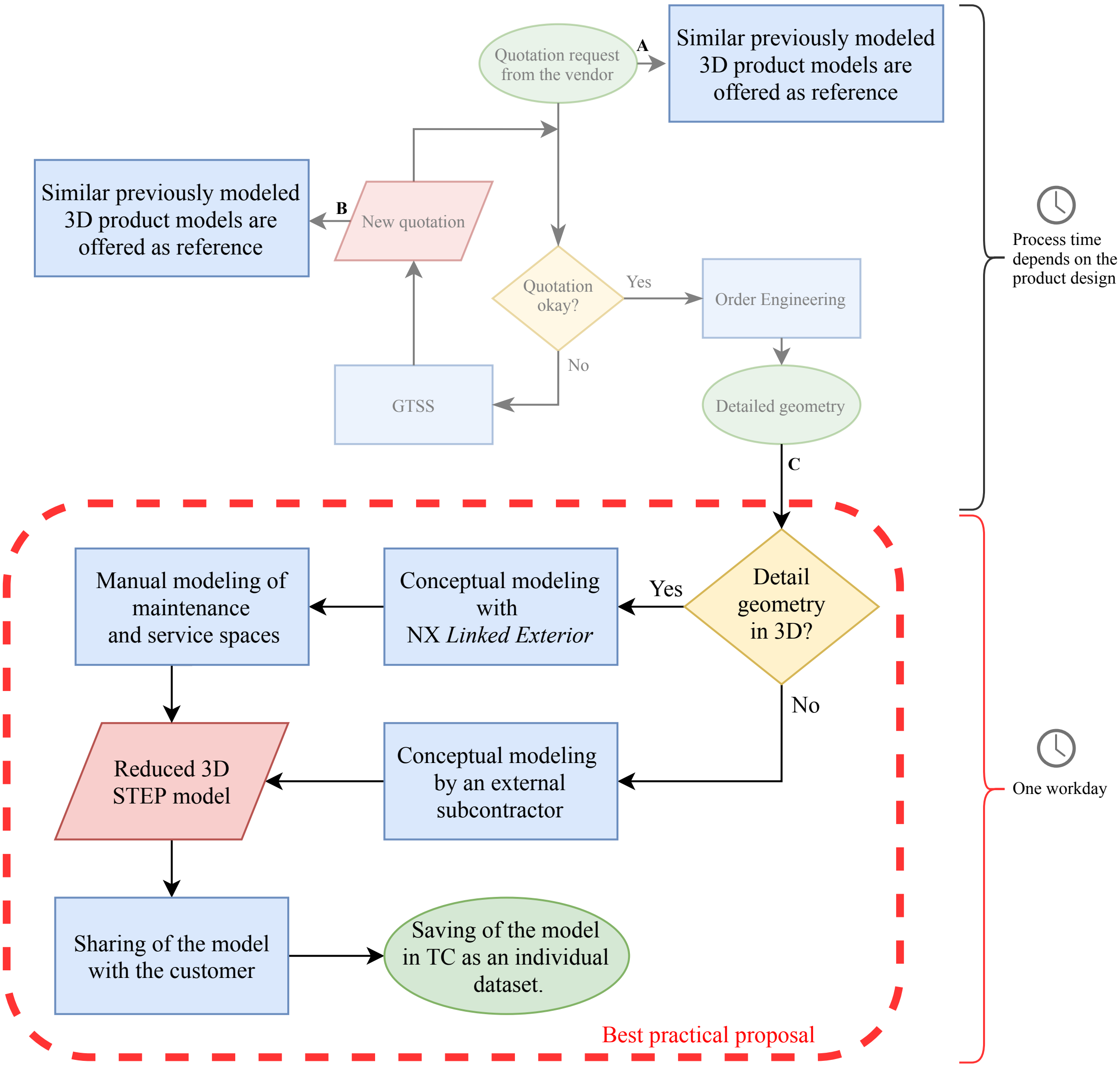

Figure 27. The best practice proposal is suggested to be an extension for the current sales process.

In more rare cases when the detail design is 2D modeled, 3D modeling task is outsourced to the external subcontractor. Then the designer prepares the main dimension drawing and creates a new request for the 3D model.

At this point, the conceptual 3D model has been obtained either by *Linked Exterior* or external subcontractor. For the *Linked Exterior* model, maintenance and service area related space reservations are manually modeled as translucent solids according to the product manual. The designer needs to be sure that the maintenance and service spaces are requested by a customer who is able to modify or remove the translucency features afterwards. If the situation is unclear, the areas should not be modeled. For externally modeled STEP models, the maintenance and service spaces are not modeled at all. Finally, either the reduced geometry alone or together with the surrounding space reservation features is exported as a STEP assembly.

The conceptual 3D model is delivered to the customer via email. Despite a few manual tasks, the conceptual model can be delivered within one workday, after which it is stored in Teamcenter. As it was noticed, there is no need to maintain a real–time connection between the conceptual and detail models. In that sense, it seems reasonable to save the conceptual model as a separate customer document, but in a way that they can be henceforth easily searched. This is implemented by informing designers to create a new individual item code for the STEP model and to save it as a distinct dataset to the BOM structure of the corresponding project. This way the models is globally accessible for ABB engineers.

According to the previous suggestion of the models being prepared rather later than earlier during the quotation, possible requests at the early stages (marked with connectors A and B in Figure 10) are this way ignored. Assuming that the uniqueness is more scarce than radical, previous customer models could be suggested as preliminary references until the exact version is modeled. For this purpose, the models are suggested to be labeled with generally agreed tags when saving them in Teamcenter so that they can be sorted out more comprehensively.

It must be clear to the customer what can possibly be requested or expected. For example, from now on in marine orders it is possible to obtain the 3D concept model at the same time with the main dimensions drawing, once the preliminary detail design is finished. Directive reference models can be inquired even earlier. The default format of the exported model is STEP with the file size under 10 MB. Additionally, some specific file formats can be requested separately. Clarifying the options is important because not all arbitrary customer wishes can be responded. Clarity also guides the requests since it is easier to request within explicit alternatives.

Although the practice is relatively simple, good results can be obtained if the proposal is followed consistently. It is good to bear in mind that one minor update to conventional actions cannot make a big change unless it is adopted as routine task. Mutual awareness and agreement of persistently applying the method in marine processes should be established. The longer this is advanced, the more library for coming quotations is collected. In future, this also allows ABB to offer 3D models earlier.

4 DISCUSSION

Early in the research process, it became clear that, given the current resources, it is not possible to come up with a fully automated solution that covers a whole range of highly customized machines. The same general conclusion is made by Jaiswal et al. (2016) who study assembly–based conceptual modeling. Thus, the only way to obtain conceptual 3D models is to extract them from existing detailed designs – either by manually modeling based on 2D drawings or by using 3D modeling tools to copy the main features from a detailed 3D structures. This is generalizable not only to to marine machines but to other tailor–made products as well.

One relatively predictable finding was that there are often problems when transferring both geometrical and non–geometrical data from one engineering software to another. These transfers occur both within ABB's internal and between ABB's and its customers' CAD systems. Respective issues cannot be solved with a single solution. In ideal world, multiple CAD software are integrated so that data transfer works seamlessly.

An interesting and also surprising finding is that the time point when conceptual 3D models are delivered turned out to be not as crucial as originally expected. Instead, the time factor becomes much more important when the customers have to deal with heavy layout assemblies resulting in increased waiting times. Therefore, the file sizes of customer models should be minimized with the best possible ways. This is noted in many studies (see for example, Cagan et al. (2002) and Hassan et al. (2017)). If the models were lighter, the supplier does not only reduce the time in its own modeling process, but also the time of its customers.

Another finding is that marine customers, indeed, widely ask for the inclusion of maintenance and service spaces in 3D models. By now, this need has not been satisfactorily addressed, maybe because these features are rarely needed in detail design stage. Further emphasis should be given on this area in the future.

Together the present findings emphasize that my proposal for the best practice is rather general and does not address small details. One such issue is how to 3D model maintenance and service areas. Further investigation in STEP files and in their support of translucent solid features were also excluded this time. Another issue is the file size constraint that was set based on the current mainstream requirements. These issues were, however, acknowledged while constructing the best practice proposal. There are also other caveats.

Only currently used software were considered and adoption of totally new methods, even though not necessarily less effective, were ignored. Additionally, I do not question or review the critical factors that came up in interviews. It must be noted that the ranking system for the critical factors was relatively rough, and I used equal weights for all of them (see Appendix II). Concerning the empirical method, interviews, a larger sample of participants would have benefited the work, but due to time constraints, I ended up with 14. Even more focus would have be given to the customer interface. I could also have conducted follow–up interviews where my proposal for the best practice would have been assessed by the interviewees. Because of the time constraint, this was not possible.

Customer needs can be very different depending on the customer, creating a continuous challenge for supplier companies. Thus, compromises must be done. The question is, how to do them efficiently? After all, the customers have certain expectations that cannot be handled automatically.

5 CONCLUSIONS

In this master's thesis, I proposed a best practice for providing reduced 3D models to marine customers at sales stage at ABB, a company designing and manufacturing large electric machines. ABB currently uses many 3D tools for conceptual modeling of customer models. Many of these methods are based on automated configurators. They are the best option for mass–produced machines where the basic product structure is designed before selling it to the customer. Tailored marine products clearly require more flexible solutions. However, there has not been a consensus at the firm on what is the right time to deliver the models or what factors are critical to customers.

To map customer needs and document current practices at ABB, I conducted a qualitative pre–study using semi–structured interviews. Then, I used thematic content analysis to find out which of the current methods suit for the needs considered critical, and came up with a best practice proposal.

Based on the interviews, I found ten critical factors related to the customer models. These can be grouped into three categories: spatial geometry, model file specification, and the desired time point when to provide the models. If the detail model is 3D modeled, I propose using *Linked Exterior* tool to produce the conceptual models. If, however, the detail design is 2D modeled, the best practice is outsourcing modeling task to an external subcontractor. In both cases, conceptual 3D models are available within one workday. The procedure I propose should decrease confusion and inconsistency during the sales process. Conceptual 3D models also benefit ABB, and not just the customer. For instance, ABB can use them in commercial presentations, acoustic calculations, and FEM analyses. Importantly, the proposed practice is generalizable also in other product categories within the firm.

However, the proposed solution does not satisfy all customer needs. Remaining issues are 1) minimizing the size of 3D CAD models, and 2) how to include maintenance and service spaces in the models using neutral file formats which do not easily support the inclusion of those spaces.

To summarize, fine CAD software alone is not sufficient to successfully 3D model conceptual customer models for sales purposes. Firstly, the customer needs have to be known as well. Secondly, the implementation of the detailed model affects the way the customer model should be constructed. The models of large motors and generators in marine industry are highly tailored. Therefore, it seems not realistic, given the current resources, to construct conceptual models before the actual detailed design is finished.

REFERENCES

Aldanondo, M., Rougé, S. and Véron, M. (2000), 'Expert configurator for concurrent engineering: Caméléon software and model', *Journal of Intelligent Manufacturing* **11**(2), 127–134.

Balkan Architect (2019), 'Beginner Revit Tutorial - 2D to 3D Floor Plan (part 2)', *YouTube* [Online], Available at: https://www.youtube.com/watch?v=kQCakJ6I5Hw. (Accessed: 19 February 2020).

Ball, A., Ding, L. and Patel, M. (2007), 'Lightweight formats for product model data exchange and preservation', PV 2007 Conference, Oberpfaffenhofen/Munich, Germany, 9/10/07 -11/10/07.

Barbosa-Póvoa, A. P., Mateus, R. and Novais, A. Q. (2002*a*), 'Optimal 3D layout of industrial facilities', *International Journal of Production Research* **40**(7), 1669–1698.

Barbosa-Póvoa, A. P., Mateus, R. and Novais, A. Q. (2002*b*), 'Optimal design and layout of industrial facilities: a simultaneous approach', *Industrial & Engineering Chemistry Research* **41**(15), 3601–3609.

Bénabès, J., Poirson, E. and Bennis, F. (2013), 'Integrated and interactive method for solving layout optimization problems', *Expert Systems with Applications* **40**(15), 5796–5803.

Berg, B. L. (2004), *Qualitative research methods for the social sciences*, 5th edn, A Pearson Education Company.

Bozlu, B. and Demirörs, O. (2008), 'A conceptual modeling methodology: from conceptual model to design', *Proceedings of the 2008 Summer Computer Simulation Conference*, Edinburgh, Scotland. January 2008.

Bremdal, B. A. and Kristiansen, S. (1986), 'Concept definition in marine system design', in Sriram, D. and Adey, R. (eds.) *Applications of Artificial Intelligence in Engineering Problems.* Berlin: A Computational Mechanics Publication, pp. 403–421.

Cagan, J., Shimada, K. and Yin, S. (2002), ‘A survey of computational approaches to three-dimensional layout problems’, *Computer-Aided Design* **34**(8), 597–611.

Contero, M., Vila, C., Aleixos Borrás, M. N. and Others (2002), ‘Product data quality and collaborative engineering’, *IEEE Computer Graphics and Applications* **22**(3), 32–42.

De Troyer, O., Bille, W. and Kleinermann, F. (2009), ’Defining the Semantics of Conceptual Modeling Concepts for 3D Complex Objects in Virtual Reality’, in Spaccapietra, S. and Delcambre, L. (eds.) *Journal on Data Semantics XIV.* Berlin: Springer Berlin Heidelberg, pp. 1–36.

Eigner, M., Handschuh, S. and Gerhardt, F. (2010), ‘Concept to enrichen lightweight, neutral data formats with CAD-based feature technology’, *Computer-Aided Design and Applications* **7**(1), 89–99.

Erlingsson, C. and Brysiewicz, P. (2017), ‘A hands-on guide to doing content analysis’, *African Journal of Emergency Medicine* **7**(3), 93–99.

Eskola, J., Lätti, J. and Vastamäki, J. (2018), ’Teemahaastattelu: lyhyt selviytymisopas’, in Valli, R. (ed.) *Ikkunoita tutkimusmetodeihin.* PS-kustannus, pp. 27–51.

Espoon kaupunki (2018), ‘LOD levels on buildings’, Available at: https://kartat.espoo.fi/3d/citymodel.html (Accessed: 2020/03/16).

Etikan, I., Alkassim, R. and Abubakar, S. (2016), ‘Comparision of snowball sampling and sequential sampling technique’, *Biometrics and Biostatistics International Journal* **3**(1).

Flick, U. (2018), *Designing Qualitative Research*, SAGE Publications Ltd.

Forza, C. and Salvador, F. (2002*a*), ‘Managing for variety in the order acquisition and fulfilment process: The contribution of product configuration systems’, *International Journal of Production Economics* **76**(1), 87–98.

Forza, C. and Salvador, F. (2002*b*), ‘Product configuration and inter-firm co-ordination: an innovative solution from a small manufacturing enterprise’, *Computers in Industry* **49**(1), 37–46.

Griffin, A. (1997), 'Drivers of NPD Success: The 1997 PDMA Report', *Chicago, IL* .

Gubrium, J. F. and Holstein, J. A. (2001), *Handbook of interview research: Context and method*, Sage Publications.

Hansen, T., Scheer, C. and Loos, P. (2003), 'Product configurators in electronic commerce–extension of the configurator concept towards customer recommendation', Proceedings of the 2nd interdisciplinary world congress on mass customization and personalization (mcp).

Hartman, N. W. (2009), 'Evaluating lightweight 3D graphics formats for product visualization and data exchange', *Journal of Applied Science & Engineering Technology* **3**.

Hassan, F. H., Ibrahim, N., Kit, H. and Abdullah, R. (2017), Incorporating Genetic Algorithm Operators in Optimization Spatial Layout Design, pp. 179–183.

Haug, A., Hvam, L. and Mortensen, N. (2011), 'The impact of product configurators on lead times in engineering-oriented companies', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **25**(2), 197–206.

Hennig-Thurau, T. and Klee, A. (1997), 'The impact of customer satisfaction and relationship quality on customer retention: A critical reassessment and model development', *Psychology & marketing* **14**(8), 737–764.

Hosseini-Nasab, H., Fereidouni, S., Fatemi Ghomi, S. M. T. and Fakhrzad, M. B. (2018), 'Classification of facility layout problems: a review study', *The International Journal of Advanced Manufacturing Technology* **94**(1), 957–977.

Hvam, L., Mortensen, N. H. and Riis, J. (2008), *Product customization*, Springer Science & Business Media.

Jain, A. K., Khare, V. K. and Mishra, P. M. (2013), 'Facility planning and associated problems: a survey', *Innovative systems design and engineering* **4**(6), 1–8.

Jaiswal, P., Huang, J. and Rai, R. (2016), 'Assembly-based conceptual 3D modeling with unlabeled components using probabilistic factor graph', *Computer-Aided Design* **74**, 45–54.

Juran, J. M., and Godfrey, A. B. (1999), *Juran's quality handbook*, New York: McGraw Hill.

Kärkkäinen, H., Piippo, P. and Tuominen, M. (2001), 'Ten tools for customer-driven product development in industrial companies', *International Journal of Production Economics* **69**(2), 161–176.

Khan, S. and Tunçer, B. (2019), 'Gesture and speech elicitation for 3D CAD modeling in conceptual design', *Automation in Construction* **106**, 102847.

Kikoski, C. K. and Kikoski, J. F. (2004), *The inquiring organization: Tacit knowledge, conversation, and knowledge creation: Skills for 21st-century organizations*, Greenwood Publishing Group.

Komoto, H. and Tomiyama, T. (2012), 'A framework for computer-aided conceptual design and its application to system architecting of mechatronics products', *Computer-Aided Design* **44**(10), 931–946.

Liu, C., Ramirez-Serrano, A. and Yin, G. (2011), 'Customer-driven product design and evaluation method for collaborative design environments', *Journal of Intelligent Manufacturing* **22**(5), 751–764.

Luo, X., Yang, Y., Ge, Z., Wen, X. and Guan, F. (2015), 'Maintainability-based facility layout optimum design of ship cabin', *International Journal of Production Research* **53**(3), 677–694.

Market Watch (2020), 'Computer Aided Design (CAD) Software Market Size, share 2020 – 2026 Pointing to Capture Largest Market Growth and Share with Developed Economies | New Report by Market Reports World', Available at: https://www.marketwatch.com (Accessed: 21 April 2020).

Meller, R. D. and Gau, K.-Y. (1996), 'The facility layout problem: Recent and emerging trends and perspectives', *Journal of Manufacturing Systems* **15**(5), 351–366.

Merton, R. K., Fiske, M. and Kendall, P. L. (1956), *The focused interview: a manual of problems and procedures*, 2nd edn, The Free Press.

Nonaka, I. and Takeuchi, H. (1995), *The knowledge-creating company: How Japanese companies create the dynamics of innovation*, Oxford university press.

Patton, M. Q. (1990), *Qualitative evaluation and research methods*, 2nd edn, SAGE Publications Ltd.

Pillai, M., Hunagund, I. and Krishnan, K. (2011), 'Design of robust layout for Dynamic Plant Layout Problems', *Computers & Industrial Engineering* **61**, 813–823.

Raman, D., Nagalingam, S. V. and Lin, G. C. I. (2009), 'Towards measuring the effectiveness of a facilities layout', *Robotics and Computer-Integrated Manufacturing* **25**(1), 191–203.

Robinson, S., Arbez, G., Birta, L., Tolk, A. and Wagner, G. (2015), Conceptual Modeling: Definition, Purpose, and Benefits.

SASIG (2005), Product Data Quality Guidelines for the Global Automotive Industry, Technical report, Strategic Automotive product data Standards Industry Group.

Seidler-de Alwis, R. and Hartmann, E. (2008), 'The use of tacit knowledge within innovative companies: knowledge management in innovative enterprises', *Journal of knowledge Management* **12**(1), 133–147.

Singh, S. P. and Sharma, R. R. K. (2006), 'A review of different approaches to the facility layout problems', *The International Journal of Advanced Manufacturing Technology* **30**(5), 425–433.

Son, S., Na, S. and Kim, K. (2011), 'Product data quality validation system for product development processes in high-tech industry', *International Journal of Production Research* **49**(12), 3751–3766.

Sulankivi, K., Mäkelä, T. and Kiviniemi, M. (2009), BIM-based Site Layout and Safety Planning, *in* 'First International Conference on Improving Construction and Use through Integrated Design Solutions', number 259 *in* 'VTT Symposium', VTT Technical Research Centre of Finland, Finland, pp. 125–140.

Trentin, A., Perin, E. and Forza, C. (2012), 'Product configurator impact on product quality', *International Journal of Production Economics* **135**(2), 850–859.

Trincas, G., Mauro, F., Braidotti, L. and Bucci, V. (2018), Handling the path from concept to preliminary ship design.

Tuomi, J. and Sarajärvi, A. (2009), *Laadullinen tutkimus ja sisällönanalyysi [Qualitative research and content analysis]*, Helsinki: Tammi.

Tupper, E. C. (2013), Chapter 14 - Ship Design, *in* E. C. Tupper, ed., 'Introduction to Naval Architecture (Fifth Edition)', 5th edn, Butterworth-Heinemann, Oxford, pp. 343–377.

Vaismoradi, M., Jones, J., Turunen, H. and Snelgrove, S. (2016), 'Theme development in qualitative content analysis and thematic analysis', *Journal of Nursing Education and Practice* **6**, 100–110.

Vossen, C., Kleppe, R. and Hjørungnes, S. (2013), Ship Design and System Integration.

Wang, J., Zhang, X., Shou, W., Wang, X., Xu, B., Kim, M. J. and Wu, P. (2015), 'A BIM-based approach for automated tower crane layout planning', *Automation in Construction* **59**, 168–178.

Welfens, P. J. J., Addison, J. T., Audretsch, D. B., Gries, T. and Grupp, H. (1999), *Globalization of the Economy and Increasing International Competition*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–39.

White, P. D. and Cundiff, E. W. (1978), 'Assessing the quality of industrial products: What is the psychological impact of price and country of manufacture on professional purchasing managers?', *Journal of Marketing* **42**(1), 80–86.

Wielinga, B. and Schreiber, P. (1997), 'Configuration-design problem solving', *The International Journal of Advanced Manufacturing Technology* **12**(2), 49–56.

Xue, D. and Yang, H. (2004), 'A concurrent engineering-oriented design database representation model', *Computer-Aided Design* **36**(10), 947–965.

Yu, B. and MacCallum, K. J. (1996), 'Modelling of product configuration design and management by using product structure knowledge', in Tomiyama T., Mäntylä M., Finger S. (eds.) *JKnowledge Intensive CAD. KIC 1995. IFIP Advances in Information and Communication Technology.* Boston, MA: Springer, pp. 115–124.

Zhang, L. (2014), 'Product configuration: A review of the state-of-the-art and future research', *International Journal of Production Research* **52**, 6381–6398.

Zheng, J., Jiang, Z. and Chen, Q. (2012), 'Block spatial scheduling modelling and application in shipbuilding', *International Journal of Production Research* **50**(10), 2744–2756.

Background Information of the Interviewees

Interviewee code	Date	Contact type	Job title	*Permission 1	**Permission 2
A	16.1.2020	Face-to-face	Technical Sales Support Engineer	YES	YES
B	13.1.2020	Face-to-face	Senior Mechanical Engineer	YES	YES
C	13.1.2020	Face-to-face	Mechanical Specialist / R&D Engineer	YES	YES
D	29.1.2020	Face-to-face	R&D Principal Engineer	YES	YES
E	16.1.2020	Face-to-face	Senior Mechanical Design Engineer	YES	YES
F	29.1.2020	Face-to-face	Senior Software Engineer	YES	YES
G	21.1.2020	Face-to-face	Product Sales Specialist / Sales Manager	NO	YES
H	14.1.2020	Face-to-face	Application Owner	YES	YES
I	3.2.2020	Face-to-face	Mechanical Design Engineer	YES	YES
J	17.2.2020	Face-to-face	Senior R&D Engineer, Mechanical Design	NO	YES
K	3.2.2020	Face-to-face	PDM Local Application Owner	YES	YES
L	20.2.2020	Skype	Sales Support Development Engineer	YES	YES
M	10.2.2020	Skype	Technical Manager of Marine Systems	YES	YES
N	27.2.2020	Face-to-face	CAD/PLM Development	YES	YES

* Permission to record the interview session.

** Permission to assign one's name and relative background material forward when requested for scientific purposes.

3D Modeling Methods and Critical Factors

		Critical factors										
		Easy and fast	Flexibility	Concurrency of the 2D and 3D documents	Exported file size under 10 MB	Exported file as STEP format	Main dimensions	Connection points	Maintenance and service areas	Visual outlook	Customer models saved apart from the detail design	**TOT.**
3D modeling methods	ANSYS SpaceClaim	1	0	0	1	2	1	2	1	2	1	**11**
	ANSYS, reduced geometry	1	1	0	1	2	1	2	1	2	1	**12**
	Oikku 3D blocks	1	0	1	2	2	2	2	0	2	1	**13**
	Cuusamo	1	0	2	2	2	2	2	0	2	1	**14**
	External subcontractor	1	2	0	2	2	2	2	0	2	1	**14**
	TC Options and Variants	1	1	2	1	2	2	2	1	2	1	**15**
	NX Expressions	1	1	2	1	2	2	2	1	2	1	**15**
	NX Linked Bodies	2	2	1	1	2	2	2	1	2	1	**16**
	NX Linked Exterior	2	2	1	1	2	2	2	1	2	1	**16**

Notes: '3D modeling methods' are the methods that I considered as the most potential in ABB. 'Critical factors' are the criteria, condensed from the interviews, according to which each of the methods are ranked. Values 0–2 are given as follows:

0 – The methods is incapable to satisfy the corresponding critical factor.

1 – The method is feasible in theory, but some preliminary preparing or manual work is needed.

2 – The method directly satisfies the critical factor.