MODULAR PRODUCT DEVELOPMENT
LITERATURE REVIEW AND CASE STUDY

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ABSTRACT

Tampereen ammattikorkeakoulu
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Modular product development is an emerging approach in the area of product development. It seeks to bridge the gap between mass production and mass customization. In modular product development the product is divided into smaller sections which are called modules. There are six different types of modularity that can form this division. Modular product development can have various design goals which range from improved product service and customer satisfaction while still allowing speedy production.

This thesis introduces and reviews various modular product development methods found in the academic literature. The methods reviewed are Modular Function Deployment, Design Structure Matrix and Function Structure Heuristics. Each of these methods is specialized for certain tasks. The theory is tested in practice in the case study section of this thesis. The case study focuses on applying the theory in practice on the modular product development of environmental remediation systems produced by Doranova Ltd.

The thesis concludes that while modular product development has been discussed in the academic literature for many years more research is required and an agreement must be reached on a standard definition of modularity. To follow up the case study, further research could be done internally as a research and development project at Doranova Ltd.

Keywords: modular product development, modularisation, module

TIIVISTELMÄ

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Modulaarinen tuotekehittely on yleistyvä tuotekehittelyn keino, jolla tavoitellaan toimintaa massatuotannon ja massaräätälöinnin välimaastossa. Modulaarisessa tuotekehittelyssä tuote jaetaan tarkkaan määritettyihin osiin, joita kutsutaan moduuleiksi. Modulaarisella tuotekehittelyllä voi olla useita kehitystavoitteita, kuten tuotteiden huollon helpottaminen ja asiakastyytyväisyyden parantaminen ilman, että kokoonpanon vaatima aika kasvaa.

Opinnäytetyön tavoitteena on kartoittaa ja soveltaa kirjallisuuden esittämiä modulaarisen tuotekehittelyn konsepteja ja metodeja. Opinnäytetyössä esitellyt modulaariset tuotekehittelymetodit ovat Modular Function Deployment, Design Structure Matrix sekä heuristiset funktiorakenteet. Jokaisella metodilla on omat erikoispiirteensä ja käyttötarkoituksensa. Teorian toimivuutta kokeiltiin käytännössä tapaustutkimusosiossa, joka on osa Doranova Oy:n parhaillaan jatkuvaa ympäristönkunnostuskonttien modulaarista tuotekehittelyprosessia.

Vaikka modulaarista tuotekehittelyä on tutkittu jo useita vuosia, opinnäytetyön loppupäätelmä on, että teoreettista lisätutkimuksia modulaarisuuden käsitteistä ja niiden tarkentamisesta tarvitaan. Akateemisessa kirjallisuudessa tulisi löytää yhteisymmärrys modulaarisuuden määritelmästä. Tapaustutkimusta voidaan kehittää eteenpäin sisäisesti Doranova Oy:ssä.

Avainsanat: modulaarinen tuotekehittely, modularisointi, moduuli

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GLOSSARY

Domain Structure Matrix (DSM), a matrix based modularisation tool.

Function, a process that takes input and provides output.

Function Structure Heuristics, a function flow based modularisation tool.

Modular Function Deployment (MFD), a matrix based approach based on Quality Function Deployment of forming module candidates from a group of functions.

Modularity, the concept that products can be divided into distinct modules. Various methods of dividing the product are known as modularity types.

Modularisation, the process of forming modules

Module is defined ideally as a single part of a product with a single function.

Module Indication Matrix (MIM), a module candidate identification tool part of Modular Function Deployment.

Product diversity defines the customizability of a product.

Quality Function Deployment (QFD), a matrix based quality tool.

1 INTRODUCTION

1.1 Aim of the thesis

The aim of this thesis is to go through the basic concepts behind modular product development and analyse various modularisation methods and tools presented in the academic literature. The analysis is used as a basis for case study of modular product development for Doranova Ltd. Doranova Ltd is a Finnish environmental engineering company founded in 1995. The company specializes in various areas of environmental engineering field such as soil and groundwater remediation, water and waste treatment and renewable energy.

1.2 Mass customization and custom product development

Contemporary business world has evolved considerably in the past few decades from focusing on mass production to focusing on mass customization (Shamsuzzoha, 2010). Many engineering companies today are being pushed by tough competition to compete on smaller market segments which in turn has raised the need for more specialized and tailored products to meet the customers requirements. This has caused mass production to become less profitable and competitive in these specialized market segments. There are multiple ways to achieve mass customization - modular product development being one of them.

Pine (1993) provided insight in product mass customization which was an emerging phenomenon in the early 90s. Product mass customization aims to combine the benefits of production speed which is gained in mass production while still attempting to maintain a level of flexibility to allow product customization. In a more traditional factory setting, mass customization often works by delaying the customization process as late in the production as possible. Practical examples of such scenarios are situations where individual parts are assembled through mass production methods, but finally can be combined in different ways or parts to create a custom end product. This can be considered a certain form of modularity, which is discussed further in the next section.

Jiao et al. (2007) states that creating product variety improves profits under initial condition. Care must be taken however not to do so in excess. The meaning behind this is illustrated in Figure 1. If no mass customization is involved the process is essentially only mass production, meaning production costs and development costs remain low. Increasing the share of mass customization increases these two costs. This is known as the product diversity cost. However, since in mass production the product is not customized to meet the customer requirements, many customers may choose to sustain from purchasing the final product. The final product might be inconvenient for the customer which makes them more inclined in looking for alternative more convenient solutions. This is in turn known as customer dissatisfaction loss.

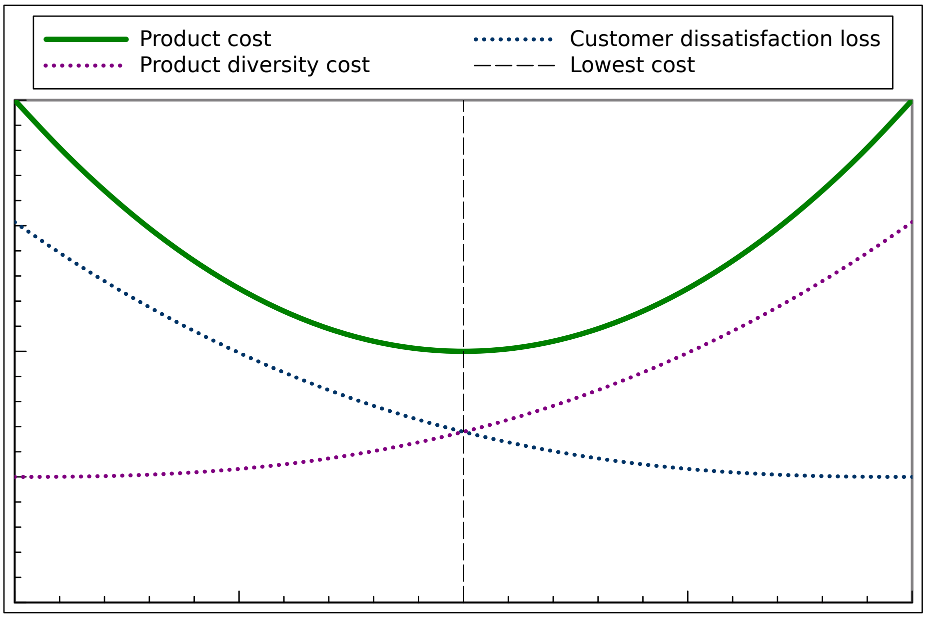

FIGURE 1. Impact of product diversity on cost benefits. Adapted from Kusiak (2011)

On the other hand with mass customization the product diversity is increased. This increases production and development costs, but at the same time reduces customer dissatisfaction loss. With proper optimization operations such as minimizing the complexity of internal product customization, the diversity costs can be further reduced for increased customer satisfaction. Company policy must determine what is the sweet spot as there is no right way to determine. A sweet spot can be considered as the optimum choice between product cost, diversity cost and dissatisfaction loss. It is not necessarily in the interests of a company to achieve the lowest possible cost as in mass production. Since customer satisfaction plays a central role in mass customization, it is reasonable to push the target at higher customer satisfaction even at the price of increased product cost. According to Piller (2005) customers are willing to pay premium of up to 150% to gain the benefits of truly customizable product.

2 MODULAR PRODUCT DEVELOPMENT

2.1 Overview of modular product development

In this section modular product development and its basic concepts are reviewed. Various methods and tools for developing and achieving modular products are reviewed for benefits and disadvantages over each other. The methods presented here are modular function deployment, design structure matrix and functional heuristic methods. These three methods are perhaps the three most commonly seen methods in academic literature on modular product development.

Modular product development falls in the middle of mass customization and mass production. Modular products are products, assemblies or components which can do various tasks and functions through carefully developed building blocks known as modules (Huang, 2000). The central idea of modularity is to increase production and development speed while also increasing customer satisfaction due to the easily customizable end product. As such it attempts to reap the benefits of both mass customization and mass production.

Hölttä-Otto (2005) points out that there is no agreement in current academic literature on the definition on modularity, largely due to lack of definition of what is the ideal module. In this thesis it is assumed that the ideal module is one that strives to perform a single major function of the product with as few sub functions as possible and as little function sharing with other modules as possible.

2.1.1 Six types of modularity

According to Stone et al. (1998) there are six basic types of modularity present in modular products. Österholm and Tuokko (2001) defines four of these as closed systems where components can be shared, swapped, fabricated to fit and mixed. The two remaining types are defined as open systems where components can be set up in either sectional or bus arrangement. The difference between closed and open systems is that the former tends to have more strict placement restrictions such as physical fit whereas the latter allows for more flexibility. The differences between these six types of modularity are further visually described in Figure-2

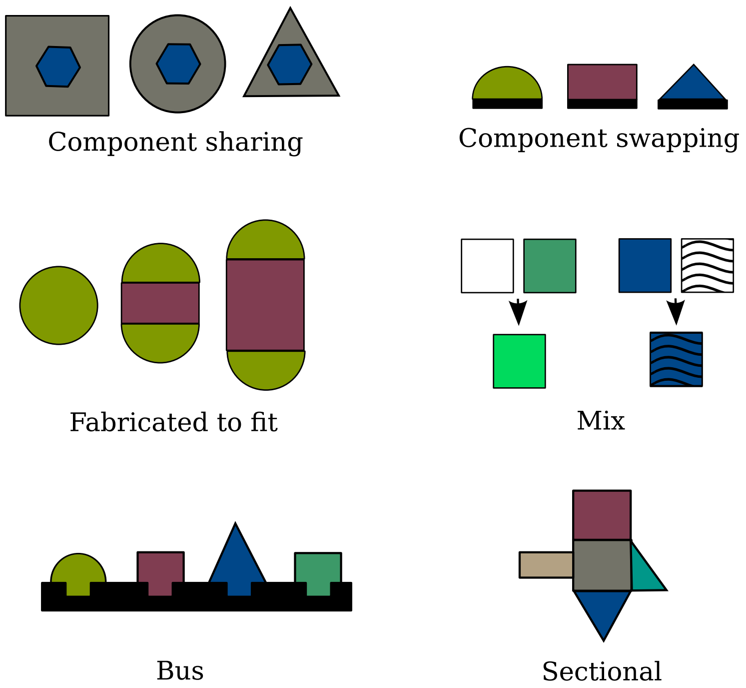

FIGURE 2. Different types of modularity. Adapted from Ulrich and Tung (1991)

In component sharing modularity the modular component is designed so that it can be used very flexibly in different product families (Swamidass, 2000). Ideally the component has an interface that can easily adapt to other parts to achieve the modularity. A good example of component sharing are printed circuit boards and the electronic components, such as resistors, that are placed on the boards.

Component swapping modularity on the other hand focuses having a standard interface between the two components. Where component sharing focuses on creating different basic products from same components, component swapping involves modifying the basic product with different components (Swamidass, 2000). Because the interface is readily defined, components can be swapped at will. Often the interface is designed so, that non-compliant components are unable to connect to the interface. This modularity is very common and can be seen in every day life: a hard disk in a computer using the SATA interface can be swapped with another one that uses the same interface. Light bulbs are also good examples of such components.

Fabricate-to-fit modularity, which is also known as cut-to-fit modularity, is a type of modularity where a standard product is created, but the physical dimensions can be modified to customer requirements after production. Examples of fabricate-to-fit modularity are insulation boards used in house construction - the boards are manufactured to standard size and are cut-to-fit on the construction site.

Mixing modularity is perhaps a less common type of modularity from engineering perspective. It essentially lacks a physical interface. Instead by combining two products through mixing a custom product can be created. A practical example of mixing modularity might be an ice cream shop that allows its customers to customise their ice cream through combining different flavours, toppings and sauces. Another good example are custom blended paints.

Bus modularity is partially related to component swapping modularity. However the most important difference between bus modularity and other forms of modularity is that the former allows more variation (Swamidass, 2000). The position and amount of components can be freely adjusted in bus modularity. Bus modularity is common in personal computers, but can also be seen to some degree in water piping networks. Finally sectional modularity is similar to component sharing. The main difference is that sectional modularity focuses on arranging the modules in unique patterns (Swamidass, 2000).

2.1.2 Modularisation

The modularity types discussed in previous section are the backbone for various modularisation processes. Modularisation is the process of grouping individual components, which make up the final product, into modules. One important aspect of this process is to make the interfaces between these modules as standardized and simple as possible. This allows for easy internal connectivity and the ability to effortlessly change modules for adjusting the functionality of the end product as needed (Österholm and Tuokko, 2001). Efficient interfacing provides good internal customization options while allowing the configuration process to remain efficient and more reliable (Shamsuzzoha, 2010). Ericsson and Erixon (1999) maintain a stance that modules should be designed in a manner to minimize interaction with the rest of the system. This can be interpreted as to mean that a module should be independent in its functions and have minimal dependency on other modules.

Modular product development creates efficiency in many phases of the product development process. A customer can help to define the requirements of the product. The product can then be configured to meet those requirements fast because the required modules have already been previously designed. Once the configured design is completed, assembly and production gains also a considerable boost in efficiency as installing and testing of modules is a lot faster than production of single components.

Faster overall development speed of new products is also achieved with modular product development. Instead of designing the whole product from scratch, only the modules which have not yet been created can be developed. Modules can be tested individually, which improves reliability of the end product and also allows for considerably more efficient maintenance process for the product when required.

The impact of efficient maintenance becomes even more apparent when the product in question is bulky and transportation is difficult. As such, maintenance needs to be performed on site and since the replacement module can be tested beforehand, the on site maintenance process can be simplified in best case scenario to simply the removal of old module and the installation of the replacement module.

However modular products can also have potential costs due to the way they are designed. Modular products may have reduced internal function sharing which can lead to excessive number of physical components (Huang, 2000). To avoid this careful planning is required in the product design phase. In addition the product might be overdeveloped when used on tasks that are considerably more simple than average target use of the product. This could make the product considerably more expensive to produce than a much simpler product that can achieve the same task. Finally there remains the risk of excessive similarity between the products in the product family. The reusability of modules can also lead into lack of innovation. Product designers might be more inclined to use existing modules instead of attempting to think outside-the-box and create new modular solutions.

2.1.3 Representing product architecture

There are many ways of representing a product by utilizing various diagrams. These architectural methods of presenting products are useful for modularisation to study the component relations and to visualize the inner functions of the product. Three architecture structures are presented in this thesis as they have appeared as to be the most well researched in the academia. These three are Modular Function Deployment (MFD), Design Structure Matrix (DSM) and Function Structure Heuristics. The following sections will review these methods and assess their pros and cons.

2.2 Modular function deployment

Modular function deployment (MFD) is a systematical method to aid in the design of modular products (Österholm and Tuokko, 2001) and is partially linked to commonly known quality tools such as the Quality Function Deployment (QFD).

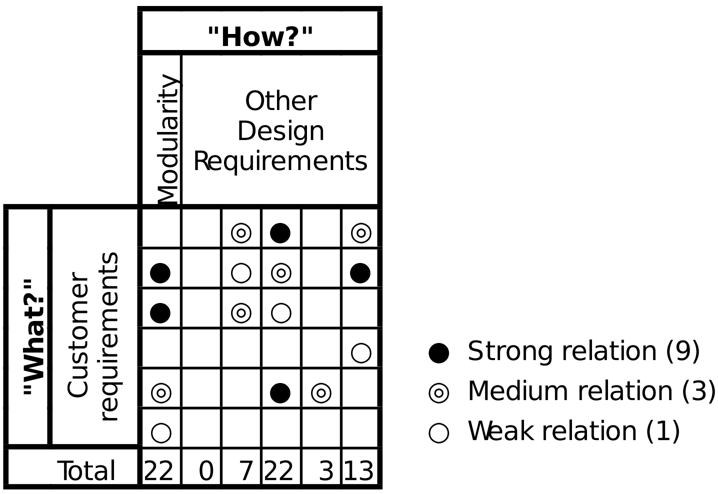

FIGURE 3. QFD matrix showing the what-how relationships (Österholm and Tuokko, 2001)

Quality Function Deployment is a design matrix tool and concept which assist in bridging the gap between customer requirements and technical solutions (Akao, 2004). Figure 3 shows an example QFD matrix.In the figure on the vertical "What?" axis customer requirements are defined. On the horizontal "How?" axis technology solutions and design requirements are defined correspondingly. The matrix is then evaluated through for each option and the relation strength is decided. After relation strengths are determined the total weight can be calculated on the bottom. These weighed numbers can be used to determine how much priority should be given to the designated design technology or requirement. The weight or stress of the relation can be determined as suitable. In this particular example 9 was given to strong relation, 3 for a medium relation and 1 for a weak relation.

MFD process can be divided into five distinct stages which are listed below as (Österholm and Tuokko, 2001)

1. Researching customer requirements
2. Forming, evaluating and choosing technical solutions
3. Forming new module candidates
4. Evaluating all module candidates and their interfacing
5. Designing individual modules

The first stage of the process focuses entirely on researching customer requirements. This is essential to achieve optimal customer satisfaction. Customer requirements and design requirements can be analysed through Quality Function Deployment (QFD), which allows for certain product requirements to be defined. (Österholm and Tuokko, 2001)

Once the product concept is determined on the abstract level, the actual technical solutions are formed in stage two. In order to form the technical solutions an architectural representation of the system can be designed. One method of such architectural representation is the hierarchical tree. Hierarchical tree is also known as function tree. An example of such function tree can be seen in Figure 4. In the function tree all required and optional functions to the process are mapped in a way that the connections between sub functions can be clearly established. Additionally the available technological solutions to achieve the functions can be added as shown in Figure 5. As there can be multiple options for technical solutions, the various solutions should be evaluated at this stage to determine the solution that appears most suitable from technical stand point.

As the technical design is in place the actual modularisation process of the technical solutions can begin in the third stage. Module indication matrix (MIM), which is also a

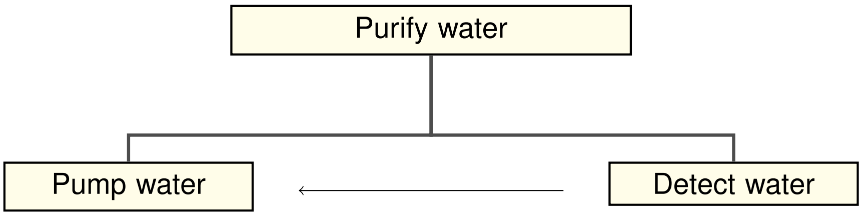

FIGURE 4. Simple function tree. Adapted from Österholm and Tuokko (2001).

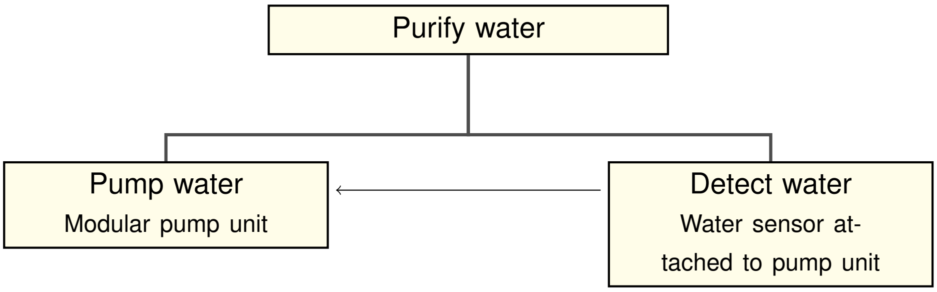

FIGURE 5. Function tree with technical solutions. Adapted from Österholm and Tuokko (2001).

QFD based matrix, can be used to assist in recognizing potential module candidates. In addition to a MIM-matrix a specially developed checklist can be utilized in assisting of the evaluation process. Module indication matrix appears similar to QFD matrix. Instead of mapping customer requirements against technology solutions, MIM maps module drivers against functions (Hölttä-Otto, 2005). Module indication matrix and module drivers are explained in greater detail in Section 2.2.1.

Again there can be multiple and conflicting module candidates that were created in the third stage. The fourth stage analyses these candidates against each other and also against previously existing modules. At this stage also the interfacing between the module candidates must be assessed as interfacing capability essentially defines the final modularity of the product. Interfacing also plays a major role in time required for product development (Österholm and Tuokko, 2001). If interfacing is too complex it can have considerable negative effects on product development speed.

The last stage of the MFD process is the individual module design phase. The goal of this phase is to improve the modular attributes of the module. Finally the technical specifications of all the modules are created (Österholm and Tuokko, 2001). The technical specifications can include all kinds of relevant data related to the module. Extra information such as target cost and future modification plans can be included. In this stage the MIM matrix can be used again to define the important development factors on individual module level.

2.2.1 Module indication matrix and the concept of module drivers

The core part of modular function deployment is the utilization of module indication matrix to form the module candidates. The module indication matrix appears similar to quality function deployment matrix, however instead of using customer requirements on the vertical axis module drivers are used instead. There are 12 module drivers defined by Erixon (1996): carry over, technology evolution, planned changes, different specification, styling, common unit, process/organization, separate testing, supplier availability, service and maintenance, upgrading and recycling. The module indication matrix can be constructed using these module drivers. Figure 6 shows an example module indication matrix. Figure 7 shows module indication matrix with the module candidates formed. The candidates were formed manually by searching for functions which shared same module drivers. From the figures it can be seen that the product driver focus is on carry over, technology evolution and service and maintenance. Five modules were formed in the example out of 8 functions, although it could be considered to combine modules one and five to reduce the number of modules to four.

Module Drivers	Function 1	Function 2	Function 3	Function 4	Function 5	Function 6	Function 7	Function 8	
Carry over			9		3			3	15
Technology evolution	3	9		1			3		16
Planned changes					9				9
Different specification		3		9					12
Styling						3			3
Common Unit			1				9		10
Process/organization	1							1	2
Separate testing			1		9				10
Supplier availability	3						1		4
Service and maintenance			9		9				18
Upgrading	9		1		1		1		12
Recycling			9					3	12
	16	12	30	10	31	3	14	7	

Strong relation (9)
Medium relation (3)
Weak relation (1)

FIGURE 6. Module indication matrix. Adapted from Hölttä-Otto (2005).

A carry over module driver is essentially a module that can be used again from an earlier generation product to a new generation product. A carry over thus denotes a module that

Module Drivers	M1	M2			M3		M4	M5	
	Function 1	Function 3	Function 5	Function 8	Function 2	Function 4	Function 6	Function 7	
Carry over		9	3	3					15
Technology evolution	3				9	1		3	16
Planned changes			9						9
Different specification					3	9			12
Styling							3		3
Common Unit		1						9	10
Process/organization	1			1					2
Separate testing		1	9						10
Supplier availability	3							1	4
Service and maintenance		9	9						18
Upgrading	9	1	1					1	12
Recycling		9		3					12
	16	30	31	7	12	10	3	14	

Strong relation (9)
Medium relation (3)
Weak relation (1)

FIGURE 7. Module indication matrix with modules candidates formed. Adapted from Hölttä-Otto (2005).

is reusable usually over a long period of time. A practical example of such module might be a water pump unit - it is unlikely that pumping technology will advance during the lifetime of the pump unit. Because of this, the pump unit is unlikely to become obsolete and has a strong carry over driver.

Technology evolution on the other hand refers to the changes in the module technology over its lifetime. This might not necessarily mean the part becomes obsolete. It does however mean that the part is likely to require upgrading as new technology and construction materials become available.

Planned changes refer to any future changes that have already been designed for the module. The changes can be related to any aspect of the module at a certain specified time.

Technical specification module drivers define modules that aim to be the main variation drivers in the product. Different technical specifications due to customer requirements should be limited to these modules. This way efficient product variation and customization can be achieved as the variations are not allowed to spread through the entire product.

Some modules can focus fashion and changing trends. These modules have the styling driver. This enables for example the outward appearance of the product to be changed according to customer requirements without interfering with the internal workings of the product.

Common units are standard modules that have relatively little variation due to product customization. Common units are often shared among different products and they usually perform basic functions of the product.

Process/organization module driver refers to finding possible modules where team work can be given specific attention. According to Erixon (1996) work content, responsibility and authority can be varied, to give a development opportunity to team members who might not be normally working with product development. It can be considered as delegation potential of a module.

Separate testing refers to the quality aspect of product development. Certain modules or group of modules might require extra testing to ensure the final product functioning properly. If every module can be tested before final assembly, final product quality is increased considerably. The sooner a problem is noticed in production, the easier and faster it is to fix it. Problems that are noticed only after the final assembly are likely to require disassembly which leads to a longer production time.

Supplier availability refers to the potential that a whole module can be bought from a supplier. This is referred as black box engineering (Erixon, 1996) because the supplier can handle everything related to the module including product development. It allows dealing with one big supplier instead of many small ones and as such reduces production costs. Various containers are examples of modules that are likely to have high supplier availability module driver.

Service and maintenance module driver applies to parts that are prone to break or require regular maintenance. Modules with this driver should be designed so that they are easy to replace, disassemble and repair. By doing this faster service time can be achieved which reduces operating costs of the product. In addition if a module becomes damaged, it can be quickly replaced by a functioning module and the repairs to the broken module can be done later without causing loss for the customer.

Upgrading capability of a module refers to modules which offer the ability to be upgraded. For example new functions might be developed for the module so it can perform tasks that it was not originally designed to do.

The last one of these module drivers is the recycling capability of the module. Modules can be designed so as to maintain the whole module recyclable. Hazardous materials that are used in the product can be attempted to combine in single module to ensure safer and easier disassembly when the product or module comes to its end of life.

2.2.2 Evaluation of modular function deployment

Modular function deployment deals with wide range of product development phases. It is a customer oriented design process - it puts significant effort in translating customer requirements to actual technical designs that suit the customers needs. As customer satisfaction is an important aspect in modular product development, this puts MFD into a very good position in the comparison of the modularisation methods.

MFD provides faster product development times since focus is also put on determining carry over modules. The carry over modules can be reused in future products of the family, reducing the development cost and time. MFD also offers the most complete work flow guidelines from abstract concept design all the way to the final product. Module drivers provide a good basis for sketching module concepts.

In very complex products modular function deployment might not be flexible enough. Especially the stage three which depends on module indication matrix might quickly become too cluttered if large number of functions are involved in the product. In such a case modular function deployment could be combined with design structure matrix, which allows very complex products to be designed.

2.3 Design structure matrix

The Design structure matrix (DSM), originally introduced by Steward (1981) provides the very basics for processing available resources. It consists of a matrix where technical solutions are listed vertically. Dependencies of these solutions on other solutions are marked down, and the matrix is processed to find clusters of dependencies which can show potential module candidates. Originally the design structure matrix was not designed for modularisation, but to manage with organizational issues in large companies. However the design structure matrix was further developed by various studies, which were combined by Browning (2001) allowing for new ways to process data as shown in Figure 8.

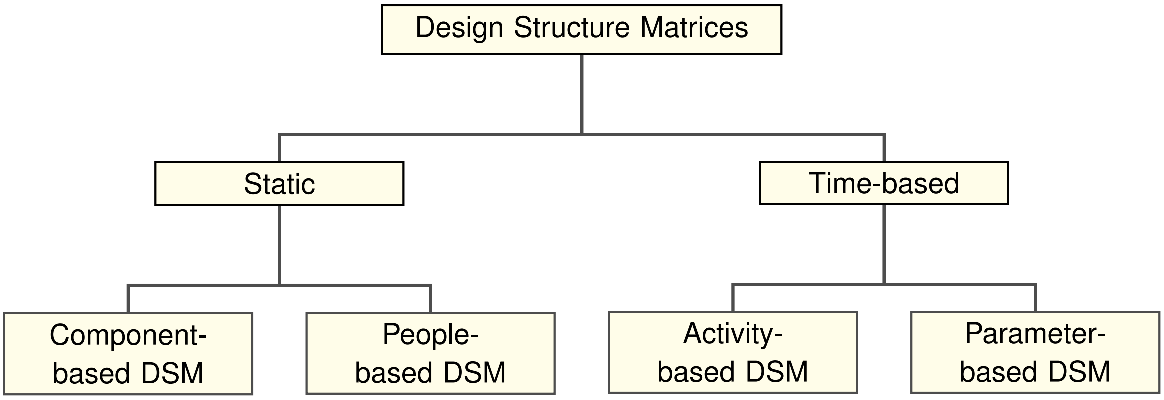

FIGURE 8. DSM branches (Browning, 2001)

The design structure matrix was originally designed for time based design structures, which were the activity and parameter design structure matrices (Browning, 2001). The branch of interest from product modularisation perspective in Figure 8 is the component based design structure matrix. At its current stage the design structure matrix can be used to process a great deal of data. The data in a design structure matrix is usually processed through a method called clustering and partitioning. Clustering is achieved by shifting positions of elements so that dependency clusters are formed visually. Partitioning is defined as the process of dividing the matrix into distinct parts which would represent the module candidates in this case. Clustering and partitioning is possible to do using professional product development software, but it is also possible to do it manually for products that do not have a too large component count.

Partitioning is demonstrated below. In Table 9 Element A has no dependencies, while Element B depends on A, and Element C depends on B and F. Using this knowledge, elements can be arranged into clusters, from which possible module solutions can be developed. In Table 10 two potential modules can be seen. Elements I and E fall in the middle since they have dependencies in both modules. If the data in the DSM matrix was based on various components, these elements would likely be parts which link the two modules together.

Element A	A									
Element B	X	B								
Element C		X	C			X				
Element D				D						
Element E	X	X		X	E					
Element F		X				F				
Element G					X		G	X		X
Element H					X			H		
Element I		X	X						I	
Element J				X			X		X	J

FIGURE 9. Unclustered DSM matrix displaying elements and their dependencies on other elements

Element A	A									
Element B	X	B								
Element C		X	C			X				
Element F		X				F				
Element I		X	X						I	
Element E	X	X		X	E					
Element J				X			X		X	J
Element D				D						
Element G					X		G	X		X
Element H					X			H		

FIGURE 10. DSM matrix after applying clustering. Two component modules are shown. Elements I & E depend on both modules.

2.3.1 Evaluation of design structure matrix

The strength of design structure matrix lies in its ability to handle products with considerably big part counts. Shamsuzzoha (2010) demonstrated a situation where a design structure matrix featuring over 200 elements was used to modularise the W32 Wärtsilä ship engine. Since design structure matrices can be analysed efficiently using computer software, it can be a very efficient method for complex products. It is however likely to be less useful with products that do not feature complex part interactions.

The design structure matrix does not deal with the whole product development process like modular function deployment does. As such it cannot serve as a stand alone solution to modular product development. It can be considered more as a supporting tool that can be combined with other aspects of modular product development. In a more complex product scenario the design structure matrix could be combined with quality function deployment introduced in the earlier section to achieve a more complete modular product development environment.

2.4 Function structure heuristics

Function structure heuristics is a module identification method explained by Stone et al. (2000). Functional Structure Heuristics does not define precise steps to take the product from design to finish. The general guideline given is split into two main phases. The functional modelling phase consists of gathering customer requirements and deriving a functional model. The second phase is product architecture phase which consists of applying the heuristics approach to identify module candidates and then generating the modular concepts. The methods for gathering of customer requirements are left on a generic level, but the very basic requirement for function structure heuristics is a well refined functional model of the product. Such functional models were briefly discussed in Section 2.2. However the functional model presented in Section 2.2 is too too minimalistic to suit the needs of heuristic approach and requires considerable expansion of available information. To suit the heuristic approach the functional model should include all input and output flows in the system. The flows describe the energy, material and signals that move through the product. These flow types are demonstrated in Figure 11. The figure shows a"black box" model of a power hand drill and all the relevant flows going through the product.

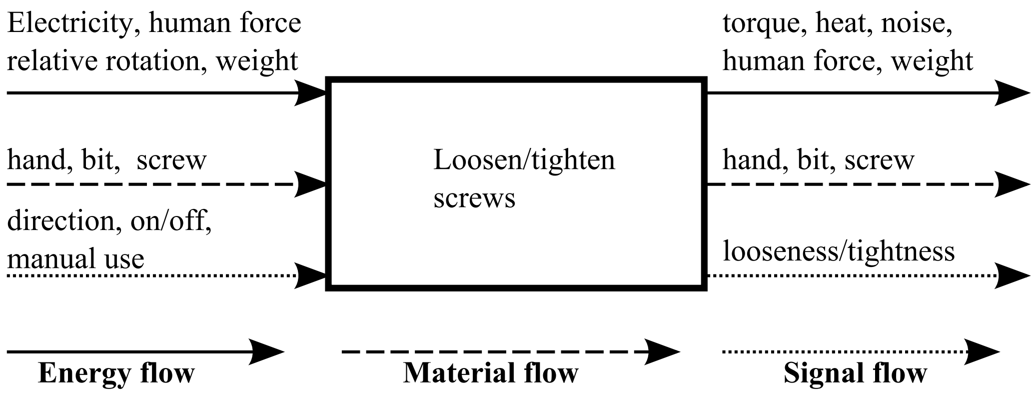

FIGURE 11. Different flows passing through a power hand drill. Adapted from Stone et al. (2000).

The Heuristic approach states that there are three kind of flows:

1. A flow can pass through the product unchanged

2. A flow can branch inside the product

3. A flow can be converted into another flow type

The aim of the heuriststic approach is to observe the product from the perspective of these flows and form the most practical modules based on the flow characteristics. Stone et al. (2000) defines the flows as dominant flow, branching flow and conversion-transmission flow respectively. The dominant flow defines a module from a set of sub-functions which a flow passes through until it exits the system or is converted. An example of such dominant flow module can be seen in Figure 12. In the figure blank boxes represent various functions of the product. Material and energy flows can be seen passing through the system. Material flow forms a dominant flow module. Required interfaces between modules can be readily pointed out in the figure.

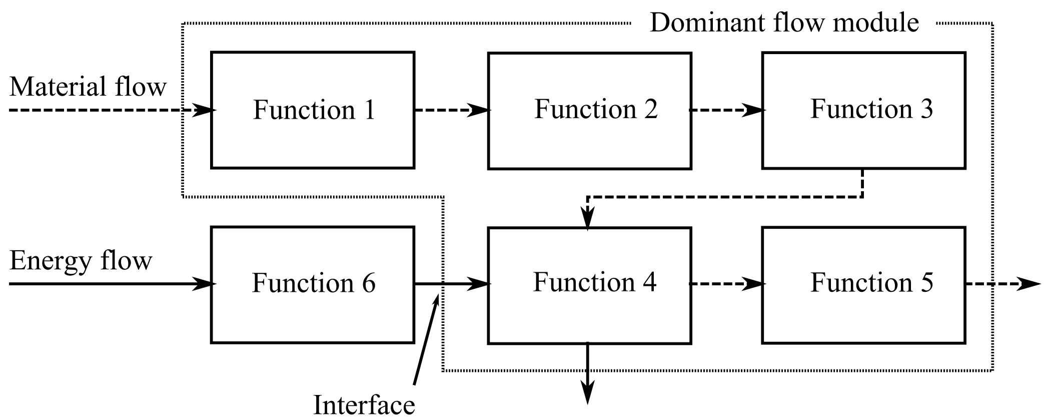

FIGURE 12. Dominant flow module. Adapted from Stone et al. (2000).

Branching flow attempts to detect parallel flows and create modules that interface from the branch point to the rest of the product. In the functional model these branches are called limbs of parallel function chain. Branching flow is demonstrated in Figure 13. The conversion-transmission heuristics represents components that are often already modules themselves which have been built to convert flows. Simply put the conversion-transmission module is usually a module that contains a single component which is already a module in itself. Examples of such modules could be electrical motors, generators or electric heaters. The earlier Figure 12 can demonstrate a conversion-transmission module at the bottom left where energy is inputted into the system.

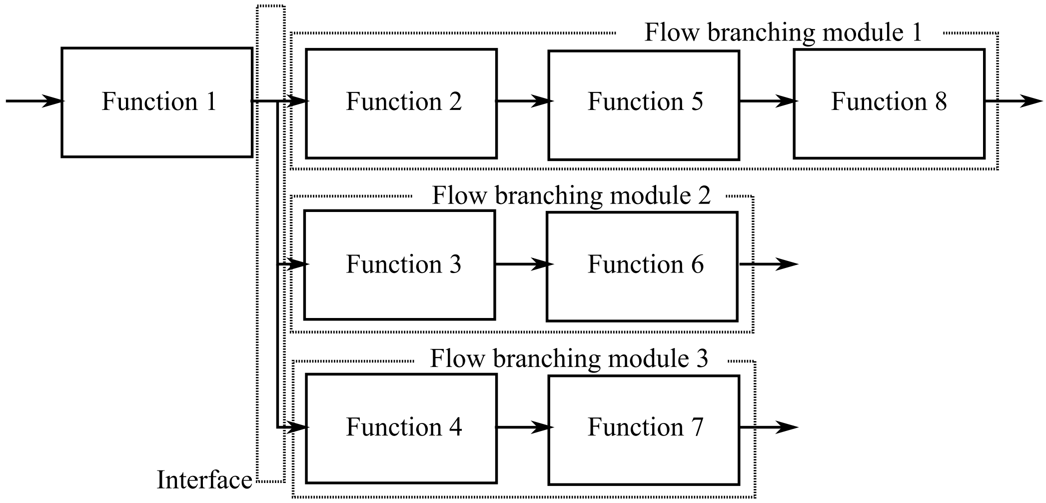

FIGURE 13. Branched flow module. Adapted from Stone et al. (2000).

2.4.1 Evaluation of function structure heuristics

Function structure heuristics remains as a very open approach to modularisation. It is not a step-by-step process, but leaves a lot to the designer insight and judgement (Hölttä-Otto, 2005). This can be very efficient and speedy method if the designer is skilled and at the same time can lead into a dead end. As such function structure heuristics seems to serve as a good secondary and brainstorming method for modular product design.

3 CASE STUDY

In the case study focus will be given to the modularisation of the product family offered by Doranova Ltd. The current family has well established base components that build up the products. This case study will focus on analysing these components and determining the appropriate module candidates. In addition interfacing between the modules and space requirements will be studied.

The case study was initiated with a brainstorming session with the company workers. The session focus was to determine various functions that exist in the products of Doranova Ltd. All of these functions naturally have one or more technical solutions already available. Table 1 shows the possible main functions which are present in an environmental remediation container.

TABLE 1. High-level functions and their technical solutions gathered at the company brainstorming session.

Functions	Technical solutions
Contain the product	Intermodal container 20' Intermodal container 40'
Improve external features	Facade structures Lighting Company logo
Temperature regulation	Insulation and heating system
Provide electricity	Main electric system
Provide automation	Automation system
Moving liquid	Centrifugal pump Submersible pump
Moving gas	Side channel blower Compressor
Pretreatment (liquid)	Gravity separator Bag filter Cartridge filter Oil separator
Storage	Tanks, barrels Bioreactor
Filtration	DoAct 1500 DoAct 100
Stripping	Stripper
Ultraviolet treatment	UV-light
Dividing material flow	Manifold
Dosing chemicals	Dosing pump

3.1 High-level function analysis using function structure heuristics

The functions listed in Table 1 are mainly high-level functions. These functions can be further broken down into subfunctions if modularisation of the high-level function is a goal to the product development process. In this case study, however, only the high-level functions are studied because most of the technical solutions for the functions already come as preassembled. However the consensus of the work group was that the focus should be on top-level functions only to maintain a simple and clear approach. The high-level functions and their relevant flows can be represented using the heuristic charts as discussed in section 2.4. For the purposes of the case study the heuristic methods provide a good starting point for modularisation. Figure 14 shows the material, energy and signal flows between the module candidates presented in Table 1.

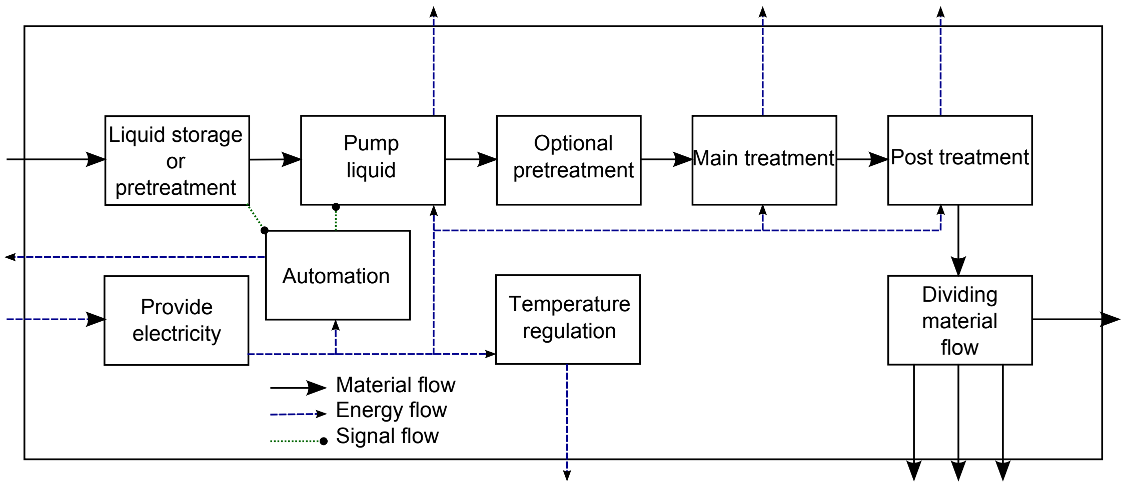

FIGURE 14. Material, energy and signal flows inside the container module.

The very first item presented in Table 1 is the contain function. Most of the other functions of the product will be contained inside this module with the exception of a few external modules. The technical solution for the containment is the ISO 6346 intermodal container (Figure 15). Intermodal containers are widely available and easy to transport. These containers, also known as sea containers, come in various ranges of sizes. Of these sizes it was determined that 20 feet and 40 feet containers suit best the applications of the company. The 20 feet container is the standard size and 40 feet container is twice as long. The bulk of the modules must be fitted inside the container with the exception of exterior modules.

Improving external features represents an optional function of the product based mainly

FIGURE 15. 20 feet intermodal sea container

on customer requirements. The intermodal containers can be modified to support the attachment of facade structures which give the customer the possibility to affect the visual appearance of the remediation container. This can help the product to blend in the landscape. Lighting and company logo are part of this function of adjusting the external look of the remediation container. External lighting could also be a suitable solution in situations where the remediation work is done in a remote location with little or no other light sources.

The internal side of the container has most of the functions. Temperature regulation is important to maintain safe operating temperatures. Since intermodal containers are steel structures and conduct easily appropriate insulation, heating and ventilation is needed to ensure the interior is able to adapt to changing external temperatures. Main electric system provides electricity for the container. The electric system generally takes three-phase electric power at 400 volts as input to provide both 230 volts and 400 volts for the equipment inside the intermodal container. The system forms a good module candidate as an electrical enclosure which contains in addition to inputs and outputs an electric meter and the fuses. Automation is provided as separate module to perform various automation tasks such as pump, valve and aeration operation.

The function of moving liquid has many technical solutions in the form of different pump types. A decision was made to limit the technical solutions to a few distinct pump types to allow for a more unified design in the product family and reduce the technical specification modularity driver of pump units. For the internal processes submersible pumps can be used as they provide easy maintenance and work well as separate modules. For processes external to the container it is often necessary to use a submersible pump. The same situation applied to the function of moving gas. Gas can be moved either with a side channel blower or a compressor when higher pressure is required.

Liquid pretreatment is a function that can be done through various technical solutions depending on the requirements. Oil and gravity separators are generally big and bulky containers where settling is used to separate hydrocarbons or sediment from other liquid such as water. Physically smaller solutions are various bag and cartridge filters.

Intermediate storage can be achieved through various size plastic containers. Commonly available standard intermediate bulk containers (IBC) are one option, but various other size plastic containers can be used flexibly too depending on space requirements. For filtration process Doranova's own DoAct 1500 and DoAct 100 filters can be used. In the filtration liquid or gas is purified through adsorption as it is pumped through adsorbing filtrate material. Stripping solutions are utilized for removing volatile organic compounds from liquid with the assistance of airflow.

Ultraviolet irradiation is used in combination with hydrogen peroxide to create hydroxyl radicals. These hydroxyl radicals react with many known contaminants and provide an efficient way for water treatment. Manifold function is often encountered in water remediation. It's a function for the equal division of effluent water for multiple effluent outputs. This can be achieved through the utilization of modular manifold. Finally there are certain dosing chemicals that are fed into the water treatment system using a dosing pump.

These functions provide the basic functionality of the end product. As can be seen already from Table 1 many of the technical solutions already represent ideal module candidates as themselves. To study further the possibilities of combining some of these functions under a single module a module indication matrix can be used.

3.2 Utilizing module indication matrix to find new module candidates

To analyse the outcome of the brainstorming session further the functions in the previous section were arranged into a modular function deployment matrix as can be seen in Figure 16

	M1			M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	
	Contain	Temperature	Electricity	Exterior	Automation	Moving liquid	Moving gas	Pretreatment	Storage	Filtration	Stripping	Ultraviolet	Flow division	Dose	
Carry over	9	3	9		3	3	3	9	3	9	3	3	9	3	69
Technology evolution			1		1			1		3					6
Planned changes			1		1										2
Different specification				3	9	3	3			1			3	1	23
Styling				9											9
Common Unit	9	3	9		3			9		9	3		3	3	51
Process/organization			1												1
Separate testing						3	3							1	7
Supplier availability	1				3	3	3			3					13
Service and maintenance		1				9	9	9		3		3		3	37
Upgrading			3		3										6
Recycling	1					1	1		1	1			1		6
	20	7	24	12	23	22	22	28	4	29	6	6	16	11	

Strong relation (9)
Medium relation (3)
Weak relation (1)

FIGURE 16. Environmental remediation functions mapped on a module indication matrix.

From the module indication matrix few indications can be observed. The main drivers are carry over, common unit and service and maintenance. This matches the modular product development goals laid out by Doranova seemingly well. Modules should have the carry over module driver so that they can be reused in new products. Common unit means that the module does not require customization allowing for fast product assembly and the service and maintenance ensures that critical modules can be replaced easily.

There is also indication that the functions of containing the product, temperature regulation, electricity and even perhaps automation could be combined into a single module. In general there is not much technical variation among these technical solutions between different products of the product family. If designed to be expendable from a modular perspective the container could have temperature regulation and electricity built in, considering the two are mandatory functions for every remediation solution. By doing this lead-time in production can be reduced. In addition the pretreatment function has some potential to be combined with storage or filtration functions, however this would be case specific solution.

3.3 Discussion of interfacing, modularity type and optimal module sizes

Two major concerns remain from the modularity aspect. The first concern is the standardization of interfaces. The topic was covered briefly in the brainstorming session. There are no internal company standards for interfacing between the various technical solutions. Various standard interfaces have been used previously including, but not limited to, claw coupling, camlock coupling and flange coupling. Each of these methods have pros and cons. Claw coupling is fast to connect but is prone to leaks and comes in variety of sizes. Camlock coupling is a tightly fitting alternative but it lacks in supplier availability and price competitiveness. In addition camlock couplings also come in variety of sizes. Flanges (Figure 17) are the slowest to connect and disconnect when considering assembly and disassembly lead time. Flanges have an advantage in that the outer diameter can be standardized leaving some room for adjusting the inner diameter and they are suitable for higher pressures without risk of leak.

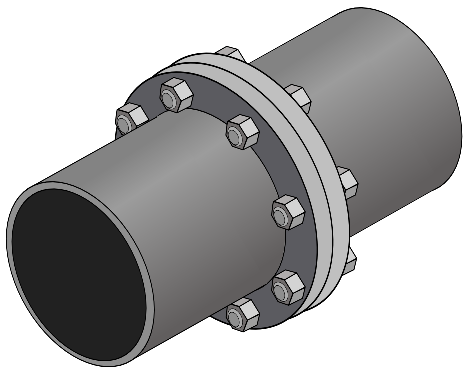

FIGURE 17. A flange coupling

The main modularity type utilized in this case study is component swapping as covered in section 2.1.1. However since there is considerable variation in the module sizes and every module requires a certain area inside the intermodal container where space is limited, it is important that modules are designed to dimensions that allow optimal positioning to avoid wasting space. One important question here is, should module size be regulated somehow or should every module have sizes that are purely dependent on the module properties?

In Figure 18 the internal floor dimensions of a 20 feet intermodal container are visualized. The dimensions are approximate, because they are influenced by the insulation of the container. One way to deal with the size issue would be to assign each module an individual size. If the total number of module candidates is low this option might be viable. On the other hand product design speed could be possibly improved if all modules followed a predictable size pattern. The modules could be for example grouped into certain size groups. In the Figure 18 two size groups are represented. One square meter module and a 0.25 square meter module. Putting two modules of size one square meter side by side leaves very little walking space in the container. This is an important factor when considering the maintenance requirements of the modules.

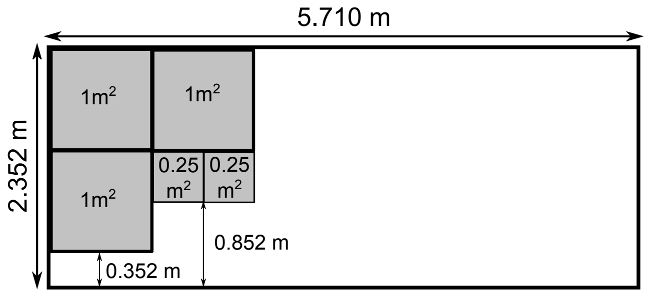

FIGURE 18. Floor dimensions of a 20 feet intermodal container

Height is also naturally a limiting factor. Intermodal containers come at a standard interior height of 2.385 meters which is considerably influenced by the insulation as mentioned earlier. Stacking modules vertically could be one option to use up the container volume more efficiently. The downside is that most of the modules are heavy and it complicates assembly, disassembly and maintenance. Module sizes could be designed so that they occupy as much as possible of the vertical space. For some technical solutions this has already been done. The Doranova DoAct 1500 filter for example has a height that is some 20 centimetres less than the container height. This leaves some room for the varying interior dimensions.

These open questions presented in this section should be considered when continuing the product development at Doranova Oy. Once agreement has been made on the standard interface or interfaces and on module size guidelines the product concepts are ready to go for production. As the development process is ongoing the final decisions remain outside the scope of this thesis.

4 CONCLUSIONS

The theory section of this thesis demonstrated three distinct methods for modular product development. These three methods have slightly different usage prospects. Modular function deployment aims to give the user the tools for product development from start to finish. The main attraction of MFD is the Module Indication Matrix which was a matrix based method for identifying module candidates and module drivers. Domain structure matrix focused on complex component dependencies. The heuristic approach on the other hand focused on material and energy flows between functions. It can be concluded that each of these methods provide a different approach to solving some of the problems of modularisation. Suitable procedure should be tailored to individual and/or company requirements. Other factors affecting the choice are product complexity and knowledge and understanding of the product designers on modular product development. Utilizing quality function deployment for the first phase of the product development, heuristic approach for brainstorming and modular function deployment for verifying and finding alternative solutions could yield the best results. Design structure matrix remains as a tertiary alternative for designing complex modular products.

The aim of this thesis has been to review available modular product development tools in the academic literature. Three methods represented in this thesis were the most visible ones in academic literature and as such the most well defined ones. The thesis has sought to find suitable methods for Doranova Ltd. to utilize for their modular product development. Modular function deployment seemed like the most complete solution. It however occurred that heuristic function deployment and module indication matrix were the most useful tools for analysing the module candidates in this case study.

Modular product development has been discussed in scientific publications for more than two decades. This thesis was based on existing studies and reinforced the research outcomes made by those studies. The subject still requires more research and hopefully in the future a solid agreement on defining the concepts of modularity.

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