Establishment of a Directly Applicable Design Framework for Frugal, Reconfigurable Manufacturing Systems

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By

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Abstract

Frugal innovation, an innovation philosophy encapsulating a significant reduction of costs and focus on core functionality of products is used by companies across the globe to reach expanded markets. Nevertheless, manufacturing processes seem to have largely been excluded from frugal innovation applications. Reconfigurable manufacturing systems offer large opportunities for increasing both the efficiency and flexibility of production systems yet have not considered manufacturing sustainability or resource-constraints. The combination of frugal and reconfigurable manufacturing into frugal, reconfigurable manufacturing systems (F-RMSs) therefore inherently offers opportunities to make frugal manufacturing viable and RMSs less wasteful. F-RMSs are explored in this paper. The opportunities inherent in their combination are explored, the exact meaning of F-RMSs delineated and criteria for its success defined. A list of core characteristics and enablers is also defined to further distinguish the F-RMS as a manufacturing system. As such the F-RMS is fully conceptualized. Subsequently, a design framework for F-RMSs is defined based on this definition and criteria. In this way F-RMS design is facilitated and its eventual implementation enabled. The framework is focused on a requirements gathering and basic design step, where advanced design and implementation guidelines are defined on a case-by-case basis. The thesis is finalized with a set of case studies where the framework is carried out at different companies to (re)design an F-RMS. The functioning of the F-RMS is thereby validated, with the opportunities inherent in their combination recognized in the practical designs created.

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Contents

1 Introduction

To capture the vast 'bottom of the pyramid' market emerging in the global south, frugal innovation is increasingly being used as a paradigm for the design of products, processes and services. Frugal innovation, an innovation philosophy encapsulating a significant reduction of "the total cost of ownership by focusing on core functionalities and reducing non-core features [1] is used by companies across the globe to cut costs whilst continuing to provide core functionalities. Nonetheless, manufacturing processes seem to have largely been excluded from the frugal innovation process, with current industrial innovation being characterized by the fourth industrial revolution focusing on "digitalization and enabling technologies for increasing the efficiency and flexibility of production" [2]. Therefore, whilst consumer goods and other products are increasingly being 'frugalized,' the processes with which they are manufactured are not studied and innovated upon correspondingly [3].

Reconfigurable manufacturing systems (RMSs), albeit predating the advent of industry 4.0, offer large opportunities for increasing both the efficiency and flexibility of production systems [4]. Increasing amounts of literature characterize this broad category of manufacturing systems as one of the key tools for facing increasing market volatility by designing manufacturing systems that can adopt different configurations through the repeated changing or rearranging of components in a cost-effective way [5]. Although the opportunities of RMSs are therefore large and varied, the design of RMSs with frugal innovation has not been explicitly considered. Nevertheless, reconfigurable manufacturing systems could provide an opportunity of enhancing the frugality of manufacturing processes as they inherently reduce capital requirements by combining functions. Vice-versa, the opportunities of reconfigurable manufacturing systems in providing product customization are enhanced by the inherent recognition of consumer requirements in frugal manufacturing.

Limited literature exists regarding the combined and enhancing combination of frugal innovation/manufacturing and RMS, and its opportunities are not fully explored and formalized. Applicability of RMSs for frugal innovation therefore remains low and the opportunities of RMSs in especially emerging economies remain underutilized. Concurrently, companies world-wide face ever-increasing challenges with increasing sustainability, globalized and complex supply chains and growing demand volatility [6]. The novel design of an RMS explicitly based in its strengths as a method of frugality therefore provides huge opportunities towards further implementation within both industry 4.0 and emerging economies. However, with a lack of design frameworks and research explicitly discussing the strength of the combination of frugality and reconfigurability within manufacturing systems, these benefits become more of a coincidental byproduct than a deliberate, fully exploited, outcome in novel designs of RMSs. Key opportunities provided by a frugal innovation approach to RMSs (or vice-versa) might thereby be missed and the full potential of the newly realized manufacturing system missed. It is therefore important to study the methods with which any novel systems utilizing a combination of frugality and reconfigurability can be designed successfully, and thereby further study the strength of combining these two functionalities.

1.1 Research Questions

This thesis aims to capture the benefits of reconfigurability for achieving frugal manufacturing by defining and formalizing frugal, reconfigurable manufacturing systems (F-RMSs). This will be done according to the research question:

How can a purposeful combination of the benefits of frugal and reconfigurable manufacturing lead to the design of frugal, reconfigurable manufacturing systems?

The design of F-RMSs will be formalized according to a number of steps. Firstly, both frugality and reconfigurability within manufacturing will be explored to propose the opportunities of reconfigurability in frugal manufacturing. A definition of F-RMSs will be provided along with what criteria would determine their suitability and success as an F-RMS. The conceptualized F-RMS characteristics and criteria will then be used as a basis for a F-RMS design framework that is adapted from existing RMS frameworks to create a practically and generically applicable design for any F-RMS. To validate the functioning of F-RMSs and the developed design framework, case studies will be performed in relevant industrial sectors. This leads to the following sub-research questions:

a) *How can reconfigurability be used to achieve frugal manufacturing?*

b) *What constitutes and defines the success of a frugal, reconfigurable manufacturing system?*

c) *How can a framework for the design of frugal, reconfigurable manufacturing systems be established?*

d) *How can the application of the designed framework to relevant industrial sectors validate its functioning and highlight the relevance of frugal, reconfigurable manufacturing systems?*

2 Methodology

2.1 Literature Review

A literature review was carried out to find the areas of overlap between frugal innovation and RMSs. Literature explicitly considering both frugality and reconfigurability is scant, with a combined search only yielding 12 results in an ABS-TITLE-KEY search on scopus. Therefore, common concepts that characterize a system were sought in order to be able to define the F-RMS. The literature review method and papers used per search term can be seen in Figure 2.1.

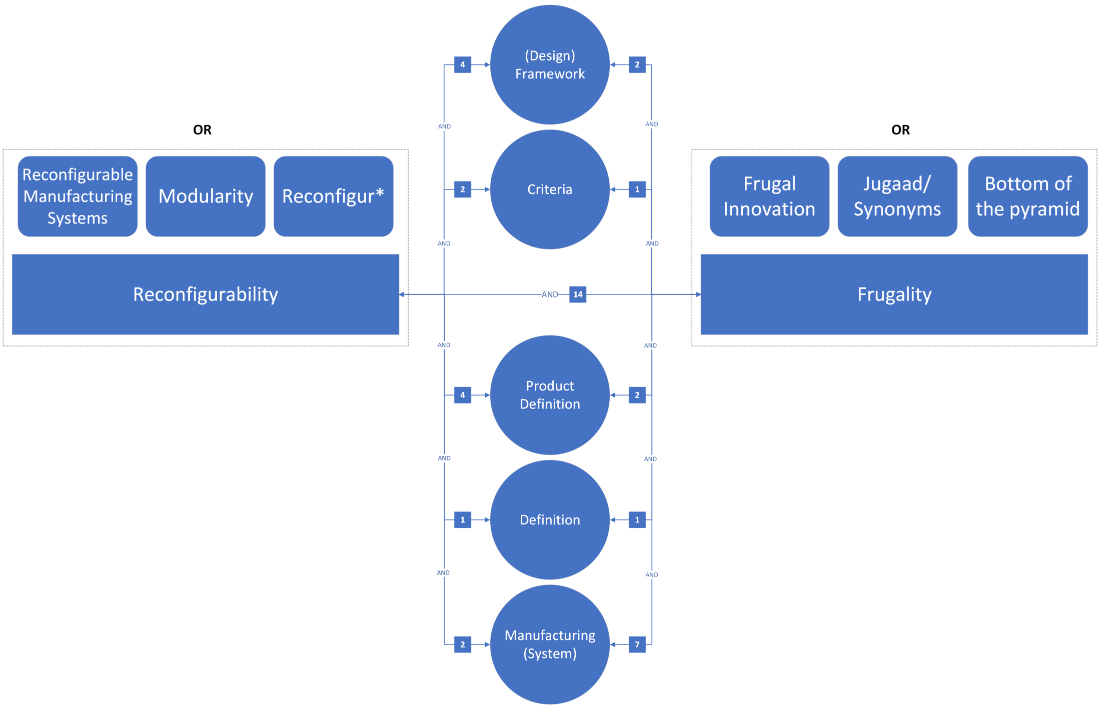


Figure 2.1: The literature review process as carried out for this thesis

As per the themes of this thesis, the additional search terms were ’framework,’ ’criteria,’ ’”product definition”,’ ’definition,’ and ’manufacturing.’ ’Framework’ refers to the design frameworks for both frugal innovation and reconfigurable manufacturing systems which this thesis aims to draw inspiration from and synthesize to a common design framework for F-RMSs. ’Criteria’ and ’definition’ were used to concretely characterize both frugal innovation and reconfigurable manufacturing systems and analyse to arrive at combined criteria for success. ’Product definition’ refers to both product-process co-definition, essential in both frugal manufacturing and reconfigurable manufacturing, and product group/family formation. It is used to define the scope of the framework and to what extent products need to and can be defined when designing a manufacturing system. Finally, an additional 'manufacturing' search term was used to specify the broad(er) category of (especially) frugal innovation literature. Additionally to this method, 14 papers were found through the snowballing method, both forward and backward (in case of less recent papers), of especially the papers by Niroumand *et al.* [7] (2), Andersen *et al.* [8] (4) and Belkadi *et al.* [9] (2). Papers were selected according to the authors judgement of suitability.

2.2 Research Methodology

Frame of reference

The first chapter will set out the theoretical basis for F-RMSs through the literature review process that is defined in the previous section. The concepts of reconfigurable manufacturing and frugal manufacturing as well as related concepts and criteria and enablers will be described and analysed. With this theoretical basis as a background, the opportunities inherent in using reconfigurability to achieve frugal manufacturing will be defined to answer the research question:

How can reconfigurability be used to achieve frugal manufacturing?

Defining a F-RMS

The F-RMS will be defined in this chapter through the synthesis of the concepts on which it is based: frugal manufacturing and RMSs. A definition will be determined by collecting aspects from the definitions of RMSs and frugal manufacturing that are relevant to both. Similarly, the core characteristics of both RMSs and frugal manufacturing that are generally agreed upon in literature will be synthesized and matched to each other to create a list of core characteristics for F-RMSs with a basis in the manufacturing systems upon which it relies. The criteria that may be used to determine the successful implementation of F-RMSs will then be set out based on these characteristics. Thereby, the F-RMSs will be made more practically applicable through the detailing of quantitative and qualitative procedures for evaluating their performance. Furthermore, enablers of F-RMSs will be synthesized from a comprehensive list of generic enablers for both frugal manufacturing and RMSs. This will be done according to the second sub- research question.

What constitutes and defines the success of a frugal, reconfigurable manufacturing system?

Design Framework

To enable the design of F-RMSs in practice, a framework for the design of F-RMSs will be described in Chapter 5. This framework will use the core characteristics, criteria and enablers for F-RMSs found in the previous chapter as an input. The general structure of the framework will be based on an existing framework for reconfigurable manufacturing systems. However, this framework will be adapted significantly to specify it to the design of the F-RMS by eliminating the design steps that are deemed to be too case specific or not contributing to frugality. Furthermore, a set of practically applicable tools will be suggested per design activity of the framework. The framework will therefore be easily applicable in practice and enable the design of F-RMSs. This is done according to the third sub-research question:

How can a framework for the design of frugal, reconfigurable manufacturing systems be established?

2.2.1 Case Studies

A set of case studies will be carried out to validate the applicability of the framework and demonstrate the relevance of F-RMSs. The results per design activity of the framework for each case study will be presented and discussed. As a result of the framework, a basic design of an F-RMS within the case study context will be determined and presented. The functioning of the F-RMS will thus be evaluated according to the criteria and theoretical conceptualization done earlier in the thesis. Each case study will be focused on a different phase of the design framework to thoroughly analyze the functioning of the framework. The final design of the case studies will also be compared to determine which characteristics and opportunities of F-RMSs are recognized in their design. This will be done according to the final sub- research question:

How can the application of the designed framework to relevant industrial sectors validate its functioning and highlight the relevance of frugal, reconfigurable manufacturing systems?

3 Frame of Reference

The development of a design framework for F-RMSs must first motivate why these systems are needed at all. F-RMSs are, to the best of the authors knowledge, as a concept a novel phenomenon within literature and industrial practice. Frugal innovation (or Frugal Manufacturing in specific) and RMSs, the theoretical concepts combined in F-RMSs, are more broadly explored in literature and have been subject to extensive literature reviews establishing their scope and relevance (e.g. [4] for RMSs and [10] for frugal production methods). Furthermore, several papers reflect on the 'frugalization' of innovative production methods, some closely related to reconfigurable manufacturing (e.g. [11], [9]). This chapter will draw on the extant literature, exploring the concepts of RMSs and frugal manufacturing to explore how reconfigurability may be a tool to achieve frugal manufacturing. In this way, the opportunities provided by the combination of these manufacturing system approaches will become apparent. This will be done according to the research question:

How can reconfigurability be used to achieve frugal manufacturing?

Firstly the concept of frugal manufacturing will be explored based on lessons drawn from the broader category of frugal innovation. Secondly, RMSs and its key opportunities will be discussed with a focus on those aspects of it which are of relevance for this thesis and frugal manufacturing. Finally, the opportunities provided by combining the concepts of reconfigurability and frugality to achieve frugal manufacturing will be presented.

3.1 Frugal Manufacturing

Frugal manufacturing is considered to be the application of frugal *innovation* to manufacturing. As such, the general concept of frugal innovation is detailed first, before this is extended to frugal manufacturing. Similarly, the defining criteria and enablers of frugal manufacturing are drawn from general frugal innovation criteria and enablers.

3.1.1 Frugal Innovation

Frugal innovation, although its exact definition is still undergoing debate, can be defined generally as:

"a resource scarce solution (i.e., product, service, process, or business model) that is designed and implemented despite financial, technological, material or other resource constraints, whereby the final outcome is significantly cheaper than competitive offerings (if available) and is good enough to meet the basic needs of customers who would otherwise remain un(der)served." ([12]

(a) Universal Nut Sheller [13]

(b) Tata Nano Car [14]

(c) Aravind Eye Hospital [15]

(d) AirBnB [16]

Figure 3.1: Examples of frugally innovative products

)

Frugal innovation is therefore focused mainly on providing a cheaper solution whilst still providing basic needs of customers. It is a broad category of innovations that can be applied to a range of products, from simple agricultural tools and cars to hospital processes and sharing platforms. Examples of these frugally innovative 'products' can be seen in Figure 3.1.

The universal nut sheller in Figure 3.1a makes it significantly easier to process (shell) peanuts whilst requiring minimal capital investment, thereby making African nut farming plausible [17]. The Tata Nano car in Figure 3.1b was [18]. The Aravind Eye hospital shown in Figure 3.1c utilizes economies of scale to drastically reduce the price of eye surgery by providing a large number of eye surgeries [19]. Finally, AirBnB has been characterized as a frugal service innovation due to its significant cost reduction of overnight stays relying on existing spaces instead of newly built real-estate (as in the case of hotels) [20].

What constitutes a frugal innovation can therefore be difficult to characterize. Whilst cost-cutting is a significant and necessary shared value, not all cost-cutting innovations can be characterized as 'frugal.' Indeed, Radjou & Prabhu [21] highlight that frugal innovation is not solely cost minimisation but to"'provide products and services that correctly meet the exact needs of the customer" with "acceptable' cost regarding to the economic context of the target market in the target regional market." In general *all* frugal innovations can be thought of to have the following acronymic attributes [22]:

- **F**unctional
- **R**obust

- **U**ser-friendly
- **G**rowing
- **A**ffordable
- **L**ocal

A large number of related terms, often rooted in local cultural customs, refer largely to the same concept as *frugal innovation*. Dabić *et al.* [3] identifies:

- Jugaad Innovation
- Gandhian Innovation
- Bottom of the Pyramid Innovation
- Constrained-based
- Catalytic Innovation
- Grassroots Innovation
- Indigenous Innovation.

Reverse innovation, where innovations are "adopted first in the developing world" before migrating to the developed world [19], is characterized as distinct. Hossain *et al.* [12] furthermore mentions:

- Cost innovation
- Resource-constrained Innovation
- Shanzaai Innovation

Furthermore, many cultures have an ingrained idea of 'bricolage'; or design through improvisation, and have a term associated with this phenomenon which closely approaches frugal innovation [23]. Aforementioned 'Jugaad' and 'Shanzaai' innovation, from India and China respectively, are key examples of this. Further terms include Arrangiarsi (Italy), Chapuza (Spain), DIY (USA), Gambiarra/ Jeitinho (Brazil), Jua Kali (Kenya), Jugaad (India), Kanju (parts of Africa), Solution D / Systeme D (France), Zizhu Chuangxin / Jiejian Chuangxin(China) and Halletmek (Turkey) [24]. These approaches might not be seen favorably in all contexts and few have a market-based approach. However, all share the same resource-constrained approach towards creating functioning solutions.

This thesis takes frugal innovation as its starting point as characterized by the establishment of a *frugal* reconfigurable manufacturing system. This was also the main term used for the literature search as outlined in Chapter 2. Due to its widespread use in literature and broad applicability, 'frugal' innovation can be easily applied to a manufacturing, or reconfigurable manufacturing, context. Nevertheless, all other terms mentioned as well as those perceived as relevant when encountered are considered in thesis. Frugal innovation is therefore taken as a guide to develop an affordable, functional manufacturing system without strictly enforcing any and all guidelines encountered in literature.

3.1.2 Frugal Manufacturing

The application of frugal innovation on the manufacturing process itself, thereby treating the manufacturing process as the product to be innovated upon, is termed 'frugal manufacturing.' A frugal, reconfigurable manufacturing system will by definition be an example of frugal manufacturing, it is therefore important to study the specific application of frugal innovation towards manufacturing. Frugal manufacturing quite simply can be defined as any manufacturing process that adheres to the criteria and definition outlined in the previous sections. A more formal definition is given by Rao [25] as:

> *Fabrication using a minimum number of low-cost processes producing zero waste for creating a net-finished-shape possessing necessary geometrical tolerances; requisite surface integrity; and appropriate properties.*

Frugal manufacturing *systems*, on the other hand, are defined by Schleinkofer *et al.* [26] as:

> *Machines, equipment and devices that meet the requirements of price-sensitive customers in industrialized countries and the fast-growing emerging markets.*

This thesis prefers this term and definition due to its broader employability and greater relevance to the manufacturing *systems* implied by reconfigurable manufacturing *systems*.

Literature discussing frugal manufacturing is limited, with a scopus ABS-TITLE-KEY search of "frugal manufacturing" only yielding 9 results (see Chapter 2). Chakravarty & Gómez [10] claim this is due to a recent focus on management and business issues in frugal innovation discourse, with their paper attempting to refocus the discussion on to frugal production and manufacturing. Examples of frugal manufacturing applications include simultaneous electrochemical and electrodischarge machining [27], pulse-assisted cryo-micro lubrication for machining of Ti-based alloys [28], and large-strain extrusion machining [29]. These high-tech manufacturing processes nevertheless seek to rescope their processes towards simpler solutions, significantly reducing costs. Schleinkofer, in a series of papers, further explores frugal manufacturing, developing a design thinking process for frugal production [30], exploring the use of cyber-physical systems in frugal manufacturing [31], knowledge acquisition for frugal manufacturing [32], and developing a framework for robust and reliable frugal manufacturing systems [26]. Similarly, Rao, in Rao [25] and Rao & Liefner [33] develops the definition of frugal manufacturing and associated processes. Hereby, a focus is placed on advanced frugal products and high-tech manufacturing processes as in the applications discussed above.

The PROREGIO project (or 'customer-driven design of product-services and production networks to adapt to regional market requirements' project) links manufacturing to frugal innovation in several ways, focusing on advancing product regionalization. This is done according to the themes (i) design of customer oriented product-services for frugal innovation in a bottom-up development process, (ii) optimization of production systems and networks based on interaction of stakeholders, and (iii) planning and control of production networks and regional production systems to enable ad-hoc re-design [34]. Several papers by Belkadi et al., ([9, 35–37]), Mourtzis et al., ([6, 38–42]) and Colledani et al., ([43–45]) are written in the context of this project and provide important links between frugal innovation and manufacturing without defining frugal manufacturing as such.

Some of the key challenges defined by the papers above in introducing frugal manufacturing are meeting regional market demand [38], difficulty in setting up supply chains [46], lack of financial and technical resources for manufacturing, including difficulty of acquiring parts for maintenance [26] and lack of skilled labour and knowledge [11]. These challenges may be uniquely addressed by the introduction of reconfigurability, as will be described later in this thesis.

3.1.3 Criteria and Enablers

Frugal innovation can be difficult to define and it success hard to measure due to the the wide range of settings in which frugal innovation can be effective in addition to a wealth of related concepts. Subsequently, frugal manufacturing also constitutes a wide range of manufacturing procedures. This, in addition to a lack of literature and practical application make it difficult to define where frugal manufacturing may be effective. Nevertheless, a number of criteria and enablers for frugal manufacturing can be defined which seek to broadly determine the key factors that can elevate frugal manufacturing success and define whether or not manufacturing is frugal. Winkler *et al.* [20] adapts criteria from Weyrauch [47] to define the following criteria for frugal *innovation*,

- Substantial cost reduction
- Concentration on core functionalities
- Optimised performance level
    - Product/service-related performance
    - User-related performance

These three criteria encapsulate both the definition of a frugal innovation and the requirements for making an innovation successfully frugal. Substantial cost reduction entails any significant cost improvements that go beyond reducing costs by a few percentage points. Costs are typically reduced by 58-97% [48]. Concentration on core functionalities involves directly targeting user requirements to reduce complexity and strip a product to its essentials [49]. The optimised performance level criterion is split by Winkler *et al.* [20] into an optimised product or service-related performance and user-related performance sub-criterion. The product or service-related performance is based on use functions according to function analysis such as robustness, speed or power. User-related performance, on the other hand, is defined according to value analysis with performance aspects such as appearance, prestige, and ease-of-use. Optimised performance level is necessary for an innovation to be frugal by requiring an examination of customer requirements and designing a product according to these requirements. With this requirement both market-specific characteristics and overengineering are addressed and frugal products perform to an exactly satisfactory level.

The settings for which frugal manufacturing is suitable also vary widely. Frugal innovation is used by both small and large companies in both emerging and developed economies (in which case it is termed 'reverse innovation') and can be applied to a wide variety of production contexts. A broad set of frugal innovation enablers can however be synthesized from literature, as is done by Niroumand *et al.* [7] and can be seen in Table 3.1.

None of the enablers proposed by Niroumand *et al.* [7] are essential to characterize an innovation as frugal. However, they do provide a guide for defining the success of frugal innovations' design and are therefore of use to the future definition of a design framework. As discussed in the previous section, literature on frugal manufacturing is limited. Furthermore, practical

Table 3.1: Frugal innovation enablers according to Niroumand *et al.* [7]

Score	Enabler	Rank
32.78	Optimization of the energy consumption of industries	1
31.35	Collaborating with local companies, other manufacturers and MNCs	2
30.82	Management supports	3
29.87	Paying attention to the needs of the local market	4
29.06	Reducing the profit margin	5
28.98	Participating in exhibitions and conferences to introduce the product	6
28.79	Empowerment of human resources	7
28.61	Investing in research and development	8
28.22	Safe and reliable designing to reduce consumer costs	9
27.91	Frugal packaging	10
27.77	Use of ICT and IT	11
27.13	Industrial estates development	12
27.12	Rapid prototyping with 3D printers	13
27.08	Evaluating customer feedback	14
27.07	Identifying the leading markets	15
26.94	World-class design and local production	16
26.72	Managing knowledge for innovation	17
26.62	Understanding and shaping consumer behavior with rewarding some buyers and content marketing	18
26.6	Using remanufacturing technologies and systems	19
26.5	government support programs	20
26.3	Production in areas where workers demand lower wages	21
26.29	Multifunctional product design	22
25.81	Investing in infrastructure	23
25.55	Simplification	24
24.86	Industrial cluster development	25
24.73	Using local materials	26
24.58	Product modularity	27
24.43	Appropriate branding of innovative product	28
24.32	Using clean & renewable energy	29
23.52	Using mobile applications to get feedback from customers	30
23.02	Pay attention to environmental pollution in product design	31
22.85	Restructuring business models	32
22.37	Bricolage	33
22.18	Use locally available energies	34
21.91	Biometric design	35
21.81	Subcontracting all work except the core business operations	36
21.78	Modeling through inventive analogies	37
21.25	Use of joint advertisements with other manufacturers	38
20.86	Use of local supply chain	39
20.68	Use of trainee youth	40
20.62	Employment of women	41
19.17	Building a culture for FI	42
19.07	Downsizing &miniaturization	43
18.93	Value engineering	44
16.26	Replacing current materials with cheaper but functional	45
15.88	Reusing old material, upcycling	46
15.52	Use of local lab	47
15.47	Cooperation with NGOs	48

applications based on the purposeful design of a manufacturing system as frugal are exceedingly rare, with manufacturing systems only being characterized as frugal retroactively [10]. Enablers therefore provide an important link between the characterization of a system and their practical applicability. Acting as a guide along which frugal manufacturing systems may be designed, these enablers allow for the shift from theoretical conceptualization to practical application.

Technology and design-based enablers can be considered to be of particular interest to frugal manufacturing and therefore to this thesis. A number of these technology and design-based enablers are included in Niroumand *et al.* [7] and are extracted as follows:

- Technology-based enablers
  - Optimization of the energy consumption of industries
  - Frugal packaging
  - Use of ICT and IT
  - Rapid prototyping with 3D printers
  - Using remanufacturing technologies and systems
  - Using clean & renewable energy
  - Using mobile applications to get feedback from customers
  - Bricolage
  - Use locally available energies
  - Replacing current materials with cheaper but functional
- Design-based enablers
  - Paying attention to the needs of the local market
  - Reducing the profit margin
  - Safe and reliable designing to reduce consumer costs
  - World-class design and local production
  - Multifunctional product design
  - Simplification
  - Using local materials
  - Pay attention to environmental pollution in product design

3.2 Reconfigurable Manufacturing Systems

3.2.1 Definition

Reconfigurable manufacturing systems (RMSs) were conceived by Koren *et al.* [50] in 1999 who offered the following definition:

> *a Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.*

RMSs are therefore a broad class of manufacturing systems that are by definition changeable. Reconfigurable manufacturing is therefore ideally suited to respond quickly to unpredictable market requirements [43]. RMSs vary from other 'intelligent' manufacturing systems such as 'flexible manufacturing systems' (FMS) or 'adaptive manufacturing systems' due to their cost-effectiveness, requiring little to no special, advanced machinery whilst maintaining high production volumes and flexibility. RMSs combine the high throughput of dedicated manufacturing and the flexibility of flexible manufacturing [8]. To achieve these benefits, RMSs use *reconfigurability* characterized by the 6 core characteristics described in Table 3.2 [51]:

Table 3.2: Six core characteristics of reconfigurability

Characteristic	**Description**
Customisation	Manufacturing systems are designed to produce a particular family of parts/products
Convertibility	Transforms existing functionalities of machines, in an operating mode, to suit new production requirements
Scalability	Throughput capacity can be rapidly and cost-effectively adjusted to abrupt changes in market demand
Diagnosability	Automatically read the current state of a system to detect and diagnose the causes of unacceptable quality of parts and reliability problems
Integrability	Ready integration of components and future integration of new technologies
Modularity	Modular major components to promote their re-use and exchange

RMSs were initially envisioned to be reconfigurable to be able to respond to changes in market or regulatory requirements, as outlined in the definition above. It has been recognized since however that RMSs are necessary for both variations in product type and variable product demand [52]. By designing the RMS for a product family rather than a single product the system becomes customizable to be used for a larger variation of product types. The modularity of the RMS allows easy reconfiguration to address variable product demand with changes in market.

The components which may constitute an RMS have also been expanded in scope from the structure, as well as hardware and software components described in the initial definition outlined by Koren *et al.* [50]. Reconfigurability has been expanded to a multi-dimensional capability, encompassing multiple reconfigurability enablers based on context-specific systems' features [5]. Specifically, reconfigurations can now be seen to encompass not only reconfiguration of modular machine tools but also logical and human-based reconfigurations enabled by the cyber-physical manufacturing systems and 'human-centricity' through the advent of industry 4.0 (extending towards industry 5.0 [2]). A reconfigurable manufacturing *system* therefore encapsulates a wide array of module types including machines, workstations and tools. A system component, considered as a module, may be a reconfigurable machine tool (RMT), incorporating a modular design itself [52]. Several papers focus on the design of these RMTs within a RMS [52–54], in contrast, this thesis focuses on the design of the manufacturing system as a whole. The design of RMTs is therefore not considered. Nevertheless, the requirements and functionalities of system components are essential to the functioning of the system as a whole. The functioning of RMTs as components within the system is therefore considered in the design of the system as a whole and henceforth recognized in this thesis.

This thesis therefore interprets RMSs in a broad manner, as was done for frugal innovation, to be able to draw lessons from as many systems as possible. A strict interpretation, excluding human-centric RMSs for example, might eliminate key intersections with frugal manufacturing. RMSs are therefore understood to encompass any (manufacturing) system which is designed at the outset for reconfigurability according to the characteristics as defined in Table 3.2. Reconfiguration might be understood to entail reconfiguration of structure and modular machine tools but also operator reassignment or logical software reconfigurations. Furthermore, the application for RMSs towards not only changes in market or regulatory requirements but also towards product type variation (and other reasons for reconfigurability) are explicitly considered. A simpler definition as in Takahashi *et al.* [55]: "a production system that allows the modification of the system configuration, such as facility layout, workers' assignment and machine function" is therefore taken as a starting point.

3.2.2 Modularity

Modularity is a key characteristic of reconfigurability. As such, *modular* product and process design is closely related to RMSs, which consist of modules by definition [56]. Furthermore, modular production processes and frugal innovation have been linked in multiple papers within the ProRegio project [44]. The design of modularity is therefore of special interest to the design of FRMSs.

Modularity entails "decomposing complex systems into independent but interconnected elements that can be treated as functional, logical, physical or organisational units" [37]. For RMSs, modules are thus the core elements that constitute a configuration, and the varying of modules therefore amounts to the reconfiguring of the system [52]. With unknown future reconfigurations, modular design allows for the co-definition of production process and product [9], with the full production process (and any reconfigurations) being developed at the same time. This is in turn useful for frugal innovation, allowing for local input of requirements for both production and product [35].

Modular function deployment (MFD) is a key method to support the design of modular products and systems, extending quality function deployment (QFD). It consists of five steps, relying heavily on two-dimensional matrices [57]:

1. Clarify customer requirements
2. Select Technical solutions

3. Generate concepts
4. Evaluate concepts
5. Improve each module

Clarifying customer requirements is a key step to capture the needs of the market and customers and translating them into product properties [58]. This is similar to the necessary capturing of core customer functionality of frugal innovation. Step 2: selecting technical solutions, is done through the breakdown of a products primary function into sub-functions, each of which will generate a technical solution, which in turn may require further product functions. After this, the Module Indication Matrix (MIM) is used to generate modular concepts based on module drivers. These module drivers usually consist of 12 generic drivers within 6 categories as originally developed by Erixon [59], namely:

- Development and design
  - Carryover
  - Technology evolution
  - Planned design changes
- Variance
  - Different specification
  - Styling
- Manufacturing
  - Common unit
  - Process/organization
- Quality
  - Separate testability
- Purchase
  - Black-box engineering suppliers
- After sales
  - Service/maintenance
  - Upgrading
  - Recycling

These concepts are then evaluated according to important characteristics such as interfacing in assembly applications or interaction of process and product in the process industry [57]. The final step consists of improving each module individually using the previous steps as a guide.

3.2.3 Criteria and Enablers

The success and feasibility of RMSs can be defined according to criteria. A limited number of general criteria for the implementation of RMSs have been explored in literature [8]. However, qualifying criteria, performance indicators and enablers of RMSs have been defined, which can be used to recognize, design and evaluate RMSs.

Qualifying criteria for RMSs are closely linked to the core characteristics of *reconfigurablity* outlined in Table 3.2. They are defined by Abdi & Labib [60] as the following:

- modular in both product and process design stages,
- rapidly integrated from product to process design,
- rapidly upgradable in process technology with new operational requirements,
- able to convert to the production of new products within each product family,

- able to adjust capacity quickly whilst changing product volumes (with predictable and/or unpredictable quantities).

These qualifying criteria outline a manufacturing system as reconfigurable by defining its abilities. The core characteristics of reconfigurability are inherent to these criteria. Modularity, integrability, and convertibility are explicitly mentioned, scalability and convertibility implied by 'rapidly upgradable' and 'adjust capacity quickly, and diagnosablity needed for the final criteria regarding both predictable and unpredictable quantities. Reconfigurability, as defined by its characteristics, can therefore be counted as the core qualifying criterion for an RMS and used as such [61].

Design criteria for RMSs consist of feasibility criteria and performance indicators which can be used to design an RMS and evaluate its functioning posteriorly. Abdi & Labib * [62] creates a fuzzy analytical hierarchical process model with an associated set of criteria to determine the feasibility of an RMS. The total set of criteria can be seen in Figure 3.2. Feasibility criteria are split into multiple levels of sub-criteria determining the economic and operational feasibility of an RMS. Manufacturing capacity, manufacturing functionality and reconfiguration time are identified as major attributes for the feasibility of RMSs specifically.

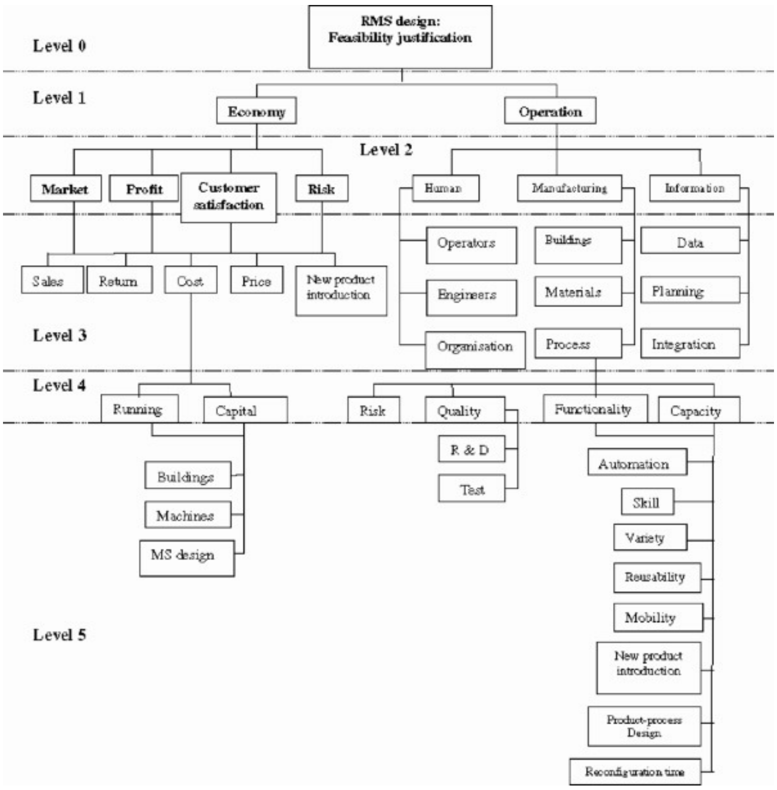


Figure 3.2: Feasibility criteria for RMS defined by Abdi & Labib [60]

Performance indicators are synthesized by Yelles-Chaouche *et al.* [63] from a study of objective functions in in RMS literature. Performance indicators are classified according to the four categories: cost, time, energy, and 'others.' Investment/capital costs, RMS operating costs, and RMS reconfiguration costs constitute the main 'cost' related performance indicators. Time required for changing a line configuration and machine change time as well as the transportation time between machines are mentioned as time related (system) performance indicators. Energy related performance indicators describe energy consumption and carbon footprint of the system directly. Finally, system reliability, system modularity, system flexibility, system availability, system utilisation and configuration convertibility are mentioned as 'other' indicators. An RMS is optimised according to a combination of these (or further) performance indicators that depend on the specific context and customer requirements (as is done by, for example, [43] and [52]). However, taken together, most RMSs can be comprehensively evaluated and designed according to the performance indicators falling in the above four categories.

RMS enablers characterize the environments in which above performance indicators and feasibility criteria are likely to be achieved. Pansare *et al.* [64], similarly to Niroumand *et al.* [7] for frugal innovation, has developed a ranked list of RMS enablers according to expert interviews. This (ranked list) can be seen in Table 3.3. The enablers are grouped according to the categories Strategy & Policy Enablers (SPE), Managerial & HR Enablers (MHE), Process oriented Enablers (POE), Technological Enablers (TEE), Organizational Enablers (OGE). For the purposes of this thesis, especially the TEE, POE, and to a more limited extent SPE enablers are of relevance. These technological and process-oriented enablers provide technical feasibility to the reconfigurable system that are key to achieving frugal manufacturing.

3.3 Opportunities

The elaboration of the concepts 'frugal manufacturing' and 'reconfigurable manufacturing systems' above demonstrate significant opportunities inherent in their combination.

Firstly, reconfigurability is useful to achieve frugality due to the possibility of lower initial capital costs. Continuing to meet the basic needs of customers, a key function of frugal innovation as defined by Hossain *et al.* [12], is only possible if a manufacturing system incorporates evolving product variety, adapting the product to individual and changing customer needs. In order to introduce new product varieties, a traditional manufacturing system can either use flexible machines or buy new machines. Both options are capital intensive with flexible machines being inherently expensive with low throughput [8] and the purchase of new machines entailing the disuse of old machines. RMSs are uniquely able to provide flexibility towards a manufacturing system efficiently (and cheaply) without adding too much additional complexity, making frugal manufacturing possible for continually evolving product variety.

Inherently, an RMS will be able to reduce the number of machines needed to achieve a similar level of product variety. The total cost of ownership of a manufacturing system, key to frugal innovation, can therefore be reduced. If a machine and/or manufacturing systems is reconfigurable, only modules need to be changed to achieve product variety. Therefore, an investment is only needed in new modules instead of entire machines, significantly reducing the capital requirements. Similarly, there is no need to invest heavily in flexible machines from the outset. Investments can therefore be portioned to match the exact functions needed by changing demands. The first criterion of Winkler *et al.* [20] defined in Section 3.1, reducing cost substantially, can therefore be met through reconfigurability.

Table 3.3: RMS enablers according to Pansare *et al.* [64]

Rank	Enabler	Code	Global weight
1	Availability of advanced technologies	TEE4	0.0518
2	Top management commitment and clear vision	SPE1	0.0516
3	Advanced CAD/CAM technologies	TEE2	0.0491
4	Prediction and analysis of changing customer demands	SPE4	0.0437
5	Government policies and regulations	SPE2	0.0432
6	Reconfigurable material handling systems such as robotics/AGV	TEE3	0.0405
7	Rapid prototyping facilities	POE4	0.0362
8	Resource optimization	POE2	0.0347
9	The flexible and reconfigurable manufacturing systems	TEE6	0.0343
10	Continuous customer feedback and analysis	SPE6	0.0338
11	Funds for RMS implementation	SPE3	0.0334
12	Quality control activities	POE1	0.0333
13	Effective long term planning for RMS	SPE7	0.0302
14	Understanding VOC	OGE4	0.0301
15	Reconfigurable working environment	MHE4	0.0298
16	Employee rewards and recognition	MHE3	0.0289
17	Automated and programmable production lines	POE6	0.0286
18	Education and training of employees	MHE2	0.0279
19	Multi-skill employees	MHE6	0.0276
20	Effective communication using IT techniques	TEE5	0.0275
21	Availability of Resources and sufficient space	OGE2	0.0269
22	Motivated team supportive to reconfiguration	MHE5	0.0268
23	Employee empowerment	MHE1	0.0258
24	Improved customer satisfaction	MHE7	0.0241
25	Availibility of methodologies like MRP, MAP, etc.	OGE3	0.024
26	Reconfigurable quality assurance practices	POE8	0.0235
27	Supplier integration	OGE5	0.0226
28	Research and New Product development (NPD) activities	OGE1	0.0211
29	Coordination among employees	MHE8	0.0192
30	Improved organizational performance	OGE6	0.0185
31	Minimized lead time/ reconfiguration time	POE5	0.0184
32	Interfaces of modules	TEE1	0.0124
33	Maintenance & repair facilities	POE7	0.008
34	Product testing & government approvals	SPE5	0.0067
35	Reduced wastes	POE3	0.006

Furthermore, inherent reconfigurability in a manufacturing system with low reconfiguration *effort* and *cost* can enhance frugality by combining functionalities. Costs can be reduced, and frugality enhanced, by achieving the same number of operations with a lesser number of system modules. A process may entail a number of consecutive steps of the same operation (e.g. fixing, cutting, drilling) at different dimensions. In a dedicated manufacturing system, the same number of consecutive modules as consecutive steps will need to be installed. Through reconfigurability, a single module can be used repeatedly to achieve any number of operations. For example, in an assembly process 6 drilling operations of different dimensions may need to be carried out. Through reconfiguring the same machine may be equipped with the required drill dimensions to achieve the same functionality as the 6 machines required in the dedicated manufacturing case.

Finally, increased product regionalization is a key aspect of frugal innovation enabled by reconfigurability. This is a key focus of the PROREGIO project detailed in Section 3.1.2. Modularity in particular, a key feature of reconfigurability, enables a product to be "customized so as to satisfy different target markets or market segments." [40]. The 'local' characteristic of frugal innovation, signifying local manufacturing for frugal manufacturing, is ideally suitable to be addressed by reconfigurable manufacturing. Companies seeking to relocate production to the markets they serve can draw on existing facilities in other markets and easily tune their facilities to the local conditions and market. As RMSs are uniquely "rapidly upgradable in process technology with new operational requirements" (see Section 3.2.3) the new operational requirements imposed by the new setting can be rapidly adjusted to. This is in addition to the adaptability to any product variety that may be required when introducing a new product into a market.

4 Defining a F-RMS

A definition of what constitutes and qualifies as a frugal reconfigurable manufacturing system is essential to be able to design such a manufacturing system. This chapter aims to define exactly what constitutes a F-RMS, its core characteristics, criteria and its enablers. This is done according to the research question:

What constitutes and defines the success of a frugal, reconfigurable manufacturing system?

The definition and the defining core characteristics of F-RMSs are based on a critical comparison of the reconfigurable manufacturing systems and frugal manufacturing systems which F-RMSs are an amalgamation of. From these characteristics, 3 criteria that may be used to determine the success of a manufacturing system as a F-RMS are synthesized. The chapter is concluded with an analysis of the enablers that may aid a F-RMS in achieving success.

4.1 Frugal, Reconfigurable, Manufacturing Systems

A frugal, reconfigurable manufacturing system is defined by combining the definitions as found in the previous sections:

A frugal, reconfigurable manufacturing system is designed in a resource-scarce manner at the outset for rapid and cost-effective changes in its configuration, in order to provide production capacity and functionality significantly cheaper than competitive alternatives whilst continually meeting evolving basic needs of its customers and the market

Frugality is ensured by the inclusion of a ″resource-scare manner,″ ″providing production capacity and functionality significantly cheaper than competitive alternatives,″ and ″basic needs″ of customers. Reconfigurability, in line with the broader definition adopted in Chapter 3, is included through the definition of ″design at the outset for ... changes in its configuration″ and the continuous meeting of ″evolving″ basic needs of customers and the market. Already, the inherent overlap of frugal innovation and RMS can be seen by the applicability of (core) functionality towards both.

The core characteristics of frugal manufacturing and RMSs show further overlap. Convertibility of RMSs concerning 'transforming existing functionalities' lies close to the functional characteristics of RMSs by providing the best functionality for customers. Customization allows for user-friendly operations, whilst diagnosability and robustness both increase the reliability of the product or manufacturing system significantly. Similarly, scalability and growing refer to the same concept of product growth whilst integrability is a necessary requirement to convert a global product to a local one. Modularity and affordability are less directly linked. The following 7 core characteristics of a F-RMS can therefore be deduced.

- Modularity
- Affordability
- User-customizability
- Reliability
- Local Integrability
- Scalability
- Core functionality

4.1.1 Modularity

Modularity entails decomposing a complex system into ”independent but interconnected parts that can be treated as conceptual, logical, physical or organizational units” [65]. Modularity is, as discussed, one of the core characteristics of reconfigurability, ensuring ease of reconfiguration. [37] also suggests modularity as a key tool for achieving frugality. Nevertheless, a frugal manufacturing system without modularity can be envisioned whilst this is unfeasible for an RMS. Modularity is nonetheless a key characteristic of F-RMS, allowing a manufacturing system that is able to use reconfigurability to achieve frugality.

4.1.2 Affordability

Affordability is an essential characteristic of frugality, serving as the reason for innovating frugally. Affordability can be characterized beyond financial cost for frugal innovation in general through the consideration of externalities towards society and the environment [1]. As such, the product becomes ‘affordable’ to the context of the frugal consumer in general. For manufacturing purposes, it is considered more practical to refer to monetary values, which may or may not encapsulate these externalities. Schleinkofer *et al.* [32] takes affordable in frugal manufacturing to entail ”manufacturing costs and the resulting acquisition costs of a product,” for example. For reconfigurability, affordability is ingrained into the objective of lowering reconfiguration costs along with reconfiguration effort. As such, a F-RMS is designed to be affordable in initial configuration and reconfiguration from the outset.

4.1.3 User-customizability

User-customizability is defined from the combination of the frugal characteristic ‘user-friendly,’ and the RMS characteristic ‘customizability.’ Customization to the user is key to providing user-friendliness in frugal innovation [38]. System customization in manufacturing, especially, allows for the consideration regional or local user requirements that are integral to the success of frugal innovation[11]. Customizability is also a core characteristic that allows for reconfigurations in RMSs. The trend towards mass customization in worldwide manufacturing systems is one of the main reasons for the establishment of RMSs [45]. Zheng *et al.* [66] furthermore describes the importance of ease of customizability of RMSs for small-and-medium enterprises (SME’s). User-customizability as a characteristic of F-RMSs therefore goes beyond the need for customizability of RMSs but requires ease of customizability for the user.

An operator must be able to customize the system through reconfigurations independently according to their needs in order for an RMS of FMS to be a F-RMS.

4.1.4 Reliability

Reliability is defined from the combination of the frugal characteristic 'robustness' and the reconfigurable characteristic 'diagnosability.' Both terms aim to extend the reliability of the system to which they apply. Robustness in frugality ensures the long lifetime and insensitivity of frugal products to "influences such as extreme weather conditions, dirt, fluctuating power supply or improper handling" [26]. Diagnosability in RMSs refers not only to the diagnosability of problems after failure has occurred but also to continuous quality monitoring of its components [67]. Diagnosability therefore ensures 'active' reliability through enabling intervention in case of impending issues whilst robustness ensures 'passive' reliability by preventing issues. A F-RMS therefore has the overall characteristic of reliability, defined as the "ability to perform as required, without failure, for a given time interval, under given conditions" [68].

4.1.5 Local Integrability

The characteristics 'integrability' from reconfigurability and 'local' from frugality are combined to the characteristic of 'local integrability' for a F-RMS. The modularity of RMSs is enabled by integrability, as modules need to be integrated into the system to ensure reconfigurability [69]. Frugality requires integration of a product in local markets [40]. Local integrability therefore ensures system components can be used according to the local requirements and integrated into existing systems. This characteristic of F-RMS demonstrates the necessity of integrability of any reconfiguration to existing, local solutions.

4.1.6 Scalability

'Scalability' is directly taken from the characteristics of RMSs, and 'growing' taken to entail the same concept from frugality for the characteristic of 'scalability'. Scalability in RMSs "allows system throughput capacity to be rapidly and cost-effectively adjusted to abrupt changes in market demand" [70]. Growing on the other hand refers mainly to economies of scale achieved by mass production [32]. A F-RMS is therefore scalable in that it is able to respond to through abrupt changes in market demand whilst continuing to ensure low costs.

4.1.7 Core functionality

Core functionality is defined as a characteristic of F-RMS through the consideration of the RMS characteristic of 'convertibility' and the frugal characteristic 'functional.' Convertibility consists of adjusting capabilities to production functionality in the context of RMSs [71]. The convertibility aspect of RMSs therefore exists to provide production functionality through reconfiguration without the need for excess equipment. The 'functional' aspect of frugality characterizes frugality as focusing on fundamental functionalities of, and optimized performance for, the markets which it serves [40]. The design of a F-RMS will therefore entail a critical analysis of functionalities where core functionality may be achieved more efficiently through convertibility. As a core characteristic of F-RMSs only the core functionalities should be sought to be achieved.

4.2 Criteria

To determine the success of F-RMSs, evaluable criteria should be established. As for both frugal innovation and RMSs, criteria are largely correspondent with the characteristics of F-RMSs defined in Section 4.1.

4.2.1 Substantial Cost Reduction

The most important and inherent criterion for the success of F-RMSs is substantial cost reduction. A F-RMS must be significantly cheaper than its alternatives, which could range from a similar non-frugal RMS to multiple dedicated manufacturing systems providing the same functionalities. A core criterion of frugal innovation, cost is also used in many performance indicators of RMSs. Cost is taken to mean the cost of the system over the life cycle, including capital and production costs, where production costs are the sum of operating and reconfiguration costs [72].

System Level

The total cost over the life cycle of the system C_Σ is considered, consisting of: [73].

$$C_\Sigma = C_d + C_m + C_{rc} + C_{ru} + C_o + C_{rm} \tag{4.1}$$

Here,

- C_d is the design cost, which is the cost to analyse and design the system. This is dependent on system complexity.
- C_m is the manufacturing/Implementation cost, which is the cost to build the system. The manufacturing/implementation cost is the function of system complexity.
- C_{rc} is the reconfiguration cost, which is the cost to reconfigure (or adjust) the system to satisfy the product requirements.
- C_{ru} is the ramp-up cost, which is the cost to recover the system performance.
- C_o is the operation and support cost, which is the cost to run the system.
- C_{rm} is the remanufacturing cost, which is the cost for recycling/disposal of the system.

To arrive at total cost reduction ΔC_{Σ}, a simple percent reduction can be calculated as follows:

$$\Delta C_{\Sigma} = \frac{C_{\Sigma,f} - C_{\Sigma,a}}{C_{\Sigma,a}}. \tag{4.2}$$

Where $C_{\Sigma,f}$ is the total lifecycle cost of the to be designed F-RMS and $C_{\Sigma,a}$ the total lifecycle cost of the alternative or existing system to which it is compared. As a criteria, the total cost reduction defined by Winkler *et al.* [20] as at least 60% cost reduction is taken:

$$\Delta C_{\Sigma} \geq 0.6. \tag{4.3}$$

Projected life cycle costs should be individually compared to the costs of similar manufacturing facilities in similar contexts, whenever available, to be able to determine if this criterion is satisfied.

Component Level

The initial investment per component should be reduced as much as possible on a component level in order to achieve a F-RMS. Due to the scalability aspect of RMSs, more machines can be bought as the system is adapted. The initial investment cost of individual machines can therefore become an important part of the system life cycle cost [70]. It is furthermore considered less important to know the life cycle cost of a single machine if overall system performance (and cost) is still sufficient. An additional benefit occurs if the components themselves are frugal, ensuring low cost without compromising on production quality. In all situations, a lower-cost machine should meet the design requirements of the customer.

4.2.2 Core functionality per configuration

Another criteria is the manufacturing functionality per configuration. Here manufacturing functionality is defined as the "operational degree of switching from a product to the other with different process requirements" [60]. A F-RMS must focus on core requirements. It should therefore be clear what functionalities are achieved in each configuration to achieve these requirements. A focus should be placed on limiting unnecessary reconfigurations and modules, both components and operational, within a configuration. Nevertheless, flexibility should be achieved through reconfiguration, allowing the F-RMS to address changing market demands. Achieving core functionality within a single configuration whilst also allowing reconfigurations to achieve different functionalities is therefore important for F-RMSs to offer increased flexibility whilst making use of the cost-cutting benefits of frugal functionality limitations.

Achieving the correct degree of functionality per configuration is accomplished through the analysis of two metrics. Achieving core configuration functionality entails reducing the amount of modules to only those providing necessary functionality. The operational capability of a single configuration should therefore be minimized. At the same time, flexibility is ensured through the enabling of reconfigurability. The reconfiguration effort of switching from the active configuration to any new one must therefore also be as low as possible.

System Level

Operational capability (OC) per configuration (p) and machine (q) is mathematically defined as in Goyal & Jain [53]:

$$OC_{p,q} = [(\sum_{k=1}^{K} \delta_{p,k}^{q}) - 1]^{Y}, \tag{4.4}$$

where Y is a power index that serves to pronounce the value of OC for a high number of operations when compared to a low number of possible operations. Its value can be deduced through a sensitivity analysis and is dependent on case-specific preferences. K is the set of all operations that machine p in configuration q is able to perform. The binary operator $\delta_{p,k}^{q}$ is defined as

$$\delta_{p,k}^{q} = \begin{cases} 1 & \text{if machine } p \text{ in configuration } q \text{ is able to perform operation } k \\ 0 & \text{otherwise} \end{cases}$$

The total operational capability of the system OC per configuration is reached by summing the results of Equation 4.4 over P, the set of all machines. As such,

$$OC_{q} = \sum_{p=1}^{P} \{[(\sum_{k=1}^{K} \delta_{p,k}^{q}) - 1]^{Y}\}. \tag{4.5}$$

OC_q is therefore simply the sum of all operations carried out by all machines within a configuration with a power index applied to affect operational preferences. The operational capability should be minimized for a F-RMS, contrary to most applications in literature (such as Goyal & Jain [53] and Ashraf & Hasan [74]). In this sense, under the assumption that a single product is produced within a single configuration, the operational capability per configuration must be minimized until only the core operations needed to produce a product are achieved.

The reconfiguration effort E_{rm} is calculated using the three components reconfiguration time, reconfiguration cost and ramp-up time [5].

$$E_{rm} = t_{rm} + C_{rm} + t_{ru} \tag{4.6}$$

The reconfiguration time t_{rm} and cost C_{rm} are the time and cost necessary to reconfigure the system, respectively. The ramp-up time t_{ru} is the time necessary for a newly introduced configuration to reach the designed levels of production for both throughput and quality [75]. A F-RMS must have minimal reconfiguration effort, such that the introduction of product variety is less effort through reconfiguration than through the introduction of system flexibility.

With sufficiently low reconfiguration effort, habitual reconfiguration within the production of a single product may be feasible, as discussed in Chapter 3 [60]. In this way, the number of modules required to achieve the operational capability for producing a product can be limited by using the same module for different operations. For this effect, the set Q_r, the set of required configurations is introduced to differentiate from Q, the set of all possible configurations. The operational capability OC of the system to be minimized then becomes:

$$OC = \sum_{q=1}^{Q_r} \sum_{p=1}^{P} \{[(\sum_{k=1}^{K} \delta_{p,k}^{q}) - 1]^{\Upsilon}\}. \tag{4.7}$$

Q_r depends on the reconfiguration effort E_{rm} and will be equal to 1 in most cases.

Component Level

At the component level the level of functionality per module should be reduced as much as possible to ensure modularity and accordingly, integrability. Accordingly, the number of 'mechatronic objects,' which provide a required processing capability [43], per module should be limited as much as possible. The operational capability of each module as expressed using Equation 4.4 should therefore be as close to 1 as possible.

Concurrently, requiring modules to be as operationally simple as possible might introduce additional difficulty in reconfiguring the system however. Fewer modules per operation also signify more modules need to be reconfigured to achieve altered functionality. A trade-off is therefore introduced between the operational capability per module (and configuration) and *machine* reconfiguration effort. The machine reconfiguration effort E_{mrm} is defined by directly considering the number of machine modules that need to be altered [76]:

$$E_{mrm} = \alpha \frac{\text{no. of modules added}}{\text{Total no. of modules}} + \beta \frac{\text{no. of modules removed}}{\text{Total no. of modules}} + \gamma \frac{\text{no. of modules readjusted}}{\text{Total no. of modules}} \tag{4.8}$$

Where, α, β and γ are constants such that $\alpha \geq \beta \geq \gamma$ and $\alpha + \beta + \gamma = 1$. As the operational capability per machine decreases the machine reconfiguration effort will often increase as more modules need to be added, removed and/or readjusted. It is therefore important to judge the importance of the considered component in the system as a whole and expected reconfigurations needed such that an optimal level of modularity and reconfigurability can be achieved.

4.2.3 System Usability

The system usability is a third key criteria. F-RMSs must be locally integrable and scalable, user-customizable, and reliable. The system must therefore be usable by those owning, operating, repairing and otherwise interacting with it. This criterion can be split into two parts: operational complexity, and system reliability. Operational complexity consists of the complexity of operational tasks within a configuration. Reduction of operational complexity serves to make the system usable by as many users as possible without the need for extended training or high-skilled labour, as well as easily customized by the user after system delivery.

The reliability consists of system robustness, as well as maintainability. A reliable system ensures that the system performs consistently in both quality and quantity requirements, with little to no maintenance needed. In case of malfunctions, problems need to be be diagnosed rapidly and reparations made simply, a key part of frugal manufacturing in general [26]. It is important to note that system usability is *not* the same as simplicity, as was discussed in Section 3.1.2, and a F-RMS can therefore still consist of advanced technology or operations.

System Level

System usability, and its sub-criteria of operational complexity and system reliability are judged qualitatively at the system level. Although efforts have been made in defining operational complexity numerically (as in [77]), these methods rely on extensive numerical models that are deemed too case specific for a general framework. Instead, qualitative methods are used more often (as in [51, 73]). Zhang *et al.* [73] uses a user-defined qualitative scale for operational complexity as a whole. Maganha *et al.* [51] further specifies three aspects:

1. Complexity of operations: indicating whether very few or many steps/operations are required.
2. Complexity of BOM: indicating whether very few or many parts/materials, and a one-line or complex bill of material are needed.
3. Complexity of product: indicating whether modular or integrated product design is used.

On a system level, the aspects used by Maganha *et al.* [51] provide a further guideline on determining complexity qualitatively and will be used in this thesis.

System reliability is a statistical measure that can be described as the ”probability with which the system is in a functioning state at a certain point in time or during a time interval under defined boundary conditions” in this view [68]. However, for a by definition continually changing system such as an F-RMS, these probabilities can become difficult to determine. For any manufacturing system, the reliability of a configuration R_q with known machine reliabilities can be calculated according to [78]

$$R_{series} = \prod_{q=1}^{n} R_q, \tag{4.9}$$

or

$$R_{parallel} = 1 - \prod_{q=1}^{n} (1 - R_q), \tag{4.10}$$

where the difference between a series and parallel system is the difference between a single machine in each stage for each configuration and more than one machines at each configuration. q is the index of the configuration as in Equation 4.4. In the case of unknown machine reliabilities, a qualitative judgement of reliability can be used, as detailed in the next section.

Component Level

On a component level, the system usability can be judged by qualitatively determining component complexity and maintainability. An integrated qualitative judgement of component complexity leads to an indication of the reliability of the component. The reduction of complexity of system components such as machines or modules by introducing simpler and more cost-efficient components can lead to a reduction in reliability. Schleinkofer *et al.* [26] introduces a matrix juxtaposing maintainability and complexity, which can be seen in Figure 4.1. As many components of a F-RMS as possible should be placed in the third quadrant of the

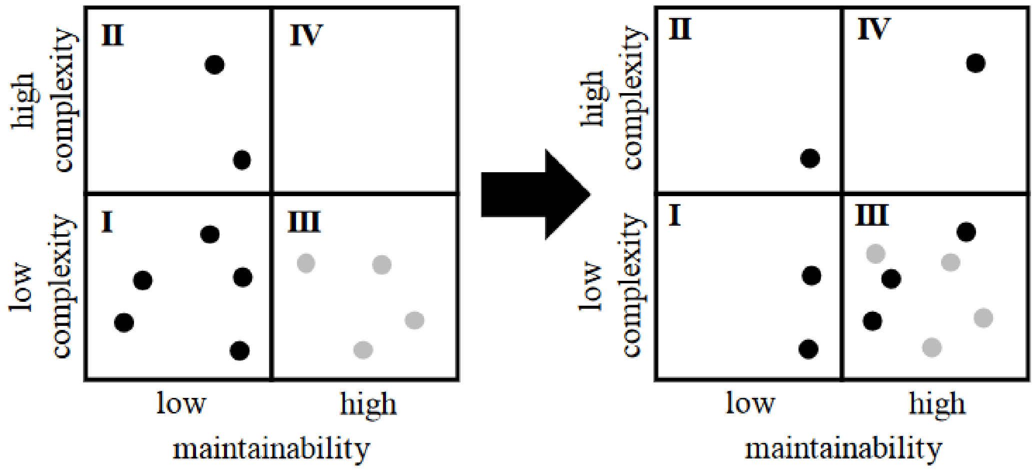


Figure 4.1: System reliability optimization matrix [26]

matrix seen in Figure 4.1, indicating both high maintainability and low complexity. 'Maintainability' is determined by the qualitative judgement of whether a component, machine or module:

1. enables easy maintenance and repair and
2. uses locally available materials.

Consecutively, (component) complexity is determined by the qualitative judgement of whether a component, machine or module:

1. has fewer components for functional fulfillment, or/and
2. uses simpler components/solutions (simpler technology as well as lower cost)

4.2.4 Context-Specific KPI's

A final set of criteria is provided by context-specific KPI's. It can be concluded rather straightforwardly that a manufacturing system must meet the KPI's set by its owners or operators. Nevertheless, this criterion is explicitly mentioned to stress the importance of the F-RMS providing local integrability and user-customizability. Context-specifc KPI's should be integrated into the F-RMS design on the same level as aforementioned criteria, ensuring the meeting of customer requirements. Depending on the context, any number of KPI's can be defined and evaluated along with the other criteria mentioned in this section. Critically, F-RMSs must therefore, as a concept, be able to accommodate a large variety of customer-set KPI's.

4.3 Enablers

Through the comparison of the ranked lists of enablers of Niroumand *et al.* [7] and Pansare *et al.* [64] shown in Table 3.1 for frugal innovation and Table 3.3 for RMSs a combined set of enablers can be established. These enablers serve as a comprehensive list of the factors that increase the likelihood of success of a F-RMS. In contrast to the criteria and characteristics defined earlier in this chapter, not all enablers are required for a manufacturing system to be considered a F-RMS. Nevertheless, their generalization provide important insights into the functioning of F-RMSs and how they can be realized.

4.3.1 Combined Enablers

Several enablers of both RMSs and Frugal Innovation in general demonstrate a direct overlap. Combined, these form an initial list of factors that enable the establishment of a F-RMS. The list of enablers that apply to both RMSs and frugal innovation can be seen in Table 4.1.

Globally, the enablers can be categorized into the following categories, although overlaps can also be inferred:

- Stakeholder support
- Customer consideration
- Employee involvement
- Organizational factors
- Resource use
- Design process
- System design

Stakeholder support, entailing support from management, governments and suppliers, is key to establishing F-RMSs. The economic justification of F-RMSs can be difficult to achieve, with a total life-cycle perspective being difficult to produce [8] whilst requiring a willingness to reconsider current approaches towards frugal practices [79]. Conducive decisions made by management, subsidies and regulative easing from involved governments, as well as active supplier engagement not only allow for an F-RMS to be approved more easily but may also serve to increase their economic justifiability. As a broad category of enablers, the different stakeholder supports are mentioned directly in the ranked list of both RMSs and frugal innovation.

Consideration of the customer, in the form of attention to demand, evaluation of feedback and guarantee of satisfaction, form another key set of F-RMS enablers. As mentioned in Section 3.3, reconfigurability itself offers opportunities to provide customer customization, key to the success of frugal innovation in general. However, actively considering the customer holds

Table 4.1: Enablers of a Frugal Reconfigurable Manufacturing System

Combined Enabler	**RMS Enabler(s)**	**Frugal Enabler(s)**
Management Support and Commitment	Top management commitment and clear vision	Management supports
Governmental cooperation	Government policies and regulations, Product testing & government approvals	Government support programs
Supplier Collaboration	Supplier integration	Use of local supply chain, Collaborating with local companies, other manufacturers and MNCs
Attention to customer demand	Prediction and analysis of changing customer demands	Paying attention to the needs of the local market
Integration of customer feedback	Continuous customer feedback and analysis (R6SPE6),Understanding VOC	Evaluating customer feedback, Using mobile applications to get feedback from customers
Customer satisfaction	Improved customer satisfaction	Understanding and shaping consumer behavior with rewarding some buyers and content marketing
Employee Empowerment	Employee empowerment	Empowerment of human resources
Employee training	Education and training of employees	Use of trainee youth
Knowledgable employees	Multi-skill employees	Managing knowledge for innovation
Conducive Organizational Culture	Motivated team supportive to reconfiguration, Reconfigurable working environment	Building a culture for FI
Reorganization	Improved organizational performance	Restructuring business models
Resource optimization	Resource optimization	Optimization of the energy consumption of industrial
Availiability of Resources and Infrastructure	Availability of Resources and sufficient space, Funds for RMS implementation	Investing in infrastructure
Reduction of waste	Reduced wastes	Value engineering, Pay attention to environmental pollution in product design
Research and Development	Research and New Product development (NPD) activities	Investing in research and development
Structured planning methodologies	Availibility of methodologies like MRP, MAP, etc.	Modeling through inventive analogies
Rapid prototyping	Rapid prototyping facilities	Rapid prototyping with 3D printers
Use of IT	Effective communication using IT techniques	Use of ICT and IT
Long-term analysis	Effective long term planning for RMS	Identifying the leading markets
Reliability assurance	Reconfigurable quality assurance practices	Safe and reliable designing to reduce consumer costs, World-class design and local production
Modularity	Interfaces of modules	Product modularity
Flexible Design	The flexible and reconfigurable manufacturing systems	Multifunctional product design

great potential to enable both RMSs and frugal innovation independently, and therefore an F-RMS. Integrating customer feedback into both the product and system design process greatly increases a firms potential at successful product regionalization [39]. Therefore, customers are more likely to take up the product, leading to increased economic viability of the F-RMSs and critically, the product it produces.

Employee involvement in the production process provides important advantages towards both productivity as well as internal innovation. Increasing knowledge (to be reached through internal training) and empowerment of employees enable them to make decisions quickly and efficiently which can be a key barrier in often complex RMSs [80]. At the same time, employees will be able to manage system aberrations independently and innovate upon the existing system without explicit management guidance [81]. Similarly, organizational factors enable a sense of innovation that can be greatly conducive to the success of F-RMSs. Through organizational restructuring towards frugal, reconfigurable operation, an organizational culture is established amongst both employees and management that enables frugal, reconfigurable decisions throughout the company.

The availability and optimization of the resources used for production enable an efficient and resource-appropriate F-RMS to be established. The inherent requirement of function reduction in frugal innovation ensures that resources are saved, greatly decreasing the cost-benefit ratio when compared to regular manufacturing system [82]. Nevertheless, whilst a F-RMS seeks to minimize the additional investment needed for realization, apt resources and the optimization of these resources through cutting waste still greatly enable their functioning [83].

Several tools, techniques and technologies are mentioned in both Niroumand *et al.* [7] and Pansare *et al.* [64] that ensure a successful design process and eventual design. The availability of rapid prototyping, IT and long-term planning techniques are all found to be suitable techniques to aid the design process of both RMSs and frugal manufacturing systems and therefore F-RMSs and their eventual smooth operation. As established in Section 4.1 and Section 4.2, an F-RMS has a number of key characteristics and criteria which also serve as enablers for the success and establishment of F-RMSs. Their re-occurrence as enablers in both review papers further ensure their relevance.

4.3.2 Non-concurring enablers

A small set of enablers defined by Niroumand *et al.* [7] and Pansare *et al.* [64] directly conflict in their intentions, shown inTable 4.2.

Table 4.2: Directly conflicting enablers as defined by Niroumand *et al.* [7] and Pansare *et al.* [64]

RMS Enabler	Frugal Enabler
Employee rewards and recognition	Production in areas where workers demand lower wages
Improved organizational performance	Reducing the profit margin
Supplier integration	Subcontracting all work except the core business operations
Availability of advanced technologies	Simplification

The central conflict in these enablers lie in the need for cost reduction in FMSs and the perceived need for additional investment in RMSs. A F-RMS seeks to reduce life time costs, as for FMSs. It is therefore important to critically assess the additional benefit of investing in the enablers mentioned in Table 4.2. Improved organizational performance may often be defined as additional company profit [84], in which case it would be antithetical to the frugal enabler of reduced profit margins. However, other factors of improved organizational performance, which might be critical to a firms long-term success may also be sought. Creative solutions may offer further opportunities for these enablers to still be utilized when setting up an F-RMS. For instance, employee recognition can still be considered an enabler of F-RMSs if offered in non-monetary ways such as workplace culture.

4.4 Conclusion

This chapter aimed to define the frugal reconfigurable manufacturing system in order to answer the question:

What constitutes and defines the success of a frugal, reconfigurable manufacturing system?

Elements from the formal definition of frugal innovation and RMSs were taken to arrive at the overarching definition of a F-RMS: "A frugal, reconfigurable manufacturing system is designed in a resource-scarce manner at the outset for rapid and cost-effective changes in its configuration, in order to provide production capacity and functionality significantly cheaper than competitive alternatives whilst continually meeting evolving basic needs of its customers and the market." Similarly, the comparison of the core characteristics of FMSs and RMSs led to the establishment of 7 core characteristics of F-RMSs, namely:

- Modularity,
- affordability,
- user-customizability,
- reliability,
- local integrability,
- scalability,
- core functionality,

where modularity and affordability are unique characteristics taken from RMSs and frugal innovation respectively. The final five core characteristics are achieved by defining the overlap of the remaining core characteristics of RMSs and frugal innovation.

These core characteristics were used as a basis for the establishment of the criteria for success of F-RMS, as widely done for both RMSs and frugal manufacturing (see Chapter 3). The three unique criteria defined were "substantial cost reduction," "core functionality per configuration," and "system usability," with each criterion being defined on both system and component level. A distinction was furthermore made between criteria that were quantitative and qualitative in nature, with substantial cost reduction and core functionality per configuration being largely based on quantitative measures whilst system usability was defined for more qualitative judgement. To highlight the importance of the user in the F-RMS it was emphasized that user-defined KPI's were to be judged at the same level as the other defined criteria.

Finally, a set of enablers for F-RMSs was synthesized from the ranked lists of both frugal innovation and RMS enablers by Niroumand *et al.* [7] and Pansare *et al.* [64], respectively. In general, stakeholder support, customer consideration, employee involvement, organizational factors, resource use, design process and system design were determined to be important categories of enablers for a F-RMS. These are not essential for a manufacturing system to be successful as a F-RMS but may aid towards this goal. A set of enablers from the defined lists that seemed to conflict was also discussed. It was demonstrated that these seemingly incompatible enablers might still be possible through the critical analysis of their interpretations and creative solutions that allow them to be achieved regardless.

5 Framework

The frugal reconfigurable manufacturing system (F-RMS) was defined in the previous chapter, along with its core characteristics, criteria and enablers. The concept of what constitutes a F-RMS is thus well established. However, the opportunities of F-RMSs outlined in Chapter 3 can only be achieved if manufacturing systems are designed (or redesigned) as an F-RMS from the outset. As a novel proposition of this thesis, no design procedures or guidelines, let alone a comprehensive framework, exist for the design of F-RMSs. As noted in Chapter 3 research reconfigurable manufacturing is more extensive, including literature outlining design procedures. The design of frugal manufacturing systems (FMSs) or reconfigurable manufacturing systems (FMSs) has often been based on their core characteristics, criteria and enablers (as in Schleinkofer *et al.* [31] for FMSs or Koren & Shpitalni [85] for RMSs, for example). Summarily, the design is often based on precisely the aspects of F-RMSs that have been described in the previous chapter. The core characteristics, criteria and enablers of F-RMSs are therefore used as a conceptual basis for the design of a comprehensive framework for the design of F-RMSs. This is done according to the research question:

How can a framework for the design of frugal, reconfigurable manufacturing systems be established?

The comprehensive framework for reconfigurable manufacturing systems as developed by Andersen *et al.* [8] is used as a basis for the F-RMS framework. The Key steps of the framework, which can be seen in Figure 5.1, will be adapted towards the design of F-RMSs using the core characteristics, criteria and enablers developed in the previous chapter as a base for individual activities described by the framework. A focus will be placed on methods and tools for the practical application for these design steps as a method of substantiation of the designed system. The design steps highlighted by Andersen *et al.* [8] will be highlighted individually and (depending on their relevance) adapted towards designing F-RMSs. This discussion of the individual steps will lead to a consolidated framework adapted to the design of F-RMSs which will be presented at the end of the chapter.

5.1 Management, Planning and Clarification of Design Task

5.1.1 Preparation of investment request

The analytical hierarchy process (AHP) is used to justify a possible investment in an F-RMSs. This method allows for the explicit prioritization of objectives which can then be used to establish weights for selection criteria. When used to justify the selection of an F-RMS, company objectives can be combined with the criteria detailed in the previous chapter to compare the performance of an F-RMS to a dedicated, flexible or conventional reconfigurable manufacturing system for a greenfield project. In the case of a brownfield project, the potential F-RMS can be compared effectively to the existing manufacturing system.

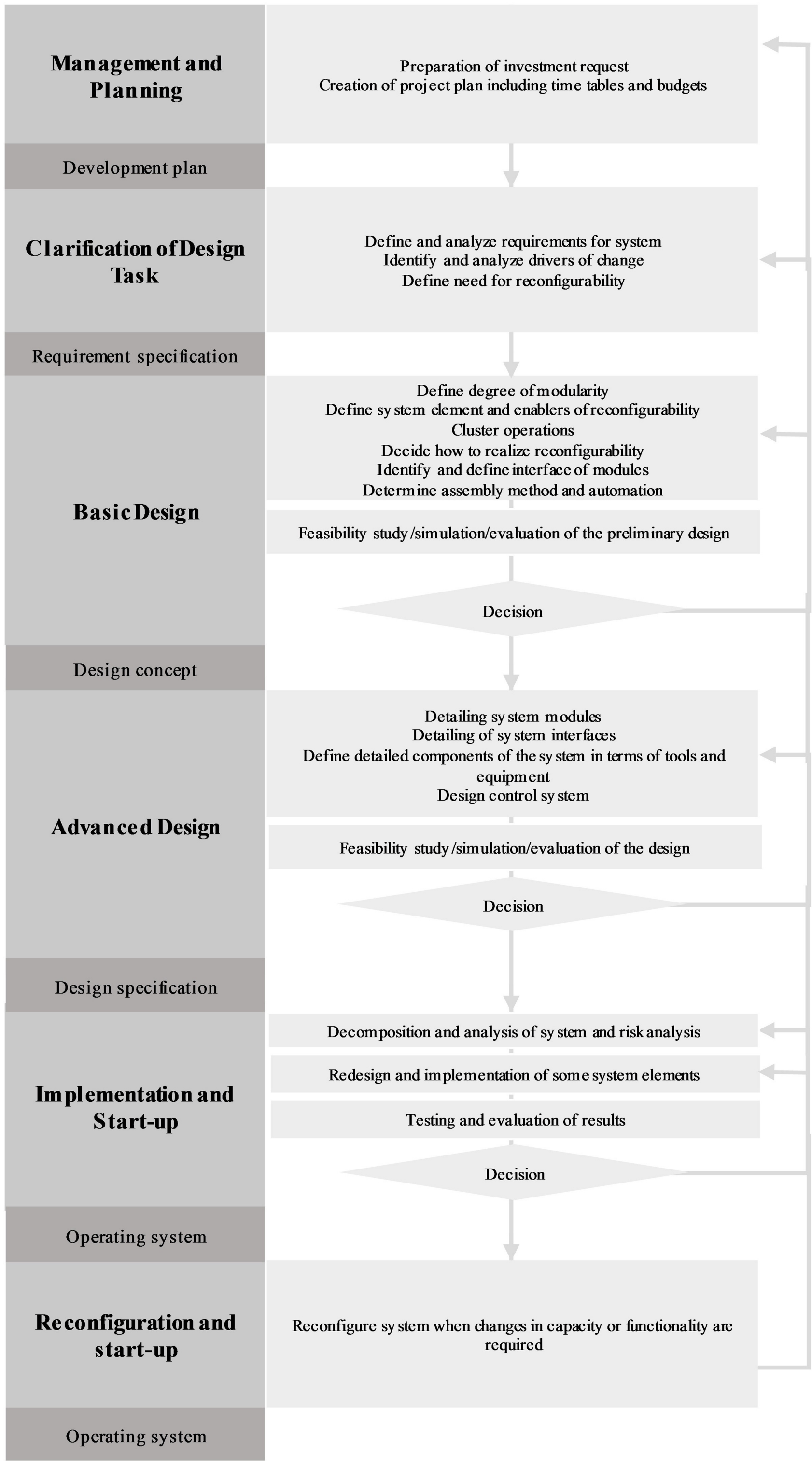


Figure 5.1: The framework as developed by Andersen *et al.* [8]

AHP is a pairwise comparison process with a hierarchical structure [71]. Pairwise weighing between n elements in a level is approximated to construct the ratio $a_{ij} = \frac{w_i}{w_j}$, which is the weight of element i relative to element j [86]. The estimated weight vector $\vec{w}$ is then found through the completion of the eigenvector problem:

$$A\vec{w} = \lambda_{max}\vec{w}. \tag{5.1}$$

Here, A is the matrix consisting of a_{ij}s, and λ_{max} is the principal eigenvalue of A. When all elements are paired consistently then $a_{ij} = \frac{1}{a_{ji}}$ for any i and j and ensuingly:

$$A \cdot \vec{w} = n \cdot \vec{w}. \tag{5.2}$$

When pairing is not consistent (as is often the case) Equation 5.1 can be expressed as $A\vec{w} = \lambda_{max}\vec{w} = \vec{E}$ where E is the principal eigenvalue, a value around n (the total number of elements in the same level). To estimate $\vec{E}$, each column of A is normalized and the average is taken over its rows. The Inconsistency Ratio (IR) is defined as

$$IR = \frac{\lambda_{max} - n}{n - 1} \tag{5.3}$$

This is equal to the variance of the error incurred in estimating matrix A. If the inconsistency $IR > 0.1$ the judgements must be revised and the problem revisited until the inconsistency ratio is sufficient [87].

The hierarchy as constructed for the selection of an F-RMS can be seen in Figure 5.2. The

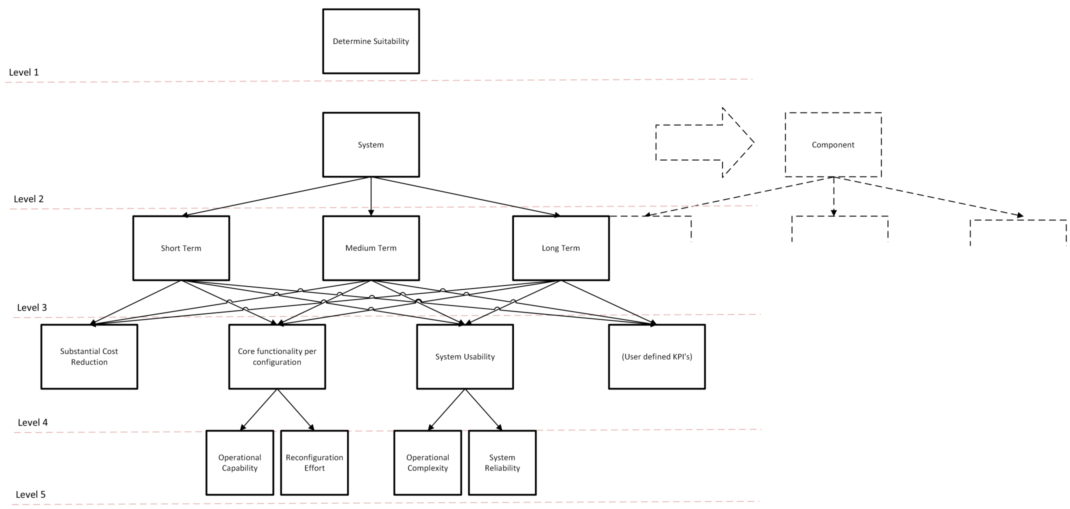


Figure 5.2: The AHP Hierarchy to be used for determining the suitability of the FRMS

criteria that were defined in Chapter 4 are used as the basis for the hierarchy. At the second level, it is important to distinguish between an evaluation for the system as a whole or for a specific component or subsystem. The different components of the hierarchy can be compared doubly if an evaluation for both the system as whole as specific sub-components is required. As per the definition of the criteria in Chapter 4, the specific definition of the criteria to be judged will vary according to which aspect of the system is evaluated.

At the third level, the planning horizon to which the focus of design or improvement is placed is decided. To evaluate the functioning of a future manufacturing system, a distinction can be made over its functioning in the short, medium or long term. Eventual designs, improvements and optimizations may then be focused towards improving performance along one of these horizons. The short term is defined as the day to day operations of the plant to be designed. The medium term concerns a company production planning period, usually over the span of several weeks - months. The long term is the planning horizon defined by the strategy of the production plant and will usually be projected over one to multiple years. Accordingly, possible changes in production may be concerned with product variant changes, volume changes or product changes for the short, medium and long term, respectively [88].

The fourth and fifth levels concern the criteria as defined in Chapter 4 directly. To evaluate the suitability of an F-RMS directly and impartially, users define their own KPIs which are judged on the same level of the hierarchy as the F-RMS specific criteria. If the user does not deem the criteria for F-RMS as important as their own KPI's, this will be reflected in the outcome of the AHP-prioritization process, and an F-RMS may not become the most suitable outcome of the evaluation. At the same time, the explicit recognition of the criteria of F-RMSs allow for the highlighting of its potential. The sub-criteria discussed in Chapter 4 are evaluated in the fifth level, as per the general functioning of AHP.

5.1.2 Creation of project plan including time tables and budgets

This step is deemed to be concerned with implementation of the system and is therefore not analysed further in this conceptual framework. F-RMSs may be developed for any time tables and will inherently require lower budgets. It is suggested to use existing company planning methods to execute this step.

5.1.3 Define and analyze requirements for system

Closely aligning an eventual product with customer requirements lies "at the basis of frugal innovation" [41]. Defining the user requirements for the manufacturing system is therefore especially important for F-RMS and must be provided by the user. Nevertheless, it might often be unclear to the user what the exact requirements of their system are. Important requirements can also be omitted if relying on self-reporting of requirements. This is especially true for reconfigurable systems, where a reconfiguration may be needed to adapt to a future (unknown) requirement [89]. F-RMSs must therefore by their nature be designed according to an open-ended set of future requirements.

A structured method of collecting requirements and collaboratively developing future scenarios with the user is therefore needed. Both Andersen *et al.* [90] and Schleinkofer *et al.* [32] identify a questionnaire as an appropriate tool to identify a list of requirements. This questionnaire should invite reflection on different future scenarios as well as different types of requirements. Andersen *et al.* [90] develops such a questionnaire for reconfigurable systems,

Table 1. Requirements for the methods used to determine requirements and their origin.

demands on methods for requirement determination which need to be considered	framework conditions		
	frugal approach	producers of manufacturing systems	EMs
radical innovation	•		
various markets			•
accuracy and objectivity	•	•	
manufacturing systems		•	
limited resources		•	
anonymous customer			•
create reference to frugal strategy	•		

Figure 5.3: The demands for a requirement determination method of frugal manufaturing as developed by Schleinkofer *et al.* [32]

whilst Schleinkofer *et al.* [32] provides a guide for developing company-specific requirements questionnaires for frugal products. Specifically, seven core demands which must be reflected upon in the company-specific questionnaire are defined, these can be seen in Figure 5.3. These lists are used as a basis for the development of a general requirements questionnaire which can be used by manufacturing firms that seek to establish a F-RMS.

To evaluate the suitability of questions directly provided and develop new questions for the development of F-RMSs in particular, questions are directly linked to the core characteristics of F-RMSs developed in Chapter 4. As the core characteristics rely on an amalgamation of the core characteristics of reconfigurable and frugal manufacturing, several of these core characteristics are already found in the original questionnaires. As F-RMSs rely on reconfigurability to ensure frugality, no questions were indeed found irrelevant from the questionnaire by Andersen *et al.* [90]. Instead questions which reflect the specific approach of frugal manufacturing design were added according to the demands presented by Schleinkofer *et al.* [32] to further encompass all core characteristics. Affordability, in particular, is not represented in Andersen *et al.* [90], being a core characteristic solely resulting from the characteristics of frugality. Several questions were therefore added to reflect any requirements towards this characteristic. Vice-versa, modularity, resulting from the core characteristics of reconfigurability was not deemed to need any additional questions to determine its role in the requirements of the user. The full questionnaire, as well as their associated characteristics can be found in appendix D.

The questionnaire is furthermore classified into the requirement categories: product, production, technology and environment. These are linked to the main drivers of change of manufacturing (see Section 5.1.4). These categories give an understandable structure to the questionnaire when carried out and invite the user to reflect upon all aspects of their manufacturing systems' requirements. To highlight the increased importance of the local environment for F-RMSs compared to RMSs, the 'environment' category was added to the three other categories present in Andersen *et al.* [90]. This invites users to reflect not only on the processes happening within their factory walls but also on any external factors that they might need to respond to in the future. An additional classification of questions is done according to the planning horizons discussed in Section 5.1.1 for processing purposes.

The questionnaire asks the user in all questions to classify their response into a very low (VL), low (L), medium (M), high (H), or very high (VH) response, the exact interpretation of which varies per question. For otherwise qualitative questions which might vary according to perspective, the user is asked to compare the extent of the quality asked to their respective industry. For instance, for the question 'To which extent is final product cost considered a processing requirement?" contributed by this thesis, respondents are asked to judge this extent when compared to their specific industry. An overview of the system users perception towards the requirement categories discussed above can therefore be created. Where a large proportion of high or very high responses in a category may indicate increased importance of that specific category of requirements. In order to determine a more specific list of requirements however, it is important that the questionnaire is not approached as a multiple choice selection but an open-ended discussion to be conducted with an interviewer present. Respondents should be encouraged to reflect upon their choices and these should be noted down as indications of requirements. The value of the questionnaire therefore primarily becomes a method to explore and define the relevance to the specific system of as many aspects as possible. It is therefore also encouraged that the questionnaire is carried out in person with an interviewer with different users of the system, or in a workshop setting where collective reflections and decisions can be made. A list of requirements can then be distilled by reflecting upon the responses to the questions given, along with the perceived overall importance indicated by the multiple choice answer.

An extra step for Frugal RMS is the revisiting of the final list of requirements and critically analysing them. Any requirements which are regarded as 'nice to have' and not 'need to have' must be eliminated to reduce the overall complexity of requirements and therefore enhance its frugality. In this way, the core requirements of the system are recognised and a frugal step is added to the cyclical nature of the framework. Design freedom to match local (technical) requirements is facilitated by reducing the customer requirements, whilst still adhering to the wishes of the client.

5.1.4 Identify and analyze drivers of change

In addition to the core requirements of a system, the reason why a change at all is needed must be analysed. These so-called 'change drivers' can be considered as 'the requirement for change to occur' [91]. For a reconfigurable manufacturing system, they might be the trigger for which a reconfiguration is initiated or reconfigurability is needed at all. For a F-RMS, reasons why the system must be frugalized should be identified. Change drivers may further serve towards prioritizing and defining requirements.

Drivers of change generally fall under strategy, technology, product, or volume drivers [92] and are defined in item 5.1. Furthermore, Ploeg *et al.* [93] and Pisoni *et al.* [94] identify constraint-based and localized drivers as drivers of frugal innovation and manufacturing. Constraint-based drivers highlight the need for simplification and affordability of production and may typically lead to frugal solutions [95]. Localized drivers consist of those drivers that encourage the system to change towards its ecosystem and the local culture [94]. This allows the F-RMS to closely allign with the local market. The expansion of the identification of drivers of reconfigurability to F-RMS must therefore include these two additional drivers. The total resulting list of F-RMS change drivers and their definitions can be seen in item 5.1.

As discussed in Section 5.1.3, the change drivers are implemented in the requirements screening questionnaire to capture the perceived need for change as broadly as possible. As per the cyclic method of designing reconfigurable systems described by Andersen *et al.* [8], change drivers must be analysed and updated regularly to plan future reconfigurations. To enhance the core functionality of the production system, change drivers may also be critically analyzed according to their perceived need. In other words, the perceived need for change needs to be critically analysed to ensure the change and any costs incurred with it are necessary to make.

5.1.5 Define need for reconfigurability and frugality

Defining the need for reconfigurability and frugality requires knowledge of the current reconfigurability [96]. The current level of frugality does not have to be judged in the same way, however. The potential for frugality should instead be judged according to the current process, without necessarily determining existing frugal aspects. In a F-RMS the potential for frugality is recognized by determining specific practical improvements in reconfigurability. As such, the need for frugality and reconfigurability are defined jointly.

A method to determine the current level of reconfigurability is provided by Boldt *et al.* [97]. This assessment takes the form of an excel-based questionnaire which generates a reconfigurability score based on qualitative assessment of the reconfigurability characteristics discussed in Section 3.2. The perceived need for reconfigurability is briefly judged according to the questions:

1. Is the machine/fixture/tool expected to handle new products?
2. Is the machine/fixture/tool expected to handle significant volume changes?

Based on these questions and the resulting reconfigurability score, a discrepancy between the perceived need for reconfigurability and the current level of reconfigurability can be demonstrated. The assessment can be carried out for different production lines or sub-processes to determine the need for reconfigurability per production line and focus the design effort.

Similarly to the determination of requirements questionnaire, the overall result of the assessment is of less relevance than the detailed insights into the reconfigurability of the process it provides. Although useful as an outcome to present towards participating companies, the qualitative method used for determining the scores means that scores may vary according to the answering stakeholder. Designers/researchers are more likely to learn about the need for reconfigurability from the reflection of the scores of the different characteristics. Furthermore, the interaction with respondents is key, and observations and discussions arising when completing the questionnaire should be noted down. Aside from helping the designer/researcher understand the reasons behind the need for reconfigurability, further requirements and insights into the necessity of processes to determine frugality may also be derived. The assessment should be carried out with multiple stakeholders, either independently or in a workshop. If scores vary significantly, this may further guide the designer/researcher about the considerations that form the perceived need for reconfiguration amongst respondents.

Table 5.1: Change drivers for F-RMSs as identified in Rösiö [92], Ploeg *et al.* [93], and Pisoni *et al.* [94]

Type	Description	Example
Product-related	Variations in basic models as well as variants within the models	1. Geometry changes of certain parts 2. Dimension, shape, surface form 3. New technology solutions in the product
Volume-related	Volume fluctuations over time	-
Technology-related	Changes in production technology	1. New joining technique 2. Machine breakdowns, tool failures
Strategy-related	A new company strategy	A decision to enter a new market
Constraint-based	Inability to acquire resources for production	1. Labor shortages 2. Supply chain issues leading to part shortages 3. Financial shortages
Localized drivers	Requirements posed by the local company ecosystem	1. Cultural changes, e.g. Increasing consumer wealth 2. Infrastructure changes, e.g. electrical power connections 3. Labor Union requirements

5.1.6 Management, Planning and Clarification of Design Task

After the management, planning and clarification of design task phase of design the need for a F-RMS and the requirements of a F-RMS should be apparent. A list of requirements is created as an output, as suggested by Schleinkofer *et al.* [32] for frugal manufacturing and Andersen *et al.* [90]. The list of requirements summarize the wishes of the customer and for a basis for the basic design which is to be carried out in the next phase. Technical requirements and functionalities, separate from the customer requirements, are identified in this ensuing phase as well.

The list of requirements may be structured according to product and process dimensions and over the life cycle phase which they affect, a set up suggested in Andersen *et al.* [98]. A requirement may therefore be categorised as pertaining to a change in the product in the short term, for example. The questionnaire, AHP and reconfigurability assessment may all serve to identify requirements. The AHP furthermore provides an initial indication of the relevance of requirements to the principles of the F-RMS.

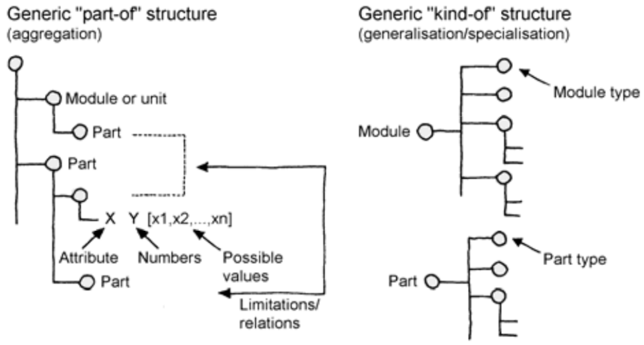
5.2 Basic Design

5.2.1 Define degree of modularity

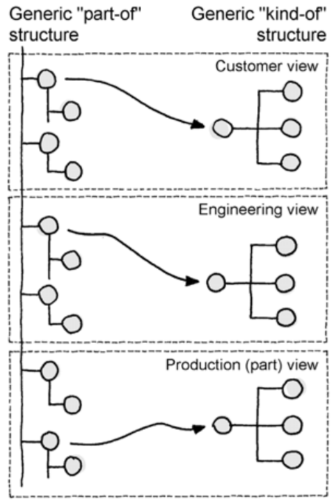
The required degree of modularity of production is a direct result of the requirements defined in the previous section as well as the production requirements of the product it produces. In particular, the variety, changability and modularity of product families determine the (reconfigurable) production capacity and functionality needed [86]. It is therefore key to determine the extent of the product variants and family to be manufactured by the F-RMS.

Beyond the definition of what products are to be produced, the question why they are being produced may also be raised to eliminate any unnecessary variants and improve the effectiveness of the manufacturing system. In line with frugal product-process co-evolution, the product functionality to customers and engineers largely determine not only their requirements and modularity, but also the requirements and modularity of their production system [9].

The product variant master (PVM) is tool that is frequently used in industry to determine the production requirements of a product family, as well as its customer requirements and functionalities [99]. In addition to providing a succinct overview of these three product aspects, it allows for a comprehensible mapping of the product variety. The product variant master's functioning can be seen in Figure 5.4. It consists of two abstraction mechanisms that are termed "part-of" and "kind-of" respectively (see Figure 5.4a. The "part-of" structure breaks down the product into the parts or modules which appear in the entire product family. For example, a bicycle may consist of two wheels, a steering wheel, a saddle, pedals, a bicycle chain and a braking system at its most basic. Characteristics and attributes of the parts can be described behind the part listing. The "kind-of" structure breaks down the parts into their possible variants. For the bicycle example, the braking system may consist of a hand brake or a brake operated by the pedals. This allows for a clear overview of the possible variety within the product family.



(a) The general principles



(b) The different views

Figure 5.4: The working of the product variant master (PVM) [99].

The PVM furthermore consists of three different views that allow the company to highlight the production requirements, customer requirements and functionality of the product (see Figure 5.4b. The "customer view" determines the product attributes that are of use to the customer (from the customers point of view). Hereby, the parts and product variety essential to the customer are visualized. The "engineering view" demonstrates the functionality of the product and shows what characteristics are essential to the products operation (i.e. the product from an engineers' point of view). The "production (part) view" describes the parts of the product and their internal structuring directly and can therefore be translated directly into the (or equates to an existing) bill of material (BoM) for production of the product. It should be noted, that whilst the production view by definition consists of physical parts, customer and engineering view characteristics may not be physical attributes (e.g. output torque, electrical compatibility).

The PVM is used to envision the modularity of the product. The production view in particular then serves as a useful guide to envision the modularity of the system. Identified product variety may lead to the implementation of a production module (see Section 5.1.4, similarly a clustering of parts to be assembled can lead to the creation of a workstation module. The engineering view may show similarity between parts in the operational functionality required for production, which can also be a driver for the creation of a manufacturing module (as suggested by Abdi & Labib [86].

The engineering and customer view furthermore serve as useful tools for increasing the frugality of the product. Summarily, the customer and engineering functions of the product should be critically evaluated and reduced to the core functionalities if possible. If production operations for specific parts are found to be complex, expensive or otherwise difficult to perform, removing the product characteristic responsible directly leads to a more frugal manufacturing system and product. The modularity and/or reconfigurability of both product and production therefore simplifies the process of isolating functionalities and removing unnecessary ones. The direct linking of the product functionalities visualized in the PVM views and their production steps furthermore directly limits the amount of production modules to only those strictly necessary to enable these characteristics.

In a brownfield product, product characteristics are often already defined. An adaptation of the product is not always possible or required, especially for manufacturing sites that manufacture products designed externally. Although still useful to reflect on how specific product characteristics may be clustered in a production module, the customer and engineering views become less important as product-process co-evolution becomes less relevant and changing product characteristics becomes unfeasible. The production view may still be relevant to determine production modularity as per the procedure outlined above and may be easily adapted from the existing product family's bill of materials if available.

5.2.2 Define system element and enablers of frugal reconfigurability

The specific system elements to be designed as or converted into a F-RMS is system dependent and can be chosen according to the identified need and requirements discussed in Section 5.1. A specific sub-system, component, workstation or the system as a whole may be appropriate for establishing a F-RMS.

The combined enablers for F-RMS described in Chapter 4 may be used to determine which aspects of production may easily be frugalized through reconfigurability. Implementation of enablers, especially those falling under the 'resource use,' 'design process' and ' system design' categories may be useful for establishing a basic design of the F-RMS. The other categories are company-level implementations that may largely result from managerial implementation or willingness rather than reconfigurable design. The general F-RMS enablers identified in Chapter 4 should be translated into specific enablers for the company.

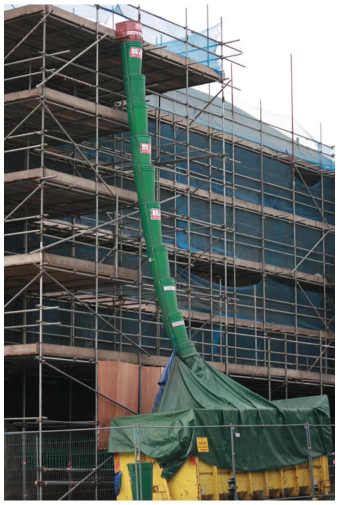
Resource use enablers consist of resource optimization and availability of resources and infrastructure. Similarly to the constraint-based change driver identified in Section 5.1.4, opportunities for resource optimization may aid in designing a system aspect to be more F-RMS. Reducing the role of an oven which uses a great deal of electricity within a drying process in the face of increasing energy prices may be considered an example of this. Similarly, the availability of resources and infrastructure may enable the frugalizing of a manufacturing system through reconfigurability. Available physical space, or the identification of potential for on-site power generation (e.g. solar panels) are examples of how availability of resources and infrastructure can be capitalized upon to make it easier to establish a F-RMS.

The design process enablers prescribe with which tools and processes it may become easier to design a F-RMS. In a brownfield project, designers should focus on existing R&D, planning, rapid prototyping, IT and long-term analysis processes and seek to find out what lessons have been learnt from these (existing, if any) processes. In a greenfield project, design enablers for different processes within the company or the product may be used to draw lessons for the new design.

System design enablers which will enable increased effectiveness of the F-RMS include integrating reliability assurance, modularity and flexible design in the system. Reliability assessment may be integrated with the use of control mechanisms and processes such as automatic error reporting. Modularity and flexible design are integrable through the use of modular and flexible machine and system parts. For example, a modular system will necessarily include modular or flexible transport between system elements that is (to some extent) adaptable to its interfaces. Examples of modular or flexible transportation systems include trolleys (agv's if automated), chute systems, or modular belt conveyor systems. Examples of these system design enablers that may be found in a brownfield project can be seen in Figure 5.5.

(a) An industrial (modular) trolley [100]

(b) A flexible roller belt [101]



(c) A simple construction chute [102]

Figure 5.5: Different types of transport system design enablers

5.2.3 Cluster operations

Clustering operations in the eventual F-RMS is done through the clustering of the operational capabilities needed for product families as suggested by Abdi & Labib [86]. Both Goyal & Jain [53] and Abdi & Labib [86] propose a grouping of products into families according to operational similarity. The implication for the manufacturing system is then that operations are clustered around these product families. In F-RMSs, operational capability is to be limited to strictly the necessary capabilities. The clustering of operational capability and product families therefore also requires a reflection on which additional operations are required for additional products to be included in a family and whether capability may instead be achieved through reconfigurability. A larger focus is therefore placed on the operations to be included themselves, rather than the product grouping.

Two different methods are used to cluster operations according to operational capability. For a brownfield project, the (frugalized) Product-Process-Resource-Skill & Variability Model (F-PPRSV) as discussed in Fidan *et al.* [11] is used. For a greenfield project, axiomatic design is suggested to couple functions to operational capability. This, in correspondence with co-evolution of the product and manufacturing process enables the clustering of the operations required to establish a basic system design [103].

The PPRSV model is a 'knowledge representation' model that demonstrates the 'dependencies between products, production processes and resources' [104]. Meixner *et al.* [104] has improved upon the product-process-resource (PPR) model by expanding it with a method of representing skills and product variability to 'enable a product and production process description.' Fidan *et al.* [11] discusses a method of frugalizing the PPRSV to create a frugal

PPRSV (F-PPRSV). This allows the F-PPRSV to capture market-specific product variants, reduce the model by eliminating unavailable materials, and decide feasibility of the resulting model [11]. The F-PPRSV's basic structure (excluding skill) can be seen in Figure 5.6. For a brownfield redesign of a manufacturing system to an F-RMS, the basic PPRS model can be created for different product variants. In case of a high amount of product variety (becoming infeasible to represent), key products/product variants that represent the breadth of operational capability can be chosen in accordance with the PVM discussed in Section 5.2.1 and discussions with company stakeholders. Operations, resources and parts to be included may be found in work instructions, bills of materials, bills of operations and company observations.

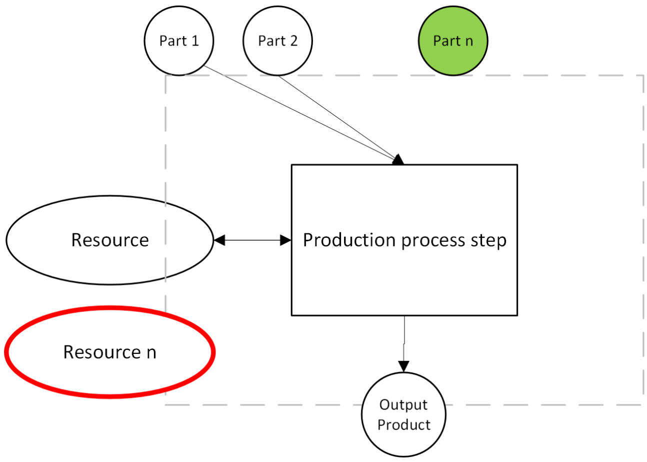


Figure 5.6: The basic structure of the F-PPRSV, with green colors and red outlines signifying product variety

To increase the usability of the model, a generalization step may be undertaken to homogenize the representation of operations, resources and parts. For example, different hand assembly steps requiring the same resources may be brought back to the single step 'hand assembly,' with all parts to be included amalgamated towards the step. Specific skills required for the operation may be modelled as a resource and used accordingly. Subsequently to the generalization the PPRS models of the different product variants may be overlaid to gain an insight into production variability. In this way, one PPRSV model is formed which demonstrates the variation from the core production process of the different product variants. Different types of variability are indicated using different types of shading. An operation, resource or part that is not homogeneous for all product variations is signified (with a green background) to indicate that flexibility or reconfigurability may be needed with this production aspect. A red outline signifies that the operation, resource or part is not found in the production of every product variation and may be a suitable candidate for removal. After truncating the model for those operations, resources and parts that are deemed unnecessary or infeasible (as proposed in Fidan *et al.* [11]), the F-PPRSV model is formed, reflecting only the core operations, resources and parts. The working of the F-PPSRV model is demonstrated in full with the case studies presented in Chapter 6.

For a greenfield project, the clustering of operations is done according to axiomatic design. Axiomatic design entails designing a product or system "in terms of relations between design objectives (i.e. Functional Requirements) and solutions (i.e. Design Parameters)" [105]. The relation between functionality and operations is therefore made causal and explicit. One functionality should therefore directly lead to only one design parameter, isolating the link between the design parameter and the functional requirement [103]. When applying product-process co-evolution, as suggested for development of frugal manufacturing by Belkadi *et al.* [9], the functional requirements of the product should be isolated to the production design parameters. This is enhanced by both modularity of product and process as discussed in Section 5.2.1.

The operations to be carried out to manufacture the product are thus directly linked to the product functions. Similarly to the F-PPRSV, the operational variety between product varieties can therefore be limited. A product function may only be added when operational capability is deemed necessary to add or vice-versa. The clustering of operations occurs according to the build-up of the product, where the (modular) production operations are structured according to the required sequence of operations for the product. Co-evolution however also entails the design of the product according to what is logical for production operation and the product design may be altered accordingly. If the final step of a product requires a resource that has thus far only been used at the beginning of a production line, a frugal clustering of operations is only ensured by redesigning the product to either:

- Allow reuse of the resource in the beginning of the product. Therefore, the build up of the product would have to be changed to allow the operation requiring the resource to be carried out in the beginning.
- Remove the product functionality that requires the resource use.

Clustering of operations is therefore enabled by axiomatic co-evolution of product and process to make as effective a use of resources as possible. Reconfigurability of resources may enlarge the operational capability of the process.

5.2.4 Decide how to realize frugality through reconfigurability

Deciding how to realize frugality through reconfigurability is case-specific and will depend on the opportunities available in both process and product of its application [8]. Nevertheless, a few general classes and tools can be made which provide handholds for realizing frugality through reconfigurability.

Identification of the areas to be reconfigured can occur through the F-PPRSV model described above. For product variants, clusters of operations which have a large degree of variability in the resources needed for production may be suitable candidates for realizing reconfigurability. Resources which are needed for every product or product variant but have some variability are especially suitable for frugalization through reconfigurability. For example, tooling duplicity can be avoided by using one reconfigurable (machine) tool for different variants when different sizes of one tool are needed for different variants. Furthermore, frugality can be established by removing the resources (and associated functionalities) which are not needed for the core product, or not needed for every product variant. Long-term reconfigurability may then aid towards keeping the option of integration of these resources open may their functionality become needed in the future. Both types of resource variability may therefore aid designers in establishing where to realize frugality and provide first guidance as to why the reconfigurability is needed to establish frugality.

Methods to carry out (frugal) reconfigurability will generally fall under the characteristics described in Chapter 4. For the general reconfigurability characteristics, these methods will be in line with the identification of reconfigurability from Boldt *et al.* [97] described in Section 5.1.5. Methods that do not fall under the core characteristics but may enable production changing in any case are described by the changeability classes of ElMaraghy & Wiendahl [106] and flexibility dimensions and attributes by Terkaj *et al.* [107]. ElMaraghy & Wiendahl [106] describes five classes of changeability:

- Changeover ability
- Flexibility
- Reconfigurability
- Transformability
- Agility

Here, reconfigurability is mentioned specifically as one of the changeability classes. The other four classes may facilitate reconfigurability or exist alongside a reconfigurable change within a system. All classes are different forms of changeable manufacturing systems but differ in the method in which this may be achieved. All may therefore be useful for establishing frugality. However, reconfigurability in general has been found to match particularly well to frugality due to it's conceptual simplicity and affordability in Chapter 3. The suitable class of changeability may be matched to the needed level of variability and frugality to determine the suitable *level* of reconfigurability (or changeability).

Similarly, Terkaj *et al.* [107] describes a set of flexibility dimensions and attributes that may also be useful for establishing reconfigurability. Dimensions are used to describe in what ways flexibility is needed. Attributes are then used to define the flexibility that is needed within these dimensions. The dimensions and attributes of flexibility as defined in the ontology of Terkaj *et al.* [107] are given in Table 5.2.

The flexibility dimensions and attributes are also useful in regards to reconfigurability for frugality. Defining the core range, resolution, mobility and uniformity give structure to defining the needed dimensions. Especially the functionality dimension is of key use towards establishing frugality, where functionalities may be reduced as much as possible to establish frugality. A F-RMS design must therefore define how it will improve the identified dimension for every attribute of the operation (cluster) to be improved.

After the (sub) system to be analyzed is chosen and possible methods of reconfiguration or changeability are explored a structured method for concept generation is needed to establish how reconfigurability is to be implemented. The modular functional deployment (MFD) method as created by Ericsson & Erixon [108] is extremely suitable for this purpose as it provides a structured method of translating customer requirements to module concepts. Modular function deployment is an iterative process consisting of five steps:

1. Defining customer requirements
2. Selecting technical solutions.
3. Generating concepts.
4. Evaluating concepts.
5. Improving each module.

Table 5.2: Flexibility dimensions and attributes as defined by Terkaj *et al.* [107]

Dimension	Definition	Attribute	Definition
Capacity	The system can execute the same operations at a different scale	Range	Expresses the extension of the differences among the various ways of behaving of the system under a given dimension
Functionality	The system can execute different operations (different features, different level of precision, etc.)	Resolution	Expresses how close the alternatives within the range of a given dimension are.
Process	The system can obtain the same result in different ways	Mobility	Expresses the ease with which it is possible to modify the behavior under a given dimension.
Production Planning	The system can change the order of execution or the resource assignment to obtain the same result	Uniformity	Expresses how the performance of the system varies while moving within the range.

Of these five steps, the first three are useful for defining how frugal reconfigurability is to be realized. The 'evaluation concepts' and 'improving each module' steps will be described in the upcoming sections. Adaptation of the method is required to adapt the product design-based method to a production system design method [109] and is suggested by Brunoe *et al.* [110] and Kjeldgaard *et al.* [111]. Further adaptation is required to improve the applicability to F-RMSs. A further adaptation is necessary for distinguishing brownfield and greenfield projects, where brownfield projects only require a focus on steps 3-5 as functions and technical solutions are largely defined [111].

The first step of MFD: 'defining customer requirements' is closely linked with the activities carried out in Section 5.1.3. Customer requirements defined in this step are linked to product features through the 'quality function deployment' (QFD) matrix. Here the customer requirements are displayed on one axis of the matrix, product properties are displayed on the other and related for the purpose of analysis through numbers in the matrix. Product properties clarify customer requirements and should be 'measurable, controllable and solution-free statements' [112]. The product properties provide measurable target values for engineers to reach in design. An example of how this is done for a car door is shown in Figure 5.7.

For the purposes of MFD, the first product property will always be modularity to 'establish the right "mindset" of project team members' [108]. Customer requirements should furthermore be ranked according to importance to clarify which customer requirements must be prioritized. Specific properties will vary when applying the QFD to production systems rather than products. The process step itself remains largely applicable, however.

For a F-RMS the QFD is an opportunity to critically analyze the effects of customer requirements on manufacturing system properties. As outlined in Section 5.1.3, customer requirements should be revisited and reduced as much as possible. When ranking the importance of customer requirements in the QFD, customer requirements which are ranked with low importance are 'easy' candidates for removal. Furthermore, the QFD provides important insights

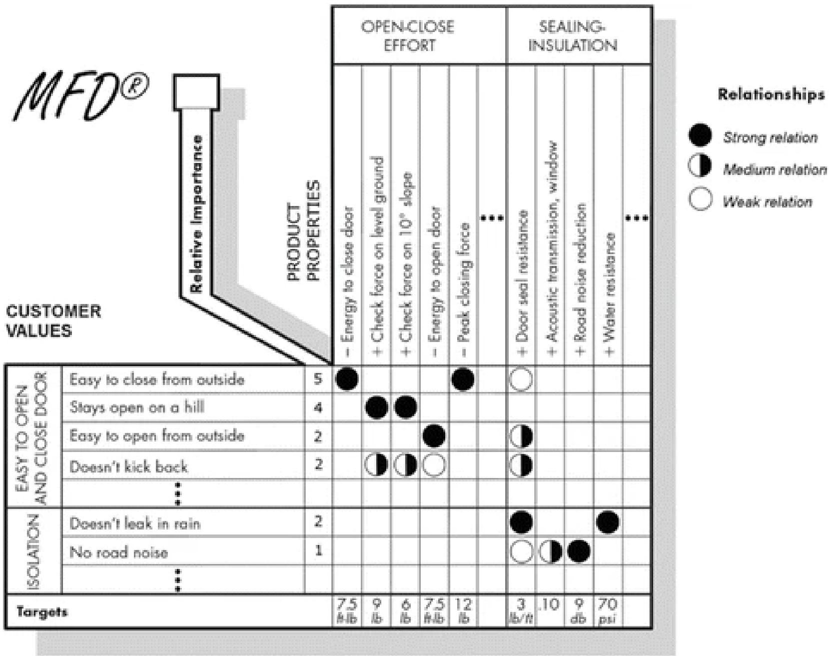


Figure 5.7: An example of the QFD matrix from Börjesson [112].

into the relations between customer requirements and system properties. Customer requirements which are only weakly related to properties or only linked to one system property may also not be considered core requirements. If a property is only linked to one customer requirement, it should be evaluated whether that system property (and its associated customer requirement) is necessary.

The second step of the modular function deployment involves converting the functions of the product to corresponding technical solutions. Functional requirements, which for F-RMSs should have been reduced to the core functionality, may be further subdivided into sub functions. Consecutively, each sub function can then be linked to a technical solution following the principles of axiomatic design as discussed in the previous section. If multiple technical solutions for a function are defined, the simplest or most affordable option should be chosen to enhance frugality. Functions and technical solutions are displayed in a functions-and-means tree that displays the relation between the different functions and sub-functions. Technical solutions may be identified in cooperation with product and production experts and are entirely case-specific. For brownfield projects, technical solutions as currently implemented are identified and their functionality isolated through reverse engineering. These technical solutions may then be reconfigured into modules in the ensuing steps.

The third step of the MFD is generating concepts. This is done according to another matrix: the module indication matrix. Here, the technical solutions identified in the previous step for greenfield projects are linked to module drivers. These module drivers are designed to be generally applicable and determine which technical solutions are suitable for conversion or grouping into modules. *Module* drivers are different from the *change* drivers identified in Section 5.1.4 as they concern the formation of modules and not the instigators of change in the process. The original module drivers of the MFD for modular products defined by

Ericsson & Erixon [108] are adapted by Brunoe *et al.* [110] and [111] towards applicability for (reconfigurable) manufacturing systems. The module drivers by Brunoe *et al.* [110] are suggested for implementation as it is more concise, improving the ease of use in practice. The module drivers to be related to the technical solutions are shown in Figure 5.8.

Driver	**Description**
Localization of Changes [3,10]	*Modules for limiting propagation of change throughout a system's lifetime*
Module Carryover [10-12]	Equipment unlikely to change over coming generations of the system
Planned System Changes [10, 12]	Equipment with planned design changes
Technology Evolution [10-12]	Equipment using underlying technology either new or likely to change
Regulation & Standards [11]	Equipment subject to certain external regulations and standards, which might incur changes
Managing Variety	*Modules for managing and creating necessary variants of manufacturing systems*
Common Unit [3,11,12,16]	Equipment common to a manufacturing segment
Different Specification [3,10,12]	Equipment creating variety in a manufacturing segment
Changeability [11]	Equipment with similar type and range of changeability
System Development [10]	*Modules implementing functions and interfaces*
Function Sharing [3,10]	Equipment sharing subfunctions
Geometric Integration & Precision [3,10]	Equipment with requirements for physical alignment in relation to each other
Portability of Interfaces [3,10]	Equipment relying on interactions and interfaces with similar portability
In use	*Modules related to how a system is handled when it's in use*
Service & Maintenance [10-12]	Equipment with similar service and maintenance intervals and/or tasks
Recycling [10-12]	Equipment handled similarly during end-of-life
Customer Requirements [11]	Equipment creating variations in system configuration/performance but not forming new variants
Upgrade [12]	Equipment replaceable by end-user for changed functionality or features
Process and/or Organization [3,12]	Equipment implementing processes always carried out in sequence
Procurement [3,10,12]	*Modules easing production and procurement of manufacturing equipment*
Vendor Capabilities [3,10,12]	Equipment sourceable from individual suppliers/vendors
Separate Testing [10-12]	Equipment requiring specific types of tests or separate tests

Figure 5.8: The module drivers for reconfigurable manufacturing systems identified by Brunoe *et al.* [110].

The module indication matrix again relates its two dimensions (technical solutions and module drivers) through a scoring system. Each technical solution is assessed per module driver according to a score of:

- 1, weak module driver.
- 3, medium module driver
- 9, strong module driver

Technical solutions which are suitable for modularization are then identified according to which technical solutions have a high module driver score attached to it. Technical solutions which have a similar pattern of module drivers may also be suitable candidates for grouping into a single module. To ensure frugality, modularity should be maximized and each individual module kept as simple as possible. Therefore, the number of technical solutions grouped into a single module should be limited [35]. An alternative option to improve the simplicity of modules is to place a focus on the module drivers of the 'managing variety' category. Modules should be standardized as much as possible to improve their integrability and simplicity, a common unit should therefore be encouraged, and different specifications and changeability (within the module) limited as much as possible [109]. In resource-constrained settings, recycling and upgrading of modules may be additional module drivers to place special focus on.

5.2.5 Identify and define interface of modules

The first three steps of the MFD provide a list of possible modules which in conjunction with the F-PPRSV provide a conceptual first look at the basic design to be made. Integration of these modules is required to arrive at the final basic system design. This can be carried out with the fourth step of the MFD method, evaluating modules.

To arrive at a final overall design, the modules identified in the previous section must be assembled together to form an overall system. The interfaces of these modules ultimately determine where they can be placed relative to each other. This is especially true in a manufacturing system, where processes will often require a fixed assembly sequence and transfer of the product between modules. The interfaces between modules can be clarified with the interface matrix. This is a matrix which has all identified modules listed on each dimension of the matrix. Interfacing modules are then indicated in the matrix with an abbreviation for the type of interface (e.g. E for electric, G for geometry). An example of an interfacing matrix can be seen in Figure 5.9. No further steps are necessary to ensure frugality when determining the interfacing of modules. If module resources are not found to be available, or interfacing of assembly steps not found to be possible with the defined modules, new modules should be defined.

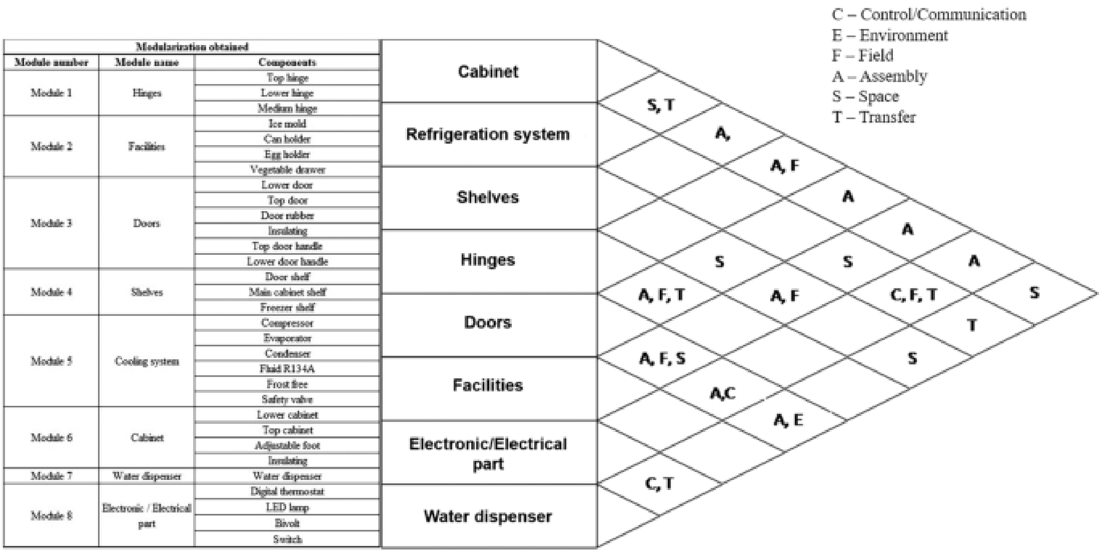


Figure 5.9: An example interfacing matrix for the home appliance industry [113].

After the interfacing matrix is completed modules which are found to interface must be assembled together. In product design, common module designs include the 'hamburger' and 'base unit' assemblies, where modules are stacked consecutively, or attached to a base unit, respectively [108]. For products For manufacturing systems, these interfaces may logically follow the procedure of operations necessary for production. A 'hamburger' assembly will resemble a production line whereas a 'base unit' assembly will consist of a workstation with necessary resources grouped around.

5.2.6 Determine assembly method and automation

This step is case-specific and not generally applicable towards the design of F-RMSs. The basic system design that has been created in the previous steps must be assembled and automated according to the existing best practices of the company, industry and culture. If automation is a customer requirement, a focus must logically be placed on a high level of automation within the F-RMS.

5.2.7 Feasibility study/simulation/evaluation of the preliminary design

The final basic design must be evaluated after completion according to the requirements and criteria defined in the previous steps. This is concurrently integrated in the MFD method and important for determining the frugality of the basic design. Adherence to both the criteria for F-RMS and customer requirements is necessary and improvements should be made to optimize the final design. The design therefore becomes a cyclic method where after each design lessons should be drawn, functionalities and features critically evaluated and modules improved.

The AHP method using the criteria from Chapter 4 defined in Figure 5.2 may be used to evaluate the design. The AHP method results in the weight vector $\vec{w}$, and each criteria (at each level) is therefore given an importance weight. The importance of the F-RMS for the specific company is therefore taken into account. If possible, the (quantitative and qualitative) procedures for determining adherence to the criteria described in Chapter 4 should be followed. However, it is often infeasible to determine the exact value of costs or the entire operational capability. The exact calculation of these criteria should therefore be implemented in the advanced design stage, whereas the strategic basic design may be concluded with an estimation of how the concept designs will perform per criteria.

When evaluation of numeric criteria is not feasible or difficult for all basic design concepts, the performance of criteria may be estimated. This is done according to the procedure described in Napoleone *et al.* [114]. The criteria and weights from the AHP are collected in a Pugh matrix and compared to the basic design concepts. The estimation of the basic design concept's effect on the criteria is reduced to a positive (+1), neutral (0), or negative (-1) score. Due to the different levels of the hierarchy, the criteria are judged to a significant degree of detail, and the concept can be evaluated at a strategic level.

All concepts should adhere to the requirements determined in Section 5.1.3. The importance of requirements is ranked in the first step of the MFD. According to this ranking, unneccesary requirements are removed in accordance with reducing the design to its core functionality. To evaluate whether all requirements have indeed been adressed, the enablers and technical solutions that contribute towards achieving requirements should be listed per requirement. The functionalities determined in Section 5.2.3 with the F-PPRSV and axiomatic design can be used to link the technical solutions and enablers to the requirements. With this re-linking of technical solutions and functionality, the total adherence to requirements can be linked in a similar manner to the linking of enablers and (reconfiguration effort) criteria in Napoleone *et al.* [5]. If it is found that a requirement is insufficiently addressed, either the requirement should be re-evaluated or a redesign should occur to better address the requirement. Hereby, the highest ranked requirements should still be prioritized when adding modules or reconfiguring the layout. The cyclic nature of the design process is thus directly achieved, with requirements forming the basis of re-evaluating the concepts. To emphasize frugality, designers should limit adding modules and evaluate the requirements of the redesign to remove unneccessary features every cycle.

5.3 Framework for Establishing F-RMSs

The general design framework for RMSs as synthesized by Andersen *et al.* [8] has been adapted towards use for F-RMSs. Not all activities described by Andersen *et al.* [8] were deemed equally relevant for the design of F-RMSs. Similarly, the adaptation of the framework was aimed towards the first three phases of the original framework: Management and planning, clarification of design task and basic design. The advanced design and implementation phases of the framework will not vary significantly between RMS and F-RMS design. Adapting management and planning and clarification of design task are especially important towards frugalizing the framework due to the increased importance frugal innovation places on adhering to customer requirements [35]. Basic system design is where overall frugal changes will have the most effect and is therefore also discussed. Resource-constraints and the definition of core functionality can also be analysed and decided in this phase. Detailed (advanced design) and implementation steps build on these phases and will therefore detail the F-RMS design without much potential for frugalizing it further.

For those activities that were found to be important towards the design of F-RMSs specific tools and methods were suggested that aid the design towards F-RMSs. These tools help designers collect customer priorities and requirements, analyze existing systems and create a basic design. An overview of these activities, and the functioning of the framework can be seen in Figure 5.10.

In the framework, the management and planning and clarification of design task phases are combined into the clarification of customer requirements phase. This phase has three activities: establishing priorities for design, definition and analysis of requirements for F-RMS, and defining existing reconfigurability. In the establishing priorities for design activity, the decision to design a F-RMS is made according to what targets the customer prioritizes for the new design. This is done with the AHP method which allows for a clarification of the priorities for both the customer and designer. The definition and analysis of requirements for F-RMS activity allows the designer to collect customer requirements to which design must adhere. A questionnaire is adapted for this from Andersen *et al.* [90] which captures both frugal and reconfigurable customer requirements according to a set of F-RMS change drivers. Finally, the current level of reconfigurability is analyzed for brownfield projects according to the existing assessment by Boldt *et al.* [97]. The existing reconfigurability may serve as a tool for designers to build upon to create frugality.

The basic design phase has the same scope as the framework developed by Andersen *et al.* [8]. Four activities are consolidated from the seven proposed by Andersen *et al.* [8]: Analysing technical F-RMS requirements, determining required functionality, generating frugal concepts, and evaluating system design. During the analysing technical F-RMS requirements activitity, product requirements on the process are analysed according to the Product Variant Master (PVM). Accordingly, the suitable degree of production modularity can be found to correspond to the product modularity. F-RMS enablers already found in the production system are also identified in this phase as technical features which can be used to make the design of F-RMSs easier. Determining the required functionality is a key activity that establishes the required operations and resources for production. The frugal product process resource skill variability model (F-PPRSV) is used for brownfield projects and axiomatic product-process co-evolution for greenfield projects to analyze the required functionalities. The functionalities determined in this step can then be used as input towards the generating frugal concepts phase, where the modular function deployment (MFD) method is used to develop system

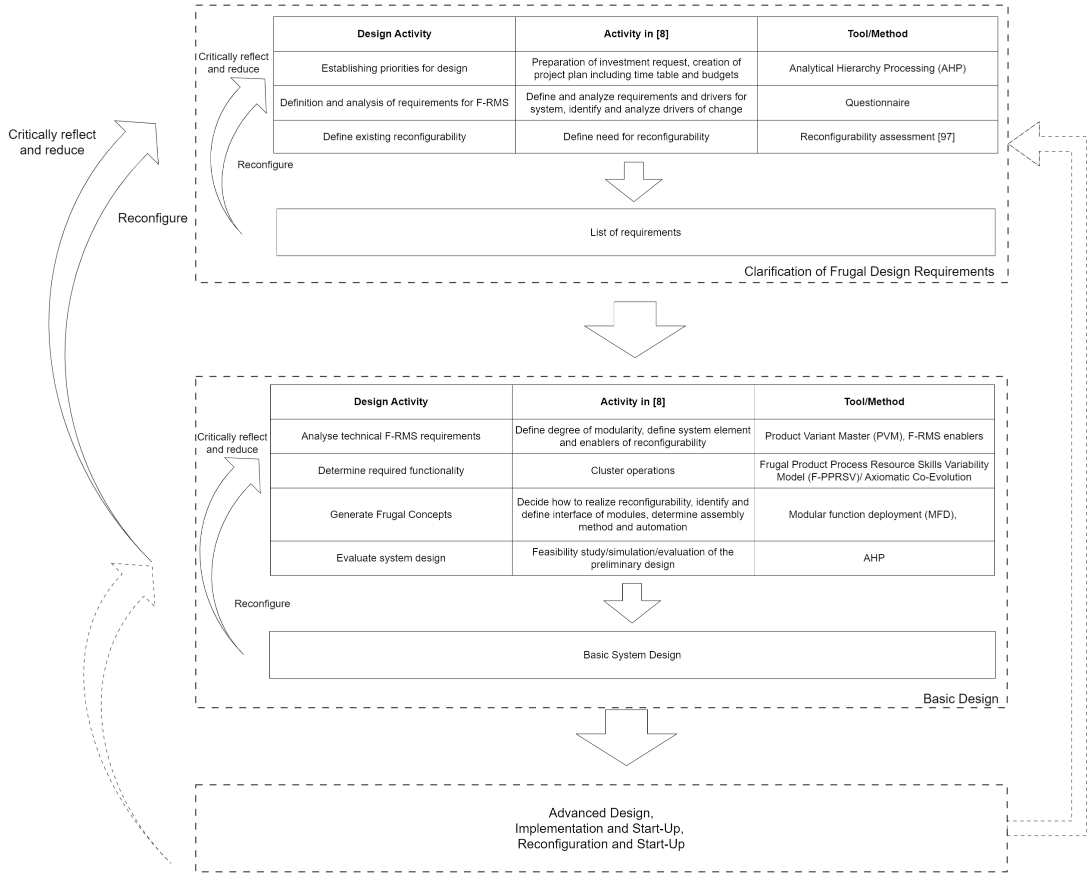


Figure 5.10: The consolidated design framework for F-RMSs

modules and integrate them. The basic design is then evaluated according to the AHP developed in the clarification of customer requirements phase.

A key addition of the F-RMS framework with regard to the RMS framework is the critical reflection and reduction of requirements, functionalities and properties at every step of design. Cyclic design is provided for in the original framework, with reconfigurability also easing adaptations of design towards new requirements and improvements. Frugal reconfigurability however also involves reflecting on improvements to reduce additional requirements and functionalities as much as possible. This is done within every activity and between phases to increase adherence to the F-RMS criteria within every aspect of design.

All activities of the F-RMS can be carried out within Microsoft excel digitally or with a paper-based method in a semi-structured interview style. No formal training, non-standard software, hardware or advanced modelling knowledge is required to carry out the framework. The F-RMS framework is therefore frugal in itself and suitable in a wide range of settings. Collecting customer requirements frugally is a key focus of research for frugal product innovation [39]. The semi-structured interview approach allows the designer to informally talk to stakeholders while guiding conversation with the developed screening tools and assessments, collecting requirements effectively and frugally. The basic design steps are also visually effective or matrix-based. Due to the absence of formal modelling with scenarios and outcome management, the simplicity of carrying out basic design steps is greatly enhanced and therefore frugalized. The usability of the framework is therefore simple, adhering to criteria three of F-RMSs defined in Chapter 4.

6 Case Studies

Case studies are carried out to validate the applicability of the framework and demonstrate the relevance of frugal reconfigurable manufacturing systems (F-RMSs) in general. The framework as described in the previous chapter is used to define a basic design of a F-RMS at the manufacturing sites studied. Multiple case studies are carried out to highlight the functioning of the F-RMS in different contexts and industries. This is done according to the research question:

How can the application of the designed framework to a relevant industrial sector validate its functioning and highlight the relevance of frugal, reconfigurable manufacturing systems?

Three case studies have been carried out at different manufacturing companies. This chapter will discuss the application of the framework and highlight the results obtained from each case study. Each case study will be highlighted separately, with a discussion of general lessons learnt included at the end.

6.1 Case Study 1

The first case study involves an electronics assembly company in the Netherlands. The company is characterized by a large variety of different products and assembles electronics for a wide range of clients. Processes consist of a machine-based PCB production step (including automatic optical inspection and soldering of smd components), hand assembly of the PCB to a composite end-product, hand soldering of larger electrical components and testing of the electronics. As the company does not design its own products, product-process co-evolution is not possible and the products to be produced are considered fixed.

The company faces a shift in production towards increasing product variability as a client with traditionally high product volume demand decreases its demand. It therefore wants to redesign its assembly floor, which is characterized by a legacy structure. A map of the current assembly floor can be seen in Figure 6.1. The assembly floor consists of a large number of workstations (desks) with specific tools and machines needed for production placed on these desks. Two examples of these workstations can be seen in Figure 6.2. Testing machines for example, are mostly placed on workstations facing the wall, with some scattered across the floor. Workstations are placed on the floor according to production lines needed in the past and products need to be moved towards specific machines which are located randomly across the floor. Products and parts are moved around on carts, which are placed in the walkways between the desks when being used at a workstation.

The company seeks to gather ideas to carry out the redesign of the assembly floor, and does not have explicit ideas about what it would like to see improved. The focus of the first case study is therefore placed on phase one of the framework: clarification of frugal design

Figure 6.1: A map of the assembly floor as it currently operates

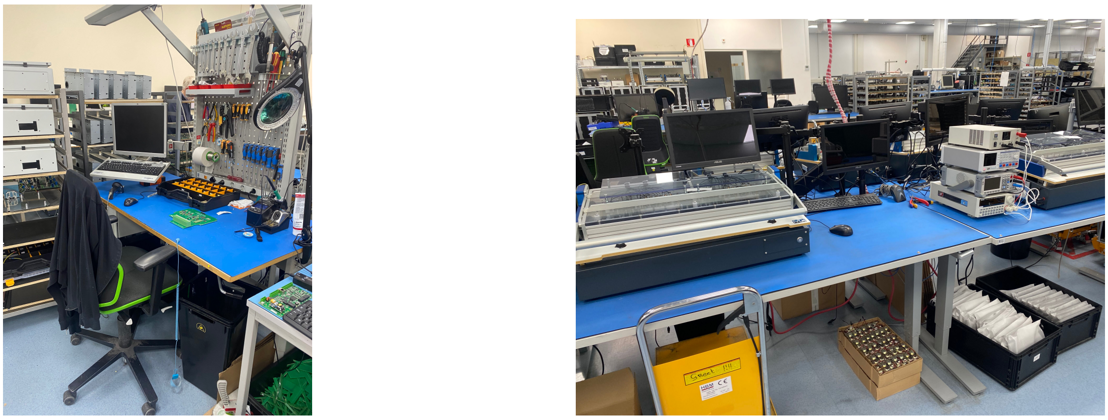
requirements. As such, not all activities described in Chapter 5 are carried out. Instead, the activities of the first phase were carried out with extra detail to draw lessons and improve the framework. The case study was carried out through a week-long in house presence of the researcher. Semi-structured interviews were carried out with the company director, floor managers, innovation managers, work planners, testing managers and account managers to capture as many different perspectives as possible.

6.1.1 Clarification of Frugal Design Requirements

All three activities were carried out for the clarification of the frugal design requirements phase. As existing figures will be reused, the case study is a brownfield case and reconfigurability screening was a logical choice to enable the reuse of existing fixtures.

The AHP was carried out separately with both the company director and a floor supervisor. This enabled the capturing of two different perspectives (a 'top-down' and 'bottom-up' perspective) on what priorities the redesign of the assembly must face. The results can be seen in Table 6.1

As additional KPI on which to judge design, the floor manager and company director both indicated that they were seeking improved efficiency. The floor manager called this 'flow' whilst the company director used the term 'efficiency.' The sub-categories defined for this user-defined KPI were 'availability,' 'quality,' and 'speed.' Here, availability was defined as the availability of production capacity, and quality and speed are self-explanatory. Notably, the company director and floor manager differed in many of their priorities. Planning for the short term, for example, was found to be most important by the company director whilst



(a) A workstation with tools

(b) A workstation with a testing machine

Figure 6.2: Two different workstations at company 1

Table 6.1: AHP results for case study 1

Level	Category	Floor Manager	Company Director	Average
Level 2	Short Term	0.24	**0.77**	**0.50**
	Medium Term	0.24	0.12	0.18
	Long Term	**0.53**	0.12	0.32
Level 3	Cost	0.06	0.14	0.10
	Functionality	0.18	**0.57**	**0.37**
	Usability	0.22	0.10	0.16
	Flow/Efficiency	**0.54**	0.19	**0.37**
Level 4	Operational Capability	0.10	**0.83**	0.47
	Reconfiguration Effort	**0.90**	0.17	**0.53**
	Operational Complexity	**0.83**	0.10	0.47
	System Reliability	0.17	**0.90**	**0.53**
	Availability	-	**0.51**	**0.51**
	Quality	-	0.05	0.05
	Speed	-	0.21	0.21

planning for the long term was found to be most important by the floor manager. Nevertheless, the higher importance given to the short term improvements by the company director ensures that planning for the short term was deemed most important. A F-RMS is justified by the relatively high priority given to the establishment of core functionality. However, cost and usability were given significantly lower priorities. Establishing frugality must therefore be focused on providing the correct functionality. Overall, sub-criteria were seen as equally important due to the differing opinions of the respondents. This means all aspects of the criteria must be addressed equally. For the level 4 sub-prioritization of efficiency, the system availability was considered especially important to be addressed with the F-RMS.

Furthermore, the reconfigurability score assessment was carried out. The overall reconfigurability score per manufacturing process/line and the overall score per characteristic can be seen in Figure 6.3.

The overall reconfigurability score shown in Figure 6.3b shows that the company already has

Name	Expected need for reconfigurability:	Reconfig. score	Discrepancy
Floor manager 1	100%	70%	-30%
Floor manager 2	100%	69%	-31%
Soldering Machine Manager	50%	63%	13%
Testers	50%	35%	-15%

(a) The reconfigurability score per manufacturing process/line

Characteristic	Char. %	Average score	Summary	
Modularity	71%	2.8		
Integrability	69%	2.754716981		
Diagnosability	48%	1.916666667	Reconfigurability	56%
Convertibility	43%	1.71875		
Scalability	54%	2.166666667		
Customisation	50%	2		

(b) The score per reconfigurability characteristic

Figure 6.3: The output of the reconfigurability assessment for company 1

a significant degree of reconfigurability integrated into its processes. Modularity especially is present to a large extent. This can be explained by the presence of many easily mobile plug and play machines and tools such as hand solders that only require electricity and are not too heavy to be carried. Diagnosability and convertibility are ranked lower, machines and tools cannot easily be converted into different functionalities. Testing machines for example can only be used for one specific product. Diagnosability is difficult to perform due to the largely manual assembly process. As visible in the breakdown of reconfigurability scores in Figure 6.3a, the largest discrepancies between the expected need for reconfigurability and current reconfigurability occur in the assembly floor. This supports the company desire to reconfigure the assembly floor and a redesign of the floor towards an F-RMS. The design effort is therefore henceforth solely focused on the (hand) assembly floor sub-system of company one's production.

The reconfigurability characteristics outcome for only the assembly floor are presented in Figure 6.4. A significantly overall level of reconfigurability can be seen across characteristics.

Assembly floor

Characteristic	Char. percentage	Average score
Modularity	73%	2.93
Integrability	79%	3.15
Diagnosability	79%	3.17
Convertibility	38%	1.50
Scalability	75%	3.00
Customisation	75%	3.00

Figure 6.4: The reconfigurability characteristics score for the assembly floor process.

Only the convertibility is significantly lower than the other characteristics. This is due to the specific functionality of many tools and machines which whilst being easily integrable to the workstations and largely modular can only perform one functionality. As larger machines and tool racks are currently placed or attached to immobile workstations, the workstations themselves are also limited in their convertibility. A workstation with a cutting machine, for example, would be illogical to use for packing the product as only a limited number of cutting machines are present on the floor. Design efforts must therefore focus on improving workstation convertibility as well.

The requirements questionnaire was completed with the company innovation manager, who had a good overall knowledge of company processes and objectives. The overall output categorized in terms of short-term, medium-term and long-term requirements is shown in Figure 6.5. Requirements for the medium-term, indicating frugal capacity changeability, were

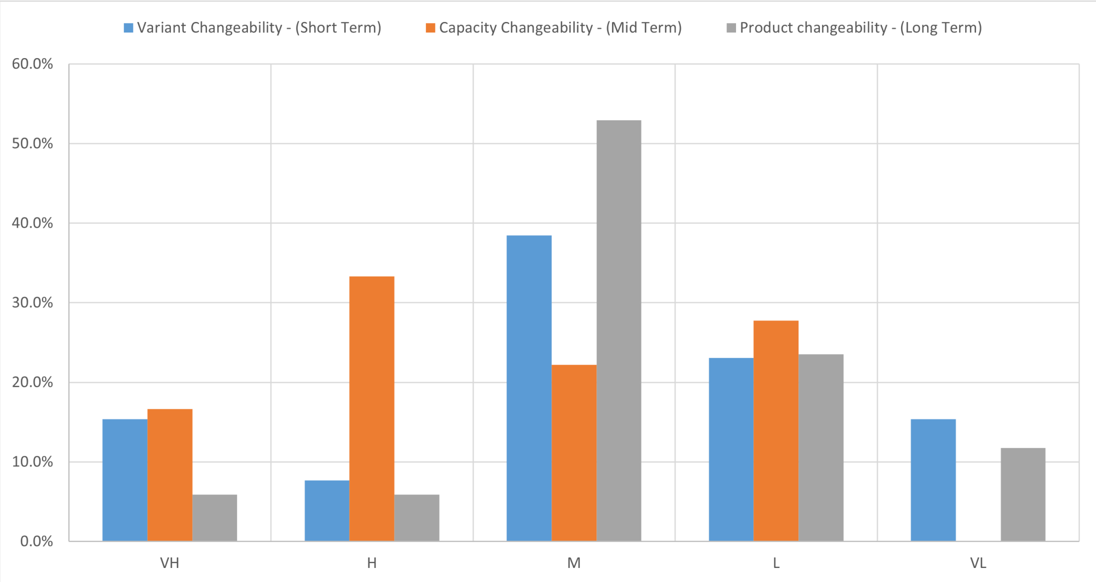


Figure 6.5: The short-term, medium-term and long term requirements screening output identified by the requirements screening questionnaire.

found to have the most 'high' to 'very high' answers. This indicates that there are many company requirements aimed at capacity changeability, which is logical due to the demand variability experienced by the company. However, the company indicated that the mid-term was not a priority in the AHP in Table 6.1. This indicates that whilst strategic and day-to-day operations are felt most urgently as problems on an abstract level, capacity change requirements may contribute towards improving operations over both these time periods. Most requirements are therefore still designated as 'mid-term,' as arising from the semi-structured interview accompanying the questionnaire. They are however expected to contribute towards improvements in the short and long term as well.

A different view for requirements analysis is looking at the answers according to product, production, technology, and environment related requirements. Figure 6.6 demonstrates the output of the questionnaire according to this view. It can be seen that a larger share of production and technology requirements are considered relevant for the company than for product and environment requirements. This reflects upon the little influence the company has on changing the products and the focus of the company on producing solely electronics. Product size variability is therefore not relevant and the company is firmly rooted in the sector, facing challenges related to its environment (e.g. inventory and supply chain management) through established procedures. The redesign of the production floor towards a F-RMS must therefore focus on these factors.

Through the semi-structured interview, further insights were gained into the specific requirements to be focused on. This resulted in the list of requirements that can be seen in Table 6.2. They are broadly characterized into requirements for the products to be produced and production itself. As products were largely assumed as unchangeable, the majority of requirements were focused on production.

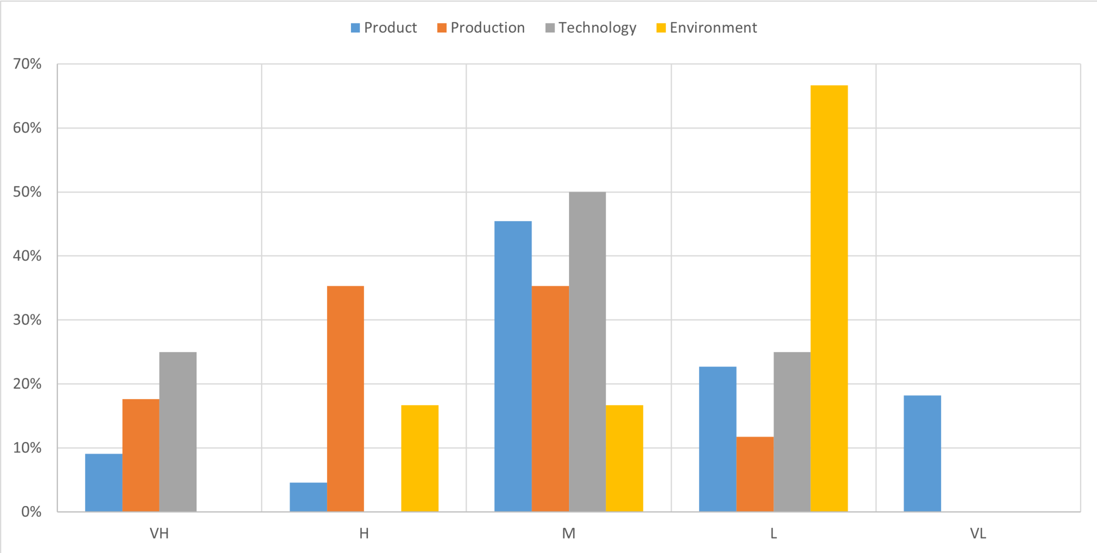


Figure 6.6: The results of the requirement screening questionnaire according to requirement category

Short term requirements focus on the need to maintain production with high product variability as it currently is. As efficiency was identified as a KPI by the company directly, efficiency increases were also a requirement for redesign. Most requirements are based on the mid-term process improvements. These are mostly focused on improving the reconfigurability of machines and workplaces. On the product side requirements are mainly geared towards improving knowledge concerning parts. In the long term, it is recommended to standardize parts and increase the reconfigurability of machines and tools themselves. The requirements thus fit well into the design of an F-RMS with a focus on simplifying and cleaning up the system through reconfigurability.

6.1.2 Basic Design

A basic design was carried out for the assembly floor as a whole. As the focus of case study 1 was on collecting and analysing requirements, formal concept generation according to the modular function deployment (MFD) was not carried out. A focus was placed on establishing technical requirements and analysing the process to reconfigure the system using existing fixtures and improvements of these. This resulted in a basic design translated directly from the list of requirements presented in Table 6.2.

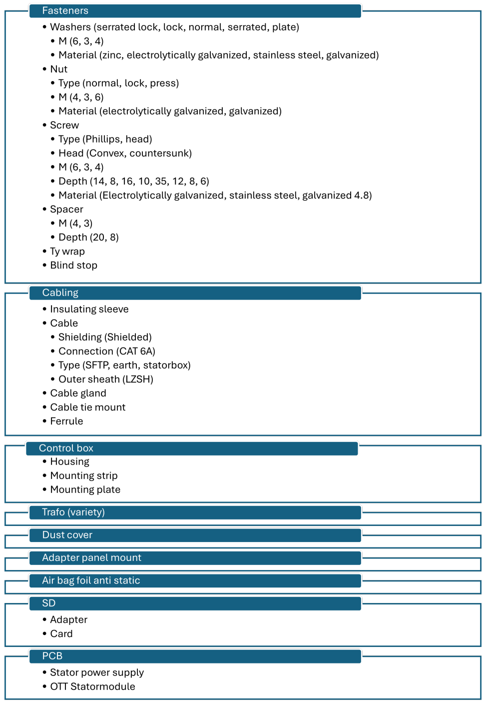
The product variant master (PVM) described in Section 5.2.1 is applied towards company 1. The company produces about 3500 different types of products, with about 10 on average being produced on the production floor concurrently. The company therefore produces many different products with almost 25000 unique parts. It is thus not feasible for the PVM to be carried out in full. The kind-of structure was left out due to the limited (to none) variety per product. Furthermore, as existing products were used, only a production view of the PVM was carried out. Customer and engineering product characteristics are largely defined and not subject to change making these views obsolete. Instead, three example products that

Table 6.2: The list of requirements for company 1

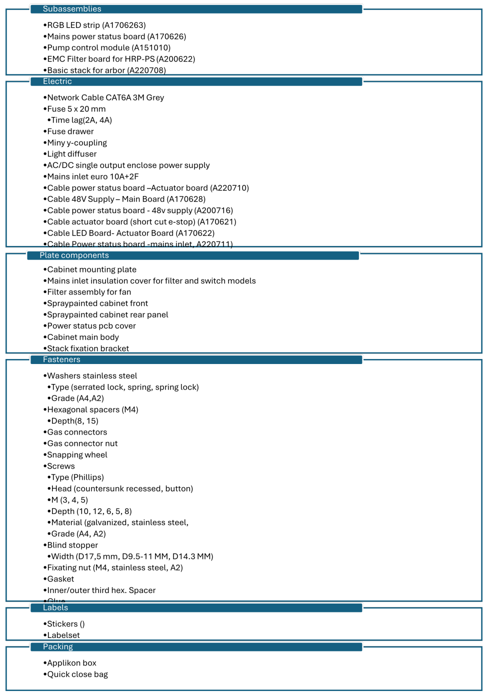
	Product	Process
Short Term	• Maintain high product variation	• Enable efficiency increase
Medium Term	• Clarify part functionality • Faster switching between products • Deal with delivery reliability	• Machine Mobility • Increased scalability (increase available space) • Increased adaptability of workstations • Increased modularity of workstations • Increased adaptability of employees
Long Term	• Deal with growing complexity	• Increased integrability of tools and machines

demonstrated the range of production possibilities of the company were chosen in cooperation with floor managers and work planners. The PVM for these three products can be seen in Figure 6.7. The first product was chosen as it includes two varieties and is otherwise a good example product that is produced primarily on the assembly floor. It is a control box for a sensor to be used on container boats and consists of printed circuit board (PCB) that is assembled by hand into the control box along with other larger electrical components. The second product was chosen as it is one of the most complex assembly projects that is done by the company and therefore demonstrates all production capabilities. The third product was chosen due to its simplicity yet ability to demonstrate all machine capabilities used in the company (e.g. machine soldering, surface mounted device (SMD) placing and inspection).

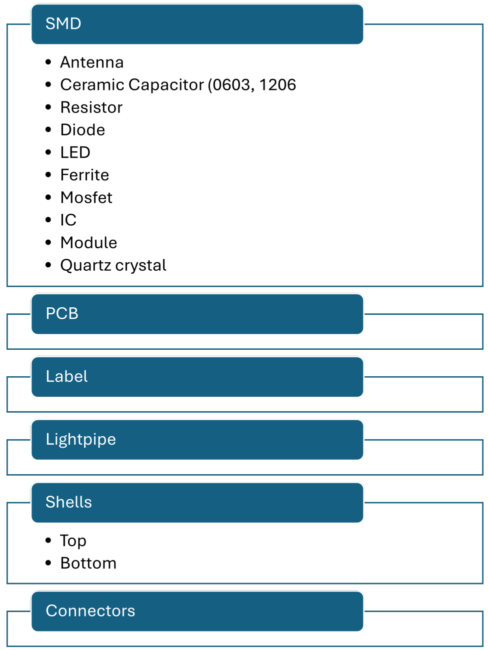
It was noted through mapping the different part variants used in the products that many different types of parts are used for no apparent reason. Fasteners such as washers, screws and nuts of different diameters, lengths, and materials are used within the same product. Production must therefore have a storage solution for all these different fasteners as well as a method to distinguish and organize them. In the long run, it is advisable for the company to cooperate with its clients to increase the standardization of parts used. In this way production and products become simpler as employees no longer need to pay attention to which screw they pick and place. This long term requirement is placed on the list of requirements described in Table 6.2, demonstrating the cyclic nature of the framework. A further mid-term requirement resulting from this observation was that the company should strive to clarify the functionality of the parts used in products, so that inefficient parts that provide limited extra functionality can be communicated back to clients, improving the frugality of the product. Furthermore, the company may seek to (in cooperation with clients) use parts from different



(a) Product 1



(b) Product 2



(c) Product 3

Figure 6.7: The partial PVM for 3 example products

products that provide similar functionality. This reduces the complexity of its inventory and increases the usability of the system, reflecting on the objectives of the F-RMS.

Enablers in the design domain recognized on company one's assembly floor included existing modularity, reliability assurance, flexible design, structured planning methodologies, reduction of waste, reorganization and the availability of resources and infrastructure. These enablers further provided assurance of the subsystem chosen and should be capitalized upon in order to ease the final concept of design. The existing modularity of most machines and workstations allows for quick conversion to a system designed for modularity. Most machines are plug and play and calibration often not necessary. Furthermore, reliability assurance practices were in place with the testing machines, therefore, quality requirements can be relaxed slightly if it is ensured that these reliability assurance practices are continued and the testing machines integrated in the frugal, reconfigurable system. Production lines had been reconfigured according to product demand in the past, demonstrating an existing flexible design of the production floor and a structured planning methodology from the floor managers. Therefore, the existing fixtures and planning methodologies should not necessarily be altered. A need for reduction of waste and openness to reorganization was also identified in the prioritization of objectives, this enables the design of a frugal manufacturing system where functions are reduced as much as possible and therefore waste eliminated. Furthermore, resources were available to buy and improve fixtures, machines. This facilitates design, which can be carried out without capital limitations.

The F-PPRSV model was used to determine the required production functionalities of the product. Work instructions from the company's internal system for the three example products were converted into the F-PPRSV format. These can be found in Appendix B. Afterwards a consolidation step was taken, it was found that whilst specific operations per product varied, all products required an initialisation, hand assembly, electrical hand assembly, machine production, programming and testing, and packing steps which were to be carried out on the assembly floor. Furthermore, tools, machines, fixtures and other resources could largely be grouped according to these steps. The consolidated F-PPRSV model for company 1 can be seen in Figure 6.8.

A large number of resources and parts were found to differ across the (example) products, with the only constant part for all products being a PCB and cabling. Every workstation should thus have a solution for storage and handling of pcbs and cabling. Resources that did not differ across products and were needed for every product included a computer, scanner, tie-wraps and a printer. It is therefore advised that every workstation has these resources available, with some (such as a printer) being shareable between stations when not in constant use. Resources and parts that differed across products (but were needed every product) included fasteners, large assembly parts, electronics housing, (packing) boxes, screwdrivers and testers. For these resources, it is advisable that their implementation in the system is reconfigurable, such that a workstation can be reconfigured towards production of a specific product. For example, increasing mobility of testing machines will enable them to be switched out and removal of testing machines designed for products not currently in production. Resources which are not needed for every product included programming capabilities, wrenches, cleaning agents, gluing stations and hand soldering equipment. These resources are advised to be seen as modules that are not always present on the assembly floor but can be accessed when required by the product. Hand solders, for example, may be stored efficiently in a closet at the edge of the assembly floor and easily accessed when required for a product. This removal of unnecessary resources from the production floor enhances the core functionality

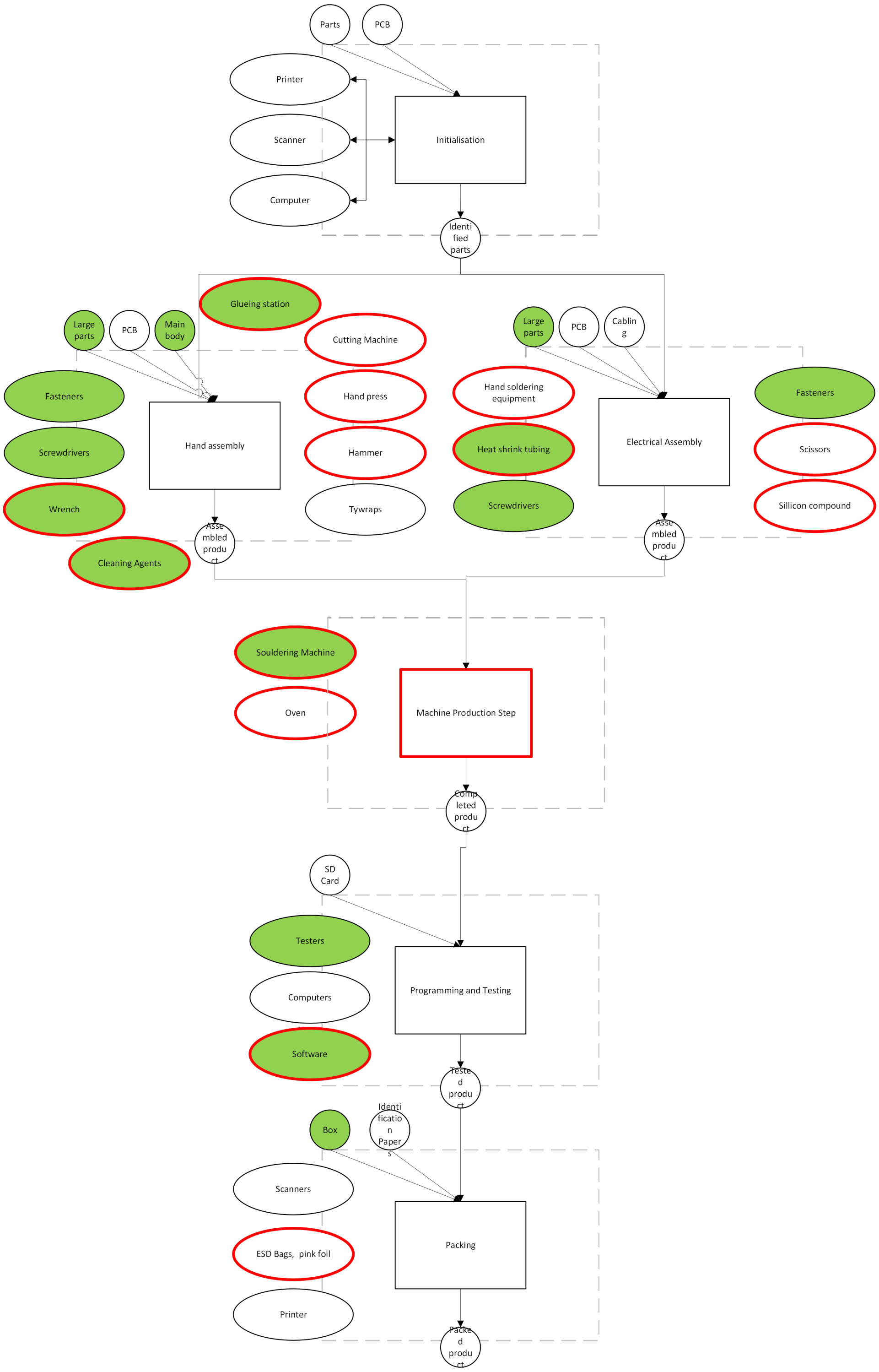


Figure 6.8: The consolidated F-PPRSV model for company 1

of the system, enhancing the frugality. Reconfigurability of the workstations ensures that all functionalities can still be achieved with a total lower number of resources.

The list of requirements and above product and functional requirements lead to the (basic) redesign of the assembly floor that can be seen in Figure 6.9.

Figure 6.9: The redesign of the assembly floor according to the principles of the F-RMS

Workstations are removed from the production floor, enhancing both the frugality and the scalability of the system. This results in extra space between workstations where product-specific parts can be brought in and stored on carts (these carts were previously stored in gangways). Storage of resources (tools, parts and machines) that are not needed for every product is concentrated in storage closets around the periphery of the assembly floor. A tool station is available at the end of every production line for those tools that are needed more often. Workstations, heavy assembly machinery and testing machines are placed on wheels to enhance mobility. As such, impromptu production and testing lines for high product volumes can be rapidly configured. Testing machines can be placed within production lines in the aforementioned workstation storage spaces or form separate testing lines to enhance flow. This is made possible by their mobility. In the long run, improving reconfigurability of the machines themselves is recommended as an options.

The system can be evaluated as an F-RMS according to the criteria developed in Chapter 4. This evaluation according to the Pugh matrix method can be seen in Table 6.3.

The short term is found to be the most important life-cycle term, consisting of 50% of the total weights. The first criteria: substantial cost reduction was not prioritized by the company in the AHP method (see Table 6.1). Nevertheless, cost reduction is achieved only in the long-term. The short term costs will increase slightly as operational costs rise with the old locations of machines, tools and workstations being in different places and employees needing to relearn how to operate the system. In the mid-term, costs are expected to stay the same with decreased ramp-up and reconfiguration costs expected to outweigh the slightly increased costs of having to implement new product lines for every product. The cost benefits start to

Table 6.3: The Pugh matrix for company 1

Level 2	**Level 3**	**Level 4**	**AHP Weight**	**Pugh score**	**Total weight**
Short term: 0.50					
Cost	0.10		5.16%	-1	-5.16%
Functionality	0.37	Operational Capability	8.69%	-1	-8.69%
		Reconfiguration Effort	9.93%	1	9.93%
Usability	0.16	Operational Complexity	3.68%	0	0.00%
		System Reliability	4.21%	0	0.00%
Flow/ Efficiency	0.37	Availability	9.43%	-1	-9.43%
		Quality	0.99%	0	0.00%
		Speed	3.82%	1	3.82%
Mid-term: 0.18					
Cost	0.10		1.82%	0	0.00%
Functionality	0.37	Operational Capability	3.06%	0	0.00%
		Reconfiguration Effort	3.50%	1	3.50%
Usability	0.16	Operational Complexity	1.30%	1	1.30%
		System Reliability	1.48%	0	0.00%
Flow/ Efficiency	0.37	Availability	3.33%	1	3.33%
		Quality	0.35%	0	0.00%
		Speed	1.35%	1	1.35%
Long term: 0.32					
Cost	0.10		3.32%	1	3.32%
Functionality	0.37	Operational Capability	5.59%	1	5.59%
		Reconfiguration Effort	6.39%	1	6.39%
Usability	0.16	Operational Complexity	2.37%	1	2.37%
		System Reliability	2.71%	0	0.00%
Flow/ Efficiency	0.37	Availability	6.07%	1	6.07%
		Quality	0.64%	0	0.00%
		Speed	2.46%	0	0.00%
				Total:	**23.70%**

become apparent in the long term as new product introductions are easily integrated and fewer new machines need to be bought.

The total operational capability of the system within a configuration decreases in the short term as machines and tools are taken away from the floor and need to be actively implemented with new product introductions. The reconfiguration effort decreases, however. Therefore the core functionality of the system is achieved, with new capabilities being added in the long term. In the long-term the operational capability of the system increases as it becomes easier to add new machines with new products, exactly matching the required functionality for new products.

The usability of the system is unaltered in the short term but increases in the mid- and long term. The operational complexity of the system is greatly reduced with the removal of unnecessary machines from the production floor. The ease of reconfiguration also allows for logical production lines and improved flow. The system reliability is likely to decrease, with machines and tools being carried around more often, being prone to breaking or not working when re-initialized. The maintainability is however improved with machines being easily removable from the production floor. Therefore the system reliability as a whole stays the same.

The flow/efficiency of the assembly floor stays the same in the short term but improves over the mid- and long term. In the short term, availability of production decreases, whilst speed is able to increase with quickly configured production lines. Over the mid-term and long term however, the availability and speed of the production system increase as machines are available at the right place if planned right. Therefore, the local availability of tools and machines is improved. The quality is unaffected by the redesign.

The requirements of company 1 were mostly addressed in the new design. In the short term the maintaining high product variation and efficiency increases are expected to be realizable. The cleaning up of the floor and removal of unnecessary machines are expected to increase efficiency whilst no machines are removed from the floor permanently. Faster switching between product, dealing with delivery reliability, machine mobility, and workstation requirements are addressed by the quick reconfigurability and mobility of the workstations, with the basic parts always required always present at the workstation. The increased mobility of machines furthermore allows for increased integrability of tools and machines whilst directly increasing the availability of space as machines can be quickly reconfigured. Dealing with growing complexity and clarifying part functionalities are requirements that, whilst enabled by the redesign, should be addressed in separate processes. In any case, the storing of small parts such as washers, nuts and screws on the floor would only be possible after part functionality but would increase efficiency significantly by reducing the number of reconfigurations needed.

As the focus of case study 1 was on determining customer requirements, the MFD was not carried out and the basic design is limited. However, the overall score of the Pugh matrix is positive, indicating that the design achieves objectives prioritized by the company. It is recommended that the MFD is carried out with the evaluation as an input, also further analyzing the requirements posed in the first stage of design. The short-term performance, especially is recommended to be improved in the advanced design stage or new concept basic design. This can be done by focusing on the ease of reconfiguration, and gradual implementation to ease the cost of retraining employees.

6.2 Case Study 2

The second case study was carried out at a large electronic drive company's plant in the Netherlands. It mainly produces assemblies of gear units and electric motors that are both highly customizable. As such an extremely large amount of product variety is available, with the production manager estimating about 10^{35} different types of variations of completed motor-gear unit assemblies being possible. Motor parts are picked from an inventory warehouse directly beside the motor assembly workstations. After assembly, the motors are transferred to several gear unit assembly islands, of which an example can be seen in Figure 6.10. Gear unit parts are stored within or near these islands and the gear unit is assembled as a standalone unit before being assembled to the motor (in most cases) at the end of the gear unit island work station. The assembled products are then transferred via a roller belt to a hanging system where the units are tested, spray-painted and eventually packed and shipped.

Figure 6.10: An example of a gear unit work island in company 2

The company is well established with continuous improvement operations and was mostly interested in exploring the opportunities of the new concept (of F-RMSs) applied to their production system. The focus of case study 2 was therefore placed on establishing a basic design and exploring concepts for F-RMSs within the company's context. The company is also part of a much larger (worldwide) concern. It therefore does not have control over its product design. Similarly to company 1, product-process co-evolution is therefore not possible. Work instructions for product assembly are also provided and the operational functionality required is therefore largely defined. The company however still has the freedom to arrange its processes towards greater flexibility, efficiency, or other targets. Innovation is therefore possible within boundaries. Process and product requirements are well-defined. This further accentuates the importance of focusing on concept generation, whilst making it easier for designers to gather the required information defined in Chapter 5.

6.2.1 Clarification of Frugal Design Requirements

The AHP and the frugal requirement screening were carried out as part of the clarification of frugal design requirement step to determine a list of company requirements. As company processes were already well established, the reconfigurability assessment was not carried out.

The AHP was carried out with the production manager of company 2. The production manager was in regular contact with operators and works from the factory floor. As the concept generation was focused on improving the workflow in the Netherlands and no company-wide changes would be made, this was deemed sufficient and the AHP was carried out with only one person. The AHP can be seen in Table 6.4. Customer-specific KPI's identified by the production manager were the flexibility and reliability. Flexibility entailed production flexiblity: being able to produce as much variety as possible. Reliability was further subdivided into the categories: deliver on time and (production) quality.

Table 6.4: AHP results for case study 2

Level	Category	Score
Level 2	Short Term	0.08
	Medium Term	**0.90**
	Long Term	0.01
Level 3	Cost Reduction	0.04
	Core Functionality	**0.55**
	System Usability	0.10
	Flexibility	0.10
	Reliability	0.21
Level 4	Operational Capability	0.17
	Reconfiguration Effort	**0.83**
	Operational Complexity	0.13
	System Reliability	**0.88**
	Deliver on time	0.13
	Quality	**0.88**

Of the production life cycle, the medium term, indicating stronger volume changeability, was deemed most important by a large margin. This is logical for a production manager that must seek to fulfill his orders within his planning capabilities. Nevertheless, it provides a clear direction of improvement for a redesign towards a F-RMS.

The core functionality was deemed the most important criteria to be improved upon. It was important to the production manager to be able to produce exactly what was needed. The company is already well-versed with lean production theory, which is focused on reducing wasteful processes as much as possible [115]. This ties in well with focusing on core functionality. Cost reduction was found to be the least important. Similarly to company 1, the frugalization of production to an F-RMS is therefore less concerned with affordability and more with the core-functionality and local integrability characteristics of F-RMS.

The questionnaire developed in Section 5.1.3 was used as a basis for a semi-structured interview with the production manager to define and analyze the production requirements. The overall results according to the production life cycle and requirement category can be seen in Figure 6.11 and Figure 6.12 respectively.

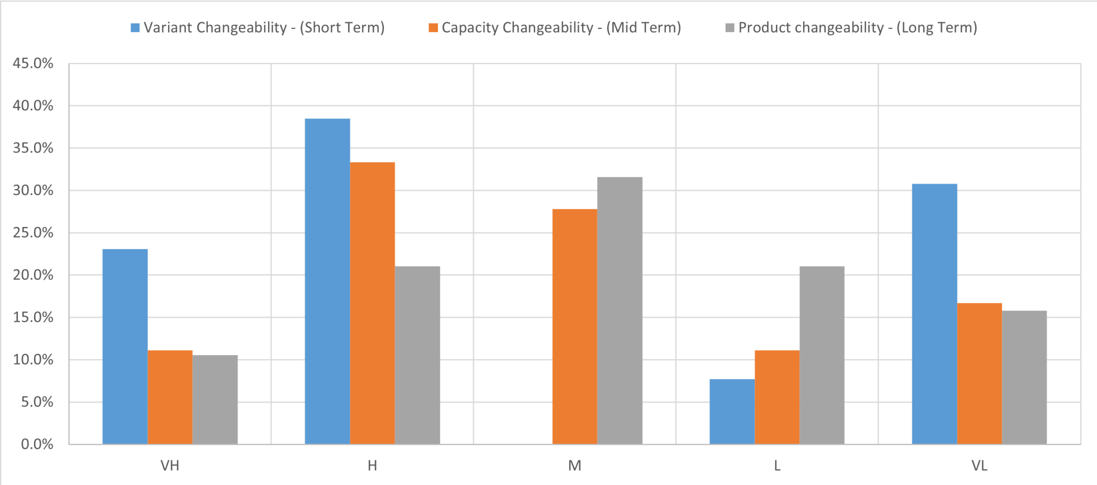


Figure 6.11: The short-term, medium-term and long term requirements screening output identified by the requirements screening questionnaire for company 2

Short term requirements were found to be important, receiving a high number of ’high’ and ’very high’ ratings in the questionnaire. The medium term also scored relatively well, matching well with the AHP prioritization. Short term and medium term requirements align with the production characteristics with a huge amount of product variety, and fluctuations of volume and product variety, with low batch sizes. As such, the manufacturing system needs to have a high degree of variant and capacity changeability. New products are introduced less often as can be seen from the relatively lower degree of important long-term requirements. Nevertheless, product changeability can form some problems, with especially physical space for new product introductions being limited. The company also wants to improve automation and digitalization of production in the long run due to some difficulty in finding workers and organization opportunites. This also aids with short and mid-term planning of variety and volume changes.

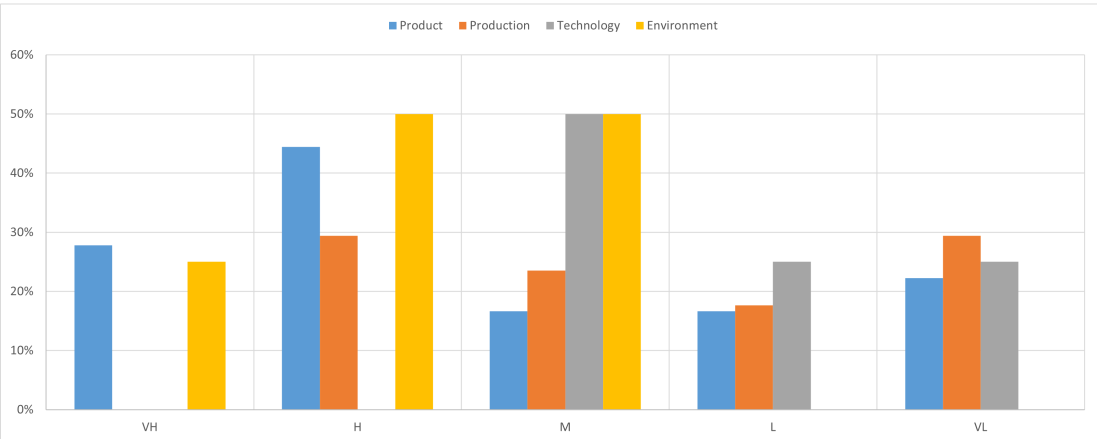


Figure 6.12: The results of the requirement screening questionnaire per requirement category for company 2

Product and environment requirement categories were generally found to be the most important. Technology upgrading is rarely required and is not likely to play a big factor in redesign. Similarly, the production process itself is well established and not expected to change for new products or variants. The increasing variability and complexity of products was found to play a big role in manufacturing system design, with extra features added to products and therefore more production time and employee training needed to produce these. Similarly, environmental factors play a big role in determining requirements for the manufacturing system. Supply chain issues were manageable at the moment but projected to increase, the local market is extremely important to the company, being the Dutch site of the otherwise global company. As such requirements are also geared towards the needs of local customers.

The above considerations, along with observations from the semi-structured interview carried out alongside the questionnaire lead to the list of requirements presented in Table 6.5. The list

Table 6.5: The list of requirements for company 2

	Product	**Process**
Short Term	• Maintain high product variety	• Manage variety fluctuations
Medium Term	• ~~Retention of quality~~ • Cost awareness	• Volume fluctuations • Reduce physical space needed
Long Term	• Increase part commonality	• Automatizability/ customizable automation • Production location changability • Process Digitalisation/ Customizable digitalization

of requirements fits well to the design of a F-RMS. Achieving the overall core functionality of the manufacturing system, providing customized orders to local customers quickly and reliably, is however the most important. Therefore, short term requirements of maintaining high product variety and managing variety fluctuations are created. The retention of production quality was included initially but removed as non-essential in the MFD done for the basic design (see Section 6.2.2) as achieving quality does not pose a problem and sufficient testing procedures are in place. Increased cost awareness is a first step towards greater affordability of the manufacturing system. The company as of now does not have an idea of how much it costs to produce one product variant. With increased cost awareness steps can be taken to improve affordability and match product prices to customer needs. The volume fluctuations and reduction of physical space needed requirements are both linked to the company's limited floor size which still need to handle a large amount of volume fluctuation.

In the long term,this lack of physical space might also lead to the need for production location changeability, where the company may need to produce products or move part of the process to a different location. It is therefore a requirement that the F-RMS-based redesign should interface with a different production location. Further long term requirements such as increasing part commonality to handle variety can also be investigated. However, as product design does not take place at the company, this is a long term requirement that needs to be approved by the global company headquarters. Automatization and digitalization improvements help the company reduce its dependence on having enough workers and aid the overview of production (also contributing to cost awareness). Furthermore, it is important that any automatization and digitalization is customizable to customer and company needs to enable the large variety handled by the company and improve local integrability.

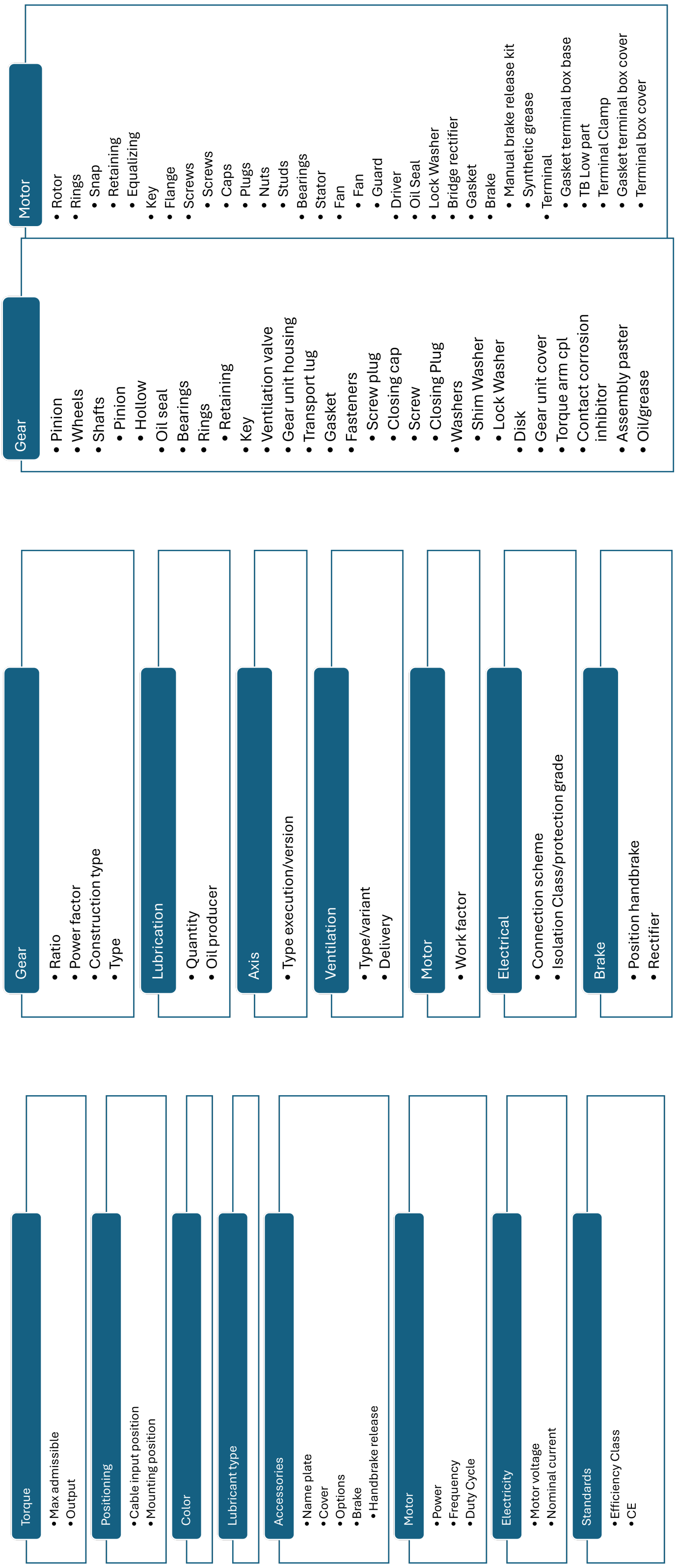
6.2.2 Basic Design

All basic design activities outlined in Figure 5.10 were carried out for company 2. This aligned with the company desire to ideate new concepts for their manufacturing system according to the principles of F-RMSs.

Similarly to company 1, the company has a degree of variety that is not feasible to capture in full in the PVM. Although only one product is sold, it has a significant amount of variety that can not be captured for the PVM. The 'kind-of structure' is therefore not carried out. Instead, the three views of the PVM are carried out, indicating the aspects of the product which can be varied upon. As the product itself is not changeable, it is found to be more important to establish what product functionalities might be need to be varied in production, and the product variants themselves are less important. The three views of the PVM can be seen in Figure 6.13.

The customer view was captured with the assistance of a sample product's order specification. Customers may select a motor that is variable according to functional properties such as torque, positioning and electrical power, aesthetic properties such as color and accessories or safety properties such as food-grade lubricants and adherence to specific standards. Similarly to the principles of axiomatic design, many of these properties are related to a specific product part and production step. For example, the output torque is related to the type of gear unit placed on the motor and the color is only dependent on the spray painting production step. As such, when frugalizing these products, a reduction of customer properties would also reduce the number of parts required to be kept in inventory or the number of production steps required.

The engineering view demonstrates the direct link between parts and customer properties more directly. Engineering properties include variations of parts that enable the customer properties detailed above. The ventilation, for example, can be altered to increase the operable ambient temperatures of the motor drive. As the company mainly provides a business to business service, selling to manufacturing companies, a blending of the customer and engineering view is observed. Engineers employed by the customers may already describe specific functions required. The positions of the handbrake, for example, is placed in the engineering view as the related customer property would be 'ability to brake.' However, a customer of company 2 might specify a specific position of the handbrake according to their perceived positioning within their manufacturing line. The engineering view is therefore characterized as just as relevant to the local integrability and user-customizability of the system as the customer view.



(a) Customer View

(b) Engineering View

(c) Production View

Figure 6.13: The partial PVM for company 2

The production view is separated into the two sub-modules of the drive units sold by company 2 (which in rare cases are sold separately). The company products are modularized to a large extent, enabling the large variety of products. The modularization found in the production view of the PVM (Figure 6.13c also relates to the production modularity, with the two main submodules (motor and gear unit) being produced separately and joined as end-products. Furthermore, the motor, in particular, is found to have a large degree of modularity integrated already, with product properties being alterable by the changing of a part or module, such as the stator or brake. The properties of the gear unit depended largely on the type of gear unit to be produced. The pinion, gear, and output shaft placement within these units determines their properties such as maximum admissible torque. This is reflected in the production system, with the motor assembly being possible at multiple workstations located close to part storage and gear units being produced at variant-specific work islands with parts stored within. When discussing the possibilities of F-RMSs, it was therefore established that reconfigurability of the gear unit work islands towards multiple variants might be a key opportunity for meeting requirements.

Several F-RMS enablers were identified for the gear unit work island, further justifying the choice for this subsystem. Modularity of the product and potential modularity for production formed the biggest enabler, as mentioned. Reliability assurance is carried out in a separate step after the gear unit work island and quality fluctuations are therefore not detrimental to the overall process. Structured planning methodologies are in place for the planning of gear unit production, with a production outlook on a week by week basis created. As such, possible reconfigurations are planned and do not need to be carried out ad hoc. Research and development is carried out regardless in the company in the form of continual improvement and is also an example of a conducive organizational culture. Therefore, the existing testing capabilities and innovative spirit of the company may be utilized in setting up a sample F-RMS island. Furthermore, the gear unit work island is standardized technology wise, with an ingrained use of IT in the form of digital product information displayed on screens, buying new resources is not an issue due to the availability of resources and infrastructure. Integrating new features to the work island is therefore simplified and new modules easily bought. Finally, the employees are trained to produce the product variants without too many detailed instructions. Therefore, a reconfigurable work island would not require extensive training of the employees, who are aware of the required functionalities and how they can use different tools.

The determination of the required functionality activity was therefore carried out to determine the functionality required by a *general* gear unit work island/station. As case study 2 is also a brownfield project, the F-PPRSV was used. The F-PPRSV is carried out according to the work instructions of four gear units. As inspiration of how a general gear unit work island might be established two gear unit variants that are already produced on the same island are analysed. Furthermore, to ensure that no functionality missed a gear unit with a unique island is also analysed. Gear units 1, 2a and 2b are produced on the same work island, where 2a and 2b are the same variant in different sizes. Gear unit 3 is produced on its own unique island and is furthermore one of the newest product variants produced in the manufacturing system, highlighting some updated processes and functionalities. The PPRSVs of the individual products can be seen in Appendix B. The consolidated F-PPRSV for these four product variants can be seen in Figure 6.14.

The assembly process for gear units is consolidated into six steps which can be identified in all four gear unit assembly processes:

1. Pressambling the housing/pressing in bearings

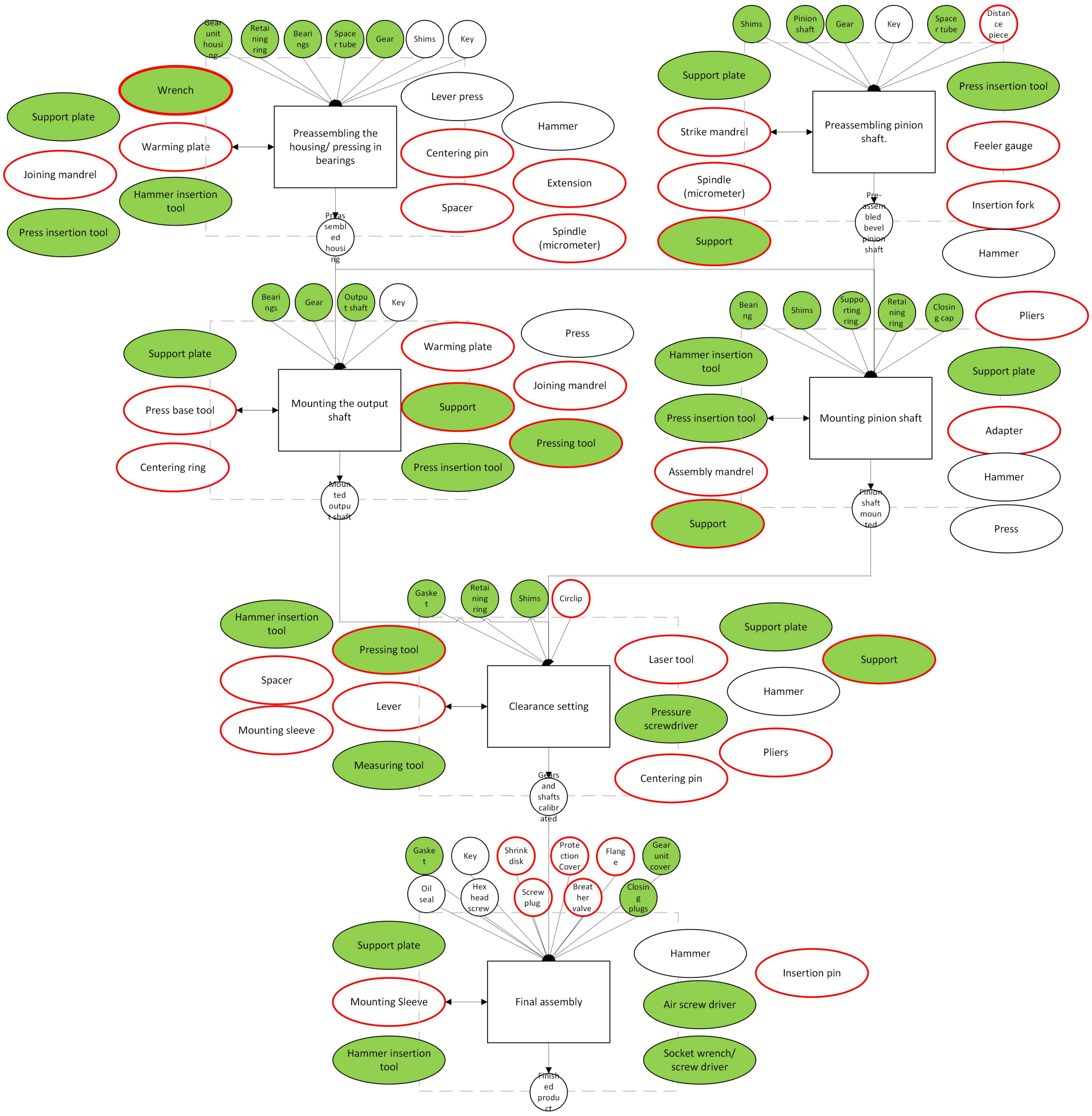


Figure 6.14: The consolidated F PPRSV for company 2

2. Mounting the output shaft
3. Pinion shaft
    a) Preassembling the pinion shaft
    b) Mounting the pinion shaft
4. Clearance testing
5. Final assembly

These steps do not necessarily occur in this order in every product. Preassembling of the housing and final assembly can however be considered the start and end, respectively, of every gear unit variant assembly process. Resources needed for these steps are needed for multiple steps. Support plates, hammer insertion tools and press insertion tools are found in almost all steps. This suggests that a workstation layout rather than a production line may be most relevant in terms of process functionality. The frugality of the system is furthermore enhanced by avoiding the need for multiple sets of these tools.

Furthermore, relatively few resources and parts are found to be homogeneously needed for every product variant. Only a hammer and press are consistently found as resources in every product variant in the same configuration. The same can be stated for the shims, keys and some final assembly parts such as the oil seal and housing cover screws (hex head screw). A large set of resources are needed for every product but in a different configuration. This suggests that reconfigurability would be highly beneficial to a general gear unit work island. Parts, especially, are often needed for every product but in different configurations or sizes. Bearings are for example implemented in every gear unit but are matched to the gear unit variant and several different types of bearings would need to be available in the general work island. The storage of bearings in the work island is therefore suggested to be made reconfigurable, so that a large variety of bearing types can be stored.

The number of resources that is not needed for every product and would therefore be suitable for removal from the production floor is also substantial. A large number of these occur due to the product variation introduction period. It is noted that older products use different resources than newer products. Measuring for example, is updated and requires different resources for different product variants. It is suggested that it is investigated if the same measuring process can be carried out with the older tools, facilitating the removal of extra variants. Furthermore, several resources are similar in functionality but referred to in different terminology in the work instructions. It is therefore recommended that the general work island has some space available for unique functionalities per product variant. However, it is also suggested that a review is carried out as to why resources are different across products and if their functionality can be combined.

Finally, the MFD was carried out to generate concepts for work island modules. First, the list of requirements presented in Table 6.5 was revisited to reestablish requirements for design. The full quality function deployment matrix was not carried out as functions are known to the company and company requirements were deemed more important to revisit within limited investigation time. The ranking of the requirements can be seen in Table 6.6. In line with the proposal to remove unnecessary requirements for the establishment of F-RMSs the company decided that the retention of quality was an unnecessary requirement for production as sufficient testing procedures were already in place. When applied to the gear unit work islands, the handling of product variety, cost awareness and volume fluctuations was found to be most important. Furthermore, of the long term requirements the customization of

Customer/Company Requirements	Importance
Short Term	
Product Variety	5
Variety Fluctuations	2
Medium Term	
Cost Awareness	5
Volume Fluctuations	5
~~Retention of Quality~~	
Supply Chain Fluctuations	1
Physical Space Reduction	2
Long Term	
Automatizability	1
Customizable Automation	1
Increase Part Commonality	1
Production Location Changability	3
Digitalization	3
Customizable Digitalization	4

Table 6.6: Customer/Company Requirements and their Importance for Company 2

any digitalization initiatives was found to be most important. All of these most important company requirements connect with the local integrability of the production system, with the system being able to handle and produce for local customers as reliably as possible.

Step 2 of the MFD was not carried out as the functional requirements and related technical solutions are known within the brownfield project. The technical solutions, (the parts of the production system present) were therefore directly used as an input to the module indication matrix of step 3 of the MFD. The full module indication matrix can be found in appendix C. The resulting modules identified can be seen in Table 6.7

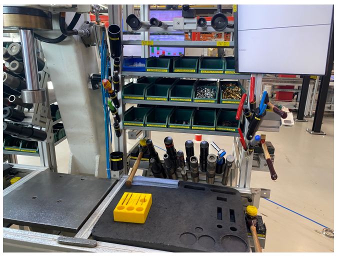
Ericsson & Erixon [108] states that the ideal number of modules for a product is equal to the square root of the operations to be carried out on the product. There are 35 technological solutions and on average 45 operations to be carried out for each product. Interpreting this statement for the design of modular manufacturing systems, the ideal number of modules for the gear unit working island is from $\sqrt{35} = 5.9 \approx 6$ to $\sqrt{45} = 6.7 \approx 7$. Six modules were identified, albeit with submodules included. These modules were all implemented in the current system and no new machinery is therefore needed with the exception of a reconfigurable screw driver. The submodules are therefore demonstrated as they occur in the current system in Figure 6.15.

The fixture module consists of the main structure of the work island with submodules that do not need to be altered for product variation and technology that is not required to be updated for future products. Module carryover is therefore the strongest module driver for this module. Submodules such as press and a generic tool rack are included to allow for easy service and maintenance.

The storage closet includes all parts that are integrably product variant specific. This may include housings, bearings and gears and pinion and output shafts. The storage closet should be mobile, easily accesible, integrable to the fixture and reconfigurable. In this way, a product variant specific storage closet may be stored away from the production floor when the variant is not in production and easily integrated into the workstation when available. Submodules

Table 6.7: The resulting modules identified with the module identification matrix

Module	**Submodules**	**Technical Solutions**	**Most important module driver**
Fixture	• Generic tool rack • Press • Information screen + bar code scanner	Roller Bench, hydraulic press, information screen, workspace plate, heating plate	Carryover
Storage closet	• Housing storage • Bearings & spacer tubes storage • Gears & shafts storage	Housing storage closet, bearings containers, spacer tube containers, gear containers, shaft and bevel gear storage	Portability of interfaces
Small parts rack	• Containers	Shim containers, key containers, ring containers, closing caps containers	Common unit
Tool rack	• Hammer and press insertion tools rack • Assembly mandrels and strike mandrels rack • Support plates and supports rack • (Free rack)	Hammer insertion tool, press insertion tool, assembly mandrel, strike mandrel, spindle, support plate, centering pin, adapter, extensions, spacers	Different specification
Drill/screwdriver	-	-	Regulation and standards
Oil filling mechanism	-	-	Function Sharing



(a) Fixture module, with press and generic tools

(b) One submodule of the storage closet module (housing)

(c) Other submodule of the storage closet module (specific parts)

(d) Small parts rack module

(e) Tool rack module

(f) Screwdriver module

(g) Oil filling mechanism module

Figure 6.15: The modules designated by the MFD, as they are implemented in the present state

of the storage closet module include housing storage, bearings and spacer tubes storage and gears and shaft storage. In this way, variant parts can be easily restocked and replaced if upgrades are required. As the parts in the storage closet form the core of the product and will therefore interact with all the rest of the modules, the portability of interfaces is the most module driver for the storage closet module.

The small parts rack is a module that is similar in function to the storage closet. However, parts stored in the small parts rack may often be needed for multiple products and are needed in larger quantities. The ‘submodules’ of the small parts rack module are containers containing the shims, keys and rings that are needed for multiple product variants. This aids with quick restocking. As the parts contained within the small parts rack are needed for multiple (albeit not all) product variants, the small parts rack will need to be reconfigured less often than the storage closet. Mobility and quick integrability are therefore less important for the storage closet and a higher reconfiguration effort acceptable.

The tool rack contains all product specific tools needed for production and is therefore unique per product variant. The tool rack has four submodules that are designed according to their functionality. In this way, tool upgrades and service and maintenance of specific tools can be carried out easily and efficiently. The tool rack should furthermore be integrable to the fixture in a way so that workers may access the tools easily, rapidly and comfortably. The specific nature of the tools in the tools rack make different specification the most important module driver for the tool rack module.

The final two modules are the pneumatic drill/screwdriver and oil filling mechanism that are needed for every product variant yet have unique features that make them difficult to integrate with other modules. The pneumatic drill/screwdriver is currently different per gear unit island, and tuned to a specific output torque to avoid over-stressing screws. With increased digitalization of the gear unit production process, the screwdrivers can be replaced by electric, reconfigurable screwdrivers that are automatically set to the required output torque with automatic product identification. With this reconfigurable screwdriver, the screwdriver will remain as part of the fixture and its modularity is only necessary for service, maintenance and upgrading. Similarly, the oil filling mechanism is necessary for every gear unit variant but requires replacement of oil drums and service and maintenance. It is therefore included as a separate module with function sharing as its most important module driver.

The final concept design is finalized with the interfacing matrix of step 4 of the MFD. The interfacing matrix for the modules identified in Table 6.7 can be seen in Table 6.8

Table 6.8: The interfacing matric for the modular general gear unit work island, G = geometric interface, E= ergonomic interface, P = electric interface, O= oil tubing interface

	Fixture	Housing storage closet	Small parts rack	Tool rack	Drill/ screw-driver	Oil filling mecha-nism
Fixture	x	GE	G	GE	GEP	GO
Housing storage closet		x	E	E		
Small parts rack			x	E		
Tool rack				x		
Drill/screwdriver					x	
Oil filling mechanism						x

The common unit assembly is chosen, based on the fixture as a common unit. The oil filling mechanism and screwdriver modules will be attached to the fixture for all variants. The storage closet, small parts rack, and the tool rack modules allow for the clear and quick reconfiguration of the island to a new product variant. Frugality is achieved due to the reduction of the number of fixtures and (expensive) machinery needed for production. At the same time, the system can still handle a huge amount of variety. Cost awareness is achieved through the sub modules. Restocking of storage containers, digitized reconfigurations and service and maintenance requiring a sub module swap allow for clear tracking of costs. In the case of the tool rack, the swapping of the tool rack for the customers directly demonstrates if tools require service and maintenance and allow for tracking of their use. The system is optimally suited for volume fluctuations, with multiple fixtures being configurable to the same product variant to increase production capacity.

The integrated design is evaluated according to the weights calculated by the AHP carried out in Table 6.4, the resulting Pugh matrix can be seen in Table 6.9. The AHP sharply prioritizes the mid-term, with 90% of the total weight to be distributed being calculated according to the performance of the mid-term. The cost is not expected to be reduced substantially in the mid-term, as existing machines are already bought and utilized in the same manner as for the existing system. The costs of implementation and increased number of reconfigurations required are however expected to be offset by the reduced volume ramp-up costs and operation costs, resulting in an overall neutral effect. The core functionality per configuration is greatly enhanced by the design. The reconfiguration effort is reduced considerably due to the reconfigurable modules (which, due to the high prioritization, greatly improves the overall score) and the operational capability of the island per configuration is reduced, thereby frugalizing it. The key opportunity of F-RMSs of allowing greater overall functionality through reconfiguration is thereby achieved. Usability is reduced in the mid-term as the system becomes more complex due to the greater number of reconfigurations and the continually changing tools at the fixture. The system reliability can also be expected to decrease slightly as each module and sub-module is replaced as a whole, compounding the reliability of the general system (see Section 4.2). When a specific tool (e.g. a hammer insertion tool) breaks, a new tool rack needs to be assembled and reliability of the entire tool rack module therefore affected. As such, the system reliability decreases due to increased maintenance requirements. In terms of the user-defined KPI, the design scores favorably. The flexibility is improved through reconfigurability. The performance reliability (as defined by company 2) is improved mainly through the improvement of on-time delivery with the increased scalability. The quality is not expected to be altered.

In the long run, the cost benefits of the system become apparent, as new fixtures do not have to be created for new product. Apart from this effect, there are no significant changes expected when comparing to mid-term effects. The advanced design stage must focus on improving the short-term performance and system reliability of the concept design. However, as the overall result is positive, the concept design according to the principles of F-RMS can be thought of as a viable option for a generic gear unit work island. The relatively poor performance on quality can be considered less relevant as the revisiting of the requirements in the MFD already resulted in the scrapping of the maintaining of quality requirement.

Finally, the list of requirements that can be seen in Table 6.5 should have been addressed by the F-RMS design. Of the short term requirements, product variety and variety fluctuations are both improved in the short term. Product variety is still possible due to the product-specific modules whilst variety fluctuations become less of an issue as the same fixture is used for multiple variants. As such, fixture under-utilization for less demanded variants is

Table 6.9: Evaluation Pugh matrix for company 2

Level 2	**Level 3**	**Level 4**	**AHP Weight**	**Pugh score**	**Total weight**
Short term: 0.04					
Cost	0.04		0.20%	-1	-0.20%
Functionality	0.55	Operational Capability	0.41%	-1	-0.41%
		Reconfiguration Effort	2.06%	-1	-2.06%
Usability	0.10	Operational Complexity	0.06%	-1	-0.06%
		System Reliability	0.39%	-1	-0.39%
Flexibility	0.10		0.45%	1	0.45%
Reliability	0.21	Deliver on time	0.12%	0	0.00%
		Quality	0.81%	-1	-0.81%
Mid-term: 0.90					
Cost	0.04		4.05%	0	0.00%
Functionality	0.55	Operational Capability	8.27%	0	0.00%
		Reconfiguration Effort	41.37%	1	41.37%
Usability	0.10	Operational Complexity	1.12%	-1	-1.12%
		System Reliability	7.86%	-1	-7.86%
Flexibility	0.10		8.99%	1	8.99%
Reliability	0.21	Deliver on time	2.32%	1	2.32%
		Quality	16.26%	0	0.00%
Long term: 0.01					
Cost	0.04		0.07%	1	0.07%
Functionality	0.55	Operational Capability	0.14%	1	0.14%
		Reconfiguration Effort	0.69%	1	0.69%
Usability	0.10	Operational Complexity	0.02%	0	0.00%
		System Reliability	0.13%	-1	-0.13%
Flexibility	0.10		0.15%	1	0.15%
Reliability	0.21	Deliver on time	0.04%	1	0.04%
		Quality	0.27%	0	0.00%
				Total:	**41.16%**

reduced. In the medium term, volume fluctuations, supply chain fluctuations and a physical space reduction are also adequately addressed. The increased flexibility and function sharing of the fixtures allows the company to scale its production by assigning multiple fixtures to the same variant. Supply chain fluctuations are addressed as storage within the modules makes variant specific part shortages insightful. In the long term, increased part commonality should be achieved in a separate process as the company is currently not able to alter its products. However, the modules defined in the design clarify the functions of parts. A key method to reduce the number of reconfigurations needed is therefore to increase part commonality, which is thus achieved. Furthermore, small parts are already grouped according to their commonality for multiple variants. The production location changeability is also addressed in the long term, as the stand-alone modules should be easily implementable in different settings.

The cost awareness in the medium term, automatization ability and digitalization opportunities are addressed less directly. Cost awareness is increased indirectly by the insights into which parts are used per variant. Furthermore, the reduction of fixtures allows for a clearer oversight for managers. A manager may, for example, easily track how long a fixture is placed in which variant configuration. Cost awareness would however be addressed more succinctly if an automatic part inventory tracking system is implemented per module.

The automization and digitalization requirements can be addressed through the increased modularity of the fixture. In the proposed design, automatization and digitalization are limited by the reusing of old fixtures. For further addressing of the automization and digitalization requirements, new (customizable) modules should be introduced to the fixture. For example, the work plate that is used for assembling a gear unit may be defined as a standalone module that is assigned to each gear unit and equipped with RFID technology to identify a product and track its usage (as in [116]). The fixture can then be adapted through (software) reconfigurability to implement the correct torque in electric screwdrivers, and provide the correct information on information screens automatically. The F-RMS design of the fixture therefore leaves options open for digitalization and automatization but is limited in this regard in its striving for reuse of old fixtures to improve affordability. If long-term automatization is sought after regardless, the cyclical nature of the framework should be utilized to update the design and study which functionalities are suitable for automatization.

6.3 Case Study 3

The third case study was carried out at an apparel producing company in North Macedonia. Company 3 is mainly focused on producing for export markets elsewhere in Europe. Production in the factory site studied consists of underwear, swim suit sport wear, lingerie and pajamas production. Unlike both company 1 and 2, the company designs its own products, in consultation with its clients. Although a design of a product may be submitted by the client, detailed design (selection of materials and stitches, etc.) is always carried out together with both the company and the customer. The company has to keep its prices low and deliver high quality in order to compete with large-scale cut, machine and trim (CMT) factories in its own market. At the same time it faces increasing labor shortages and capacity shortage in peak moments. Product variety is characterized by seasonal fluctuation as new fashion lines are introduced and products for several customers are produced concurrently.

The company employs 15 employees who operate the sewing, cutting, threading and packing machines necessary for the production of apparel. Processing requirements vary. Producing swimwear is more difficult than underwear, for example, requiring more knowledgeable employees, special machines, and longer production times. Furthermore, 5 employees produce at home with company provided sewing machines, being paid per product. Production is therefore geographically mobile. The case study was carried out online, with several scheduled meetings. The different context of production when compared to case study 1 and 2 allow for an interesting exploration of the validity of F-RMSs. The design framework is therefore carried out to the maximum extent possible.

6.3.1 Clarification of Frugal Design Requirements

The requirements questionnaire was carried out as a semi-structured interview with the company owner to determine the customer requirements. The results according to the production life cycle and requirement category can be seen in Figure 6.16 and Figure 6.17.

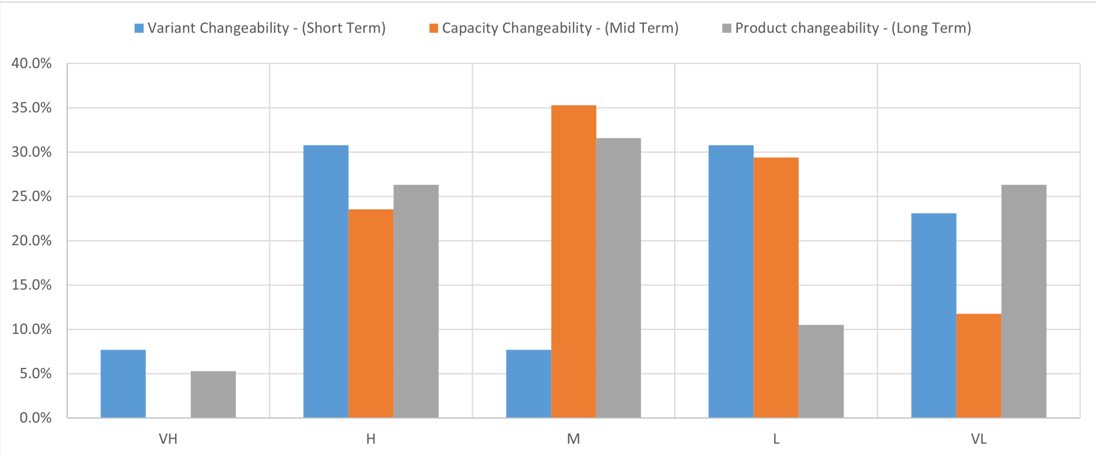


Figure 6.16: The requirements over the production life cycle for company 3

Overall, the short term, mid-term and long term changeability were found to be equally important, with no significant differences in the percentage of requirements that were rated 'high' or 'very high' in importance. Short term and long term requirements were perceived to be slightly more important than the mid-term but also had more 'very low' priority requirements associated with them. This corresponds with the challenges faced by the company across the entire life cycle. Products have a large amount of variety, being specified to each individual customer and new designs being implemented every batch. Furthermore, the scalability of production is limited with batch sizes being limited by the number of machines and labor available whilst minimum batch sizes are also necessary to keep production costs low. Many different types of products (with different processing requirements) are also produced concurrently. Long term reconfiguration towards product changeability is therefore also necessary.

The results of the requirement screening questionnaire per requirement category for company 3 per category gives a better indication of which aspects of production to focus on. Product and environment factors are more likely to receive high importance and should therefore be

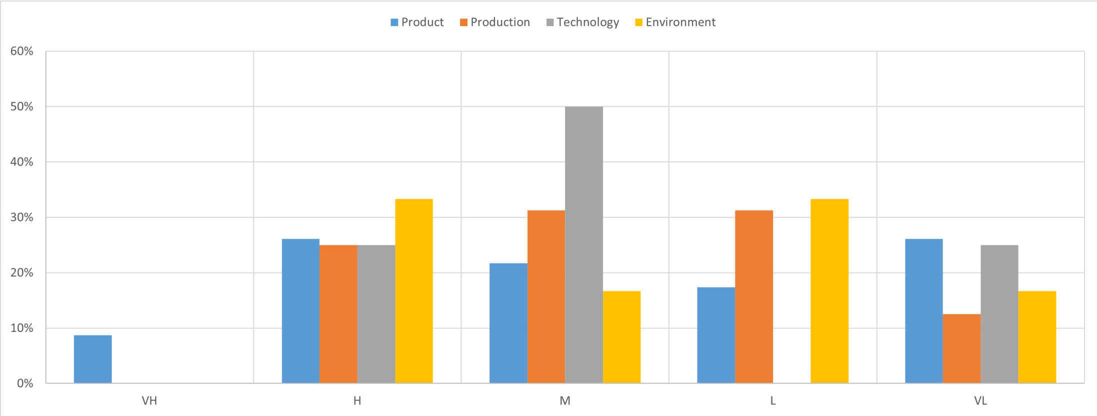


Figure 6.17: The results of the requirement questionnaire for company 3 per requirement category

focused on. Identified requirements on production in the product category mainly included the varying processing requirements per product of which the product price was a main factor. Wholesale underwear, for example, had lower processing requirements to lower the cost of production. Furthermore, new requirements posed by the customer when designing new products formed a problem to production. With regard to the environment, geographical mobility and constraints in acquiring the right resources for production (labor, especially) were the main reasons for the increased importance of this category. The production and technology requirements were ranked relatively lower, with production volumes and quality fluctuations being plannable and production cost the only important requirement to lower prices. Technology upgrading was not required, although new product materials are introduced every year.

The above considerations, along with the semi-structured interview carried out with the questionnaire led to the list of requirements that can be seen in Table 6.10. The list of requirements for company 3 can be seen to differ significantly from the list of requirements of company 1 and 2. Although customisability and variety remain a key challenge to production, product and productions costs form an integral part of the production requirements. Processing requirements and therefore quality should be actively controlled so that costs can be reduced and cheaper and more complex products produced at teh same time. Furthermore, there are more opportunities for product design, with product requirements being possible to integrate into the production systems design. Product variety through seasonality, customisability and adaptation to the client market forms a key part of adhering to local customers' requirements. Finally, increased production mobility, digitalization and flexibility are required to enable the company to work with its resource constraints in terms of acquiring enough labor for increased volumes.

6.3.2 Basic Design

Company 3 shows large potential for the design of F-RMSs due to its different context. Affordability and substantial cost reduction are integral parts of the company's requirements and it faces resource-constraint change drivers that were not found to be present in the other two

Table 6.10: The list of requirements for company 3

	Product	Process
Short Term	• Material Variability • High customisability • Variability in processing requirements	• Complex and simpler products at same time
Medium Term	• New product every season • Adaptation to client market	• Quickly adapt to new product launches • Grip on production cost • Production mobility
Long Term	• Sustainability (recycling)	• Structurally increased production volume • Digitalization of design and production • Lower production costs • Labor flexibility

case studies. The opportunity of F-RMSs to enable flexibility with low costs could therefore maximally utilized. System usability could also enable the easier attraction of labor as less training is required. A focus on core functionality per configuration would help in matching production capabilities to the requirements of the customer and the export market to which it produces. Specific materials required for a specific export market could for example be installed in a single configuration focused on that market. The basic design should be worked out further according to the steps of the framework outlined in Chapter 5.

6.4 Discussion

The purpose of the case studies was to highlight the functioning of the F-RMS in different contexts and industries and validate the applicability of the design framework. This was done according to the research question.

How can the application of the designed framework to a relevant industrial sector validate its functioning and highlight the relevance of frugal, reconfigurable manufacturing systems

Neither company explicitly indicated a desire for either frugality or reconfigurability in advance. Nevertheless, a basic design that reflected an F-RMS and adherence to company requirements was achieved in both case studies.

6.4.1 Validation of the framework

The focus of case study 1 was placed on the first phase of the design framework: clarification of frugal design requirements. Contrarily, the focus of case study 2 was placed on the second phase of the design framework: basic design. As such, not all design activities were carried out for both case studies, depending on the need of the company studied.

The framework was found to be efficient for establishing company requirements. The AHP prioritization allowed the company to reflect on strategic priorities and which aspects of the F-RMS they would prefer to have implemented. Respondents struggled at times to conceptualize the choice being given to them and the opposing priorities given by the respondents in company 1 indicate that the prioritization is somewhat open to interpretation. The AHP is therefore recommended to be carried out collaboratively with multiple stakeholders and in an easily respondable format. Nevertheless, the AHP formed a sufficient basis for the evaluation of the designs and allowed the company to reflect on the strategic vision for their manufacturing systems.

The questionnaire served as an effective basis for a semi-structured interview that collected company requirements. The company requirements were aggregated over system life-cycle and requirement category from which frugal changeability requirements could be deduced according to the change drivers described in Chapter 5. It is important to discuss the requirements for the customers and stressing the importance of removing unnecessary requirements. This allows for greater adherence to the principles of F-RMS in the final design. Differences occurred in the prioritization of the mid-term in the AHP method and number of requirements found to affect the mid-term for company 1. This required a further analysis step of whether these requirements were merely to be implemented in the mid-term or have an effect on day-to-day operations. As the mid-term requirements were found to improve short-term performance, the differences were found to be acceptable. Regardless, the questionnaire served as 'food for thought' for design ideation. The distinct requirements found in company 3 when compared to those found for company 1 and 2 demonstrates the broad applicability of the questionnaire.

The reconfigurability assessment was found to be useful for company 1, where the current functionality and status of production was not mapped. This is also the reason why it was not carried out as an explicit step for company 2 where the functionality and needed capabilities were more known. As such, the tool was mainly used for identifying areas of production where reconfigurability could be improved.

The basic design phase tools, in general, also proved to be useful for coming to a basic design. The product variant master was found to be of limited applicability to company 1 and 2, which both did not have control of their product design and had a large amount of product variety. Therefore mapping the variety itself was infeasible and pointless for both companies. The PVM nevertheless was useful as a tool for analysing the different characteristics of the company and describing the parts which could be varied upon. This then served as a basis for which operational capability should be included and some limited recommendations for future product improvements. For company 1, the standardisation of parts would enable a simplification of production itself and it was therefore recommended to inventorise if this was possible as a result of the PVM. For company 2, the PVM allowed for the identification of the sub-system to be redesigned due to part overlap.

The F-PPRSV was a key tool that allowed for a practical analysis of the functionalities, parts and resources needed for production. The F-PPRSV, as an example of a tool already aimed at frugalizing manufacturing, allowed for the easy identification of areas that could be frugalized through reconfiguration. Reconfigurability allowed for further differentiation of resourcers to be frugalized. Screwdrivers in company 2, for example, which are now calibrated to unique torques, were identified as candidates for frugalization through reconfigurability, only requiring 1 reconfigurable tool instead of multiple unique ones. The other aspect, modularizing and removing resources not needed for every product, was practiced extensively for company 1, where hand solders, for example, were not deemed to be integrated into the workstation at all times.

The MFD was only carried out for company 2 but served as a useful basis for designing modules. Through the linking of existing technological solutions to the module drivers of Brunoe *et al.* [110], logical candidates for creating modules were found that simplified the proposed reconfiguration of work gear unit islands per product variant. As the case studies analysed were brownfield projects steps 1 and 2 of the MFD could not be carried out.

Evaluating the concept designs with the AHP through the Pugh matrix allowed for a structured estimation of the designs performance as an F-RMS. Company 1 had an outcome of 23.7% whilst company 2 had an outcome of 41.16 %. Overall, both design outcomes were positive. With priorities affected positively by the design outweighing priorities affected negatively. Company 2, can be considered to have performed better than company 1. However, the strength of the Pugh matrix is primarily as a tool for comparing designs and analysing the outcome of the tools per criteria. Similarly to the way the other tools of the framework have been used, the final score of the Pugh matrix is therefore less important than the reflection on performance it invites. The outcomes of this reflection can then be used as input for the advanded design phase and for re-evaluation of frugal design requirements used to tweak basic designs.

6.4.2 Functioning of the F-RMS

The characteristics of F-RMSs described in Chapter 4 can be used to highlight the functioning of an F-RMS per case study. Overall, reconfigurability was used as a tool to achieve frugality. Modularity was present in all designs as a main enabler for reconfigurability. It is also a given outcome of the MFD. Modularity is more explicitly used in case study 2 than in case study 1, where no changes to the physical structure of existing fixtures are made and existing fixtures are seen as modules of the system as a whole.

Affordability was not a priority for both of the companies in the Netherlands. Resource-constraint change drivers were only present in terms of difficulty to obtain labor and some supply chain issues as a result of the Covid-19 pandemic. Nevertheless, cost reduction is achieved in both case studies in the long-run due to the F-RMS, primarily due to the combining of functions in one fixture in case study 2 and reduced need to buy new machines in case study 1. Therefore, affordability is improved although not needed, and is provided mainly in terms of increased efficiency. Although no design was carried out, affordability was shown to be important in different settings within the list of requirements of company 3. Designing for affordability with F-RMSs is therefore shown to be relevant and appropriate.

The user-customizability was not explicitly recognized as an objective for case study 1 or 2, as both companies were used to more or less dedicated manufacturing lines. The user-customizability of the design of case study 1 is greatly improved as practically all machines, tools and workstations can be moved or reconfigured to meet the needs of production. Production lines can be set up for high volume product introductions easily, whilst products with lower volumes can be easily produced at single workstations. The user-customizability of case study 2 is more constrained. Modules are used to adapt the system to production needs. The operator is also able to easily change out modules independently. Nevertheless, the operator is limited in functionality to the modules which are available, the functionality of production is therefore limited to the functionalities of the module, limiting the user customizability.

The reliability performance of both systems is mixed. For case study 1, the reliability of the overall system is adversely effected in the short run as system components need to be moved around more. At the same time, the diagnosability is improved due to the general reduction of operation complexity and therefore greater oversight for the floor managers. The overall reliability in the long-run is therefore not affected. For case study 2, the reliability is also unaltered, with greater diagnosability due to module swapping but also greater complexity with an increased number of moving parts (modules) within work islands. As both companies have extensive testing procedures in place and already invested in reliable machinery constantly delivering quality, the reliability aspect of F-RMSs becomes less important to innovate upon.

The local integrability of the systems are generally increased in both case studies. Case study 1, facing a legacy system that was suited for different production volumes with lower variety than currently necessary gained a far more flexible system which could easily be adapted to local needs. Inventory issues of company 1 were also addressed by highlighting the need for standardizing parts to locally, generally available parts. Case study 2 was already highly integrated with its local market, having adapted its production facility to the high variety and short lead times required by the Dutch drive market. Basic design 2 is locally integrable, with existing fixtures, tools and machines being integrated into the new design. However, the ease of use and local sourcing of materials is something which should be designed for in the advanced design stage. As both companies did not have control over which products they produced, improving local integrability of its products through material sourcing was not possible.

Scalability was improved in both designs, with scalability also being identified as a key requirement for both case study 1 and 2. The scalability of company 1 was greatly improved with additional space becoming available, dedicated production lines becoming easy to configure and machine mobility increased. The scalability of company 2 was also greatly improved in allowing the same fixture to be used for multiple products variants. As such, reconfiguration of 2 fixtures to one product variant greatly increases the production capacity for that product variant.

The core functionality of systems was actively striven for to obtain and reduced per configuration. In total, all functionalities of the existing systems were maintained however. Through the F-PPRSV, the core functionality of the existing system was practically analysed and all resources which did not provide a core functionality removed from the floor (for company 1). The core functionality of system 2 was achieved by only making available the tools and parts necessary for a single product. This reduced the system complexity as well.

The F-RMS was therefore found to be implementable according to the company requirements in both case studies. Both companies were similar in not controlling the design of their products and not having resource-constrained drivers of change. As such, challenges typically faced in frugal manufacturing settings in terms of reliability and local integrability requirements were less relevant. Nevertheless, the F-RMS still provided great opportunities for improving upon the other characteristics. Frugalizing production, in terms of lowering costs whilst achieving core functionality, through reconfigurability was found to be possible for these two companies. Efficiency gains were thought to be possible using the same, existing resources for production.

The opportunities outlined in Chapter 3 were found to be specifically achievable in for the case studies. Lower initial capital costs became apparent in the long run, enabling a cost reduction over the life cycle. For case study 1, fewer new machines need to be bought due to the reconfigurable utilization of machines according to the product functionality required. Due to the storage of machines away from the production floor and increased mobility of heavy machines, the utilization of existing machines is improved and no new machines need to be bought. For case study 2, no new fixtures and associated machinery have to be bought for new product introductions. In combinations with the limited space at the factory, this greatly reduces the initial capital costs.

Reduction of the number of machines needed for production is also apparent through the combination of fixtures for multiple product variants for case study 2. With the utilization of one fixture for multiple variants, the total number of fixtures is significantly reduced. More significantly, the number of presses, screwdrivers and other machinery needed is thereby also reduced. For company one, the removing of legacy machines and workstations demonstrate that workstations can become more efficiently utilized if more space for reconfigurability is granted, thereby reducing the number of workstations needed. Reduction of the number of machines needed for production therefore also increases the scalability of the systems by allowing physical space to be freed up.

Inherent reconfigurability within the process leading to lower capital costs is present in the reconfigurable workstations of company 1. By reducing the workstation itself to its core capabilities, the same workstation can be easily reconfigured to carry out consecutive production steps. For products with lower volumes, this increases the system usability. As only one employee needs to be trained on producing the product, operating costs also decrease. The electrical screwdrivers recommended for company 2 allow reconfigurability of the workstation within the process but are flexible tools, therefore raise initial capital costs and reduce the system frugality.

Increased product regionalization was harder to achieve without being able to carry out product-process co-evolution. Furthermore, neither company felt constrained by its regional context and therefore required no change towards this driver. Relocation of production is not an option for company 1 and a long-term possibility in company 2 that was avoided through the use of the reconfigurable gear unit work island. Company 3 was focused on the export market so also needed more generic products, although requiring some adaptations to the client market. Therefore the product regionalization opportunity of F-RMSs was not fully explored within the case studies.

7 Conclusion

Frugal reconfigurable manufacturing systems (F-RMSs) were conceptualized and designed in this thesis. A literature review was carried out to explore the concepts on which the F-RMS is based in Chapter 3. Frugal manufacturing and reconfigurable manufacturing were explored with a special focus on their underlying concepts, criteria and enablers, and exact definitions. This exploration of the theory led to an illustration of the opportunities presented by using reconfigurability to achieve frugality in manufacturing. After the reasons for F-RMSs were given, the exact definition of what constitutes an F-RMS was explored in Chapter 4 based on a synthesis of its underlying concepts (RMSs and frugal manufacturing). A definition and the core characteristics of F-RMSs described the concept of F-RMSs. Criteria and enablers were established to be able to evaluate and implement the conceptualized system in practice. These criteria, enablers and core characteristics served as a basis for the framework that was elaborated in Chapter 5. Here, a framework for the design of RMSs was adapted for use of F-RMSs based on the conceptualization of the earlier chapters. Finally, the framework and the applicability of F-RMSs themselves were validated with two case studies based in the Netherlands. This was discussed in Chapter 6. These activities served to answer the research question:

How can a purposeful combination of the benefits of frugal and reconfigurable manufacturing lead to the design of frugal, reconfigurable manufacturing systems?

This question was answered with the aid of four subquestions that closely aligned with the chapters of this thesis:

a) *How can reconfigurability be used to achieve frugal manufacturing?*

b) *What constitutes and defines the success of a frugal, reconfigurable manufacturing system?*

c) *How can a framework for the design of frugal, reconfigurable manufacturing systems be established?*

d) *How can the application of the designed framework to a relevant industrial sector validate its functioning and highlight the relevance of frugal, reconfigurable manufacturing systems?*

The conclusions of the thesis will be elaborated according to the responses to these questions.

7.1 Conclusion

Through the exploration of literature regarding both frugal manufacturing and reconfigurable manufacturing systems (RMSs), a number of opportunities inherent in using reconfigurability for achieving frugal manufacturing systems were found. Firstly, reconfigurability allowed reducing the total lifecycle cost of a production facility through the reduction of required initial capital costs. Production flexibility is achieved without the need for buying new or expensive flexible machines through reconfiguration of existing equipment. The F-RMS furthermore enables reduced total costs of ownership by reducing the total number of machines needed for production. Through reconfigurable function sharing, possible by switching modules within machines, the same amount of functionality of two machines can therefore be achieved with only an investment in new modules.

A third opportunity through which manufacturing frugality was found to be enhance through reconfigurability was by allowing inherent reconfigurations in a production line. Therefore a production line requiring multiple consequent fixtures, machines and employees may achieve the same functionality through reconfiguration of the machine, reducing the total number of fixtures or machines needed in the production line. Finally, the reconfigurability of a production facility allows for the specific tuning of a factory to its local needs. This was found to be especially useful for companies seeking to relocate production to new markets.

These opportunities led to the need to define what exactly a F-RMS can be thought of to constitute. The definition for F-RMSs was synthesized from the definition of RMSs and frugal manufacturing to create:

A frugal, reconfigurable manufacturing system is designed in a resource-scarce manner at the outset for rapid and cost-effective changes in its configuration, in order to provide production capacity and functionality significantly cheaper than competitive alternatives whilst continually meeting evolving basic needs of its customers and the market,

Whereby the (core) functionality of production was found to be an inherent overlap in the two manufacturing concepts.

The core characteristics of F-RMSs were, similarly to the definition, synthesized from the core characteristics of RMSs and frugal manufacturing. Again, the inherent overlap between RMSs and frugal manufacturing was found to be able to establish a succinct list of core characteristics:

- Modularity,
- affordability,
- user-customizability,
- reliability,
- local integrability,
- scalability,
- core functionality.

Here, modularity from RMSs and affordability for frugal manufacturing were not found to correspond to core characteristics of the other manufacturing system and were therefore used directly. The other five core characteristics were combined to reflect the specific definition of F-RMSs.

Three criteria were established that could be used to determine the success of F-RMSs. A successful F-RMS will entail a substantial cost reduction, achieve core functionality per configuration, and have high system usability. Here substantial cost reduction was defined to be a reduction of the total cost over the life cycle, which must be significantly cheaper than its alternatives. Core functionality per configuration was defined through the division into two sub-criteria, operational capability and reconfiguration effort. Operational capability, contrarily to most applications, should be reduced as much as possible per configuration to achieve only necessary functionality and therefore frugality. However, the necessary total functionality may be achieved through reducing the reconfiguration effort as much as possible. The system usability was also divided into two aspects: operational complexity and system reliability. These sub-criteria served to make the system as easy to initialize, operate and maintain as possible by its operators.

Additionally, through the same synthesis method as for the definition, core characteristics and criteria, a list of enablers was achieved that will in general make it easier to establish an F-RMS and were implementable in the framework. A large degree of these enablers was found to be non-technical or design related, outlining the strategic nature of F-RMSs. These enablers fell within the categories of stakeholder support, customer consideration, employee involvement, and organizational factors such as a conducive organization culture. Enablers that could be applied directly in the design of F-RMSs fell within the categories of making use of appropriate resources, design processes and system design techniques such as modularity and rapid prototyping. These enablers form a non-exhaustive list. However, their presence in literature as enablers of both frugality and reconfigurability substantiate their applicability.

The above definition of the F-RMS, factors defining its success, and enablers served as a basis for the generic design framework for F-RMSs that was designed in Chapter 5. The framework of Andersen *et al.* [8] for RMSs was used as a basis for the design frame of F-RMSs. As a tool to explore the general design of F-RMSs, the first two phases of the design framework were adapted: clarification of frugal design requirements and basic design. Another two phases, advanced design and implementation were determined not to have a large effect on the frugalization of the system, whereas more frugalization potential was determined in the first phases. The framework adopts the cyclical method used in the framework by Andersen *et al.* [8], however, a critical reflection and reduction task is implemented in every cycle, where requirements, functionalities and properties should be reduced as much as possible at the every design step. The framework was defined as a method to align the design of manufacturing systems to the principles of F-RMSs and is not presented as the only method possible to design F-RMSs.

The clarification of frugal design requirements phase of design consisted of three design activities. The establishing priorities for design activity is carried out to make a decision to design a F-RMS and clarify strategic priorities for both the customer and the designer according to the analytical hierarchy process (AHP) method. The criteria defined in Chapter 4 were used as a basis for the AHP. The definition and analysis of requirements for F-RMS activity allows the designer to collect customer requirements according to a questionnaire which is adapted towards a set of F-RMS change drivers. The current level of reconfigurability was analyzed for brownfield projects according to the existing assessment by Boldt *et al.* [97] to establish already existing reconfigurable practices.

The basic design phase consisted of four activities. First, technical F-RMS requirements are analysed according to the product variant master (PVM). Here, the product requirements' effect on the operational requirements are analysed. Modularity of the product especially influences the degree of modularity possible for production. Determining required functionality was found to be key to be able to reduce the manufacturing system to core functionality and was carried out according to the frugal product process resource skill variability model for brownfield projects. Axiomatic design, for greenfield projects, allowed a similar procedure of matching required operations directly to the required resources and parts. The functions and product requirements were used as an input for the modular function deployment (MFD) which was used to carry out the generating frugal concepts phase. Here module concepts were systematically generated and integrated to a final basic design. This final basic design is then evaluated according to the AHP developed in the clarification of customer requirements phase.

Finally, case studies were carried out to validate the applicability of the framework and demonstrate the relevance of frugal, reconfigurable manufacturing systems. The framework was found to be efficient for establishing company requirements and carrying out a basic design, although not all activities were carried out for all case studies. The requirements questionnaire and F-PPRSV tools especially were found to be useful tools that aided the companies studied in clarifying their requirements and functionalities. The AHP and MFD tools proved to be useful, albeit needing further guidance from the designer to reach useful conclusions. The framework nevertheless resulted in a design that adhered to the requirements of the company and F-RMSs in both cases, validating the functioning of the framework.

The final designs of the case studies validated the functioning of the F-RMSs. The opportunities of reduced initial capital investments and fewer machines needed overall were realised in both case studies with machines being removed and made available for multiple production lines. The reduction of machines needed due to reconfiguration within a production process was found to be case-specific, with only one case study capitalizing upon this opportunity to reduce the number of workstations needed per production line. Product regionalization opportunities were not found through the implementation of the F-RMS in the two case studies, as products could not be altered and production mobility not required. This is therefore recommended to be studied in further case studies.

7.2 Recommendations

F-RMSs were conceptualized and demonstrated to have great potential in this thesis. However, the system was not fully implemented and not all possibilities of F-RMSs were fully explored. A number of recommendations are therefore made for future research.

The first recommendation is to expand the number of case studies. The case studies applied in this thesis took place in the Netherlands with companies that were not significantly resource-constrained and had a relatively high use of technology, as well as employee training. Applying the framework in more contexts and for different industries would validate the functioning of the F-RMS in contexts besides these. The design of a F-RMS in contexts where frugal innovation often takes place due to necessity, in resource-constrained settings and contexts where adherence to local requirements is essential, would grant important insights into the functioning of F-RMS in unideal conditions. Furthermore, it is predicted that frugality could be achieved through reconfigurability more strongly than in the current cases.

Furthermore, implementation of the framework in real life would provide further evidence of the viability of the F-RMSs. The system has not been implemented in the case studies, leading to the evaluation of the designs to consist of (qualitative) estimations of their performance. The expansion of the F-RMS design framework to advanced design and implementation is expected to be implementable without significant alterations to existing RMS frameworks. The implementation of F-RMSs could therefore be achieved relatively simply by practitioners according to existing practices. The monitoring of F-RMS performance would grant important insights into the actual performance of the manufacturing system and which of the theoretical opportunities apply. In particular, the behavior of the F-RMS and the maintaining of frugality across multiple reconfigurations would be an interesting topic to explore within a real-life application.

It is furthermore recommended to further develop the system usability of F-RMSs within the design framework. In the case studies, it became apparent that core functionality and cost reduction achievements were more apparent than system usability and adversely affected it in some cases. The potential of F-RMSs could therefore be greatly improved if methods are found that enhance both system usability as core functionality. Reduction of operational complexity and improved system reliability were both reduced in F-RMS designs due to the introduction of reconfigurability. Integrating methods into the F-RMS that allow designers to consider system usability explicitly, backed in literature concerning the usability of reconfigurability, would improve the functioning of F-RMSs towards all criteria.

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Appendix A: Paper, Establishment of a Directly Applicable Design Framework for Frugal, Reconfigurable Manufacturing Systems

M.J. Mooij

Abstract: Frugal innovation, an innovation philosophy encapsulating a significant reduction of costs and focus on core functionality of products is used by companies across the globe to reach expanded markets. Nevertheless, manufacturing processes seem to have largely been excluded from frugal innovation applications. Reconfigurable manufacturing systems (RMSs) offer large opportunities for increasing both the efficiency and flexibility of production systems yet often do not take into account sustainability or resource-constraints. The combination of frugal and reconfigurable manufacturing into frugal, reconfigurable manufacturing systems (F-RMSs) therefore inherently offers opportunities to make frugal manufacturing viable and RMSs less wasteful. F-RMSs are explored in this paper. The opportunities inherent in their combination are explored, the exact meaning of F-RMSs delineated with a list of core characteristics and criteria for its success. As such the F-RMS is fully conceptualized. Subsequently, a design framework for F-RMSs is defined based on this definition and criteria. In this way F-RMS design is facilitated and its eventual implementation enabled. The framework is focused on a requirements gathering and basic design step, where advanced design and implementation guidelines are defined on a case-by-case basis. The thesis is finalized with a set of case studies where the framework is carried out at different companies to (re)design an F-RMS. The functioning of the F-RMS is thereby validated, with the opportunities inherent in their combination recognized in the practical designs created.

1 INTRODUCTION

Frugal innovation, an innovation philosophy encapsulating a significant reduction of "the total cost of ownership by focusing on core functionalities and reducing non-core features (Tiwari and De Waal (2018)) is used by companies across the globe to cut costs whilst continuing to provide core functionalities. Nonetheless, manufacturing processes seem to have largely been excluded from the frugal innovation process. Whilst consumer goods and other products are increasingly being 'frugalized,' the processes with which they are manufactured are not studied and innovated upon correspondingly (Dabić et al. (2022)). Reconfigurable manufacturing systems (RMSs) offer large opportunities for increasing both the efficiency and flexibility of production systems (Pansare et al. (2021)). Increasing amounts of literature characterize this broad category of manufacturing systems as one of the key paradigms for facing increasing market volatility that are designed to adopt different configurations through the repeated changing or rearranging of components in a cost-effective way (Napoleone et al. (2023)). Although the opportunities of RMSs are therefore large and varied, they are often only geared towards increased adaptability without regard for sustainability or resource-constraints. Frugal manufacturing through reconfigurability has therefore not been explicitly considered. Nevertheless, reconfigurable manufacturing systems could provide an opportunity of enhancing the frugality of manufacturing processes as they inherently reduce capital requirements by combining functions. Vice-versa, the opportunities of reconfigurable manufacturing systems in providing product customization are enhanced by the inherent recognition of consumer requirements in frugal manufacturing.

Limited literature exists regarding the combined and enhancing combination of frugal innovation/manufacturing and RMS, and its opportunities are not fully explored and formalized. Applicability of RMSs for frugal innovation therefore remains low and the opportunities of RMSs in especially emerging economies remain underutilized. The novel design of an RMS explicitly based in its strengths as a method of frugality therefore provides huge opportunities towards further implementation within both industry 4.0 and emerging economies. However, with a lack of design frameworks and research explicitly discussing the strength of the combination of frugality and reconfigurability within manufacturing systems, these benefits become more of a coincidental byproduct than a deliberate, fully exploited, outcome in novel designs of RMSs. It is therefore important to study the methods with which any novel systems utilizing a combination of frugality and reconfigurability can be designed successfully, and thereby further study the strength of combining these two functionalities.

This paper aims to capture the benefits of reconfigurability for achieving frugal manufacturing by defining and formalizing frugal, reconfigurable manufacturing systems (F-RMSs) according to the research question:

How can a purposeful combination of the benefits of frugal and reconfigurable manufacturing lead to the design of frugal, reconfigurable manufacturing systems?

Firstly, both frugality and reconfigurability within manufacturing will be explored to propose the opportunities of reconfigurability in frugal manufacturing. A definition of F-RMSs will be provided along with what criteria would determine their suitability and success as an F-RMS. The conceptualized F-RMS characteristics and criteria will then be used as a basis for a F-RMS design framework that is adapted from existing RMS frameworks to create a practically and generically applicable design for any F-RMS. To validate the functioning of F-RMSs and the developed design framework, case studies will be performed in relevant industrial sectors.

2 FRAME OF REFERENCE

2.1 *Frugal Manufacturing*

Frugal manufacturing is considered to be the application of frugal *innovation* to manufacturing. Frugal innovation, although its exact definition is still undergoing debate, can be defined generally as any innovation that performs according to the acronymic attributes (Berger (2015)): **F**unctional, **R**obust, **U**ser-friendly, **G**rowing, **A**ffordable, **L**ocal. A typical example of frugal innovation is the Tata nano car that can be seen in Figure 1. This car was developed specifically according to the frugal innovation principles, thereby creating the 'world's cheapest car' by stripping excess features such as air conditioning, radio systems, and airbags.

Fig. 1. Tata Nano Car, an example of a frugally innovative product (Pathania and Mint (2013))

A frugal, reconfigurable manufacturing system will by definition be an example of frugal manufacturing, it is therefore important to study the specific application of frugal innovation towards manufacturing. Frugal manufacturing systems, are defined by Schleinkofer et al. (2019) as:

Machines, equipment and devices that meet the requirements of price-sensitive customers in industrialized countries and the fast-growing emerging markets.

Literature discussing frugal manufacturing is limited. Chakravarty and Gómez (2023) claim this is due to a recent focus on management and business issues in frugal innovation discourse, with their paper attempting to refocus the discussion on to frugal production and manufacturing. However, the PROREGIO project links manufacturing to frugal innovation in several ways, focusing on advancing product regionalization. This is done according to the themes (i) design of customer oriented product-services for frugal innovation in a bottom-up development process, (ii) optimization of production systems and networks based on interaction of stakeholders, and (iii) planning and control of production networks and regional production systems to enable ad-hoc re-design (Commission and Technologie (2022)). Some of the key challenges faced by frugal manufacturing are meeting regional market demand (Mourtzis et al. (2016)), lack of financial and technical resources for manufacturing, (Schleinkofer et al. (2019)) and lack of skilled labour and knowledge (Fidan et al. (2021)). These challenges may be uniquely addressed by the introduction of reconfigurability.

2.2 *Reconfigurable Manufacturing*

Reconfigurable manufacturing systems (RMSs) were conceived by Koren et al. (1999) in 1999 as

designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.

RMSs vary from other 'intelligent' manufacturing systems such as 'flexible manufacturing systems' or 'dedicated manufacturing systems' due to their cost-effectiveness, requiring little to no special, advanced machinery whilst maintaining high production volumes and flexibility. To achieve these benefits, RMSs use *reconfigurability* characterized by the 6 core characteristicsMaganha et al. (2019): customisation, convertibility, scalability, diagnosability, integrability and modularity.

RMSs were initially envisioned to be reconfigurable to be able to respond to changes in market or regulatory requirements, as outlined in the definition above. It has been recognized since however that RMSs are also necessary for both predictable variations in product type and variable product demand without changes in the market (Ameer and Dahane (2023)). The components which may constitute an RMS have also been expanded in scope to to a multi-dimensional capability, encompassing multiple reconfigurability enablers based on context-specific systems' features (sNapoleone et al. (2023)). This paper therefore interprets RMSs in a broad manner to be able to draw lessons from as many systems as possible.

2.3 *Opportunities of frugal, reconfigurable manufacturing*

The elaboration of the concepts 'frugal manufacturing' and 'reconfigurable manufacturing systems' above demonstrate significant opportunities inherent in their combination. Reconfigurability is useful to achieve frugality due to the possibility of lower initial capital costs. In order to introduce new product varieties, traditionally either flexible machines or new machines need to be acquired, both expensive options. RMSs are uniquely able to provide flexibility towards a manufacturing system efficiently (and cheaply) without adding too much additional complexity, making frugal manufacturing possible for continually evolving product variety.

Secondly, an RMS will inherently be able to reduce the number of machines needed to achieve a similar level of product variety. The total cost of ownership of a manufacturing system, key to frugal innovation, can therefore be reduced. As only modules need to be changed to achieve product variety in an RMS, there is no need to invest heavily in flexible machines from the outset. Investments can therefore be portioned to match the exact functions needed by changing demands.

Furthermore, inherent reconfigurability in a manufacturing system with low reconfiguration *effort* and *cost* can enhance frugality by combining functionalities. A process may entail a number of consecutive steps of the same operation (e.g. fixing, cutting, drilling) at different dimensions. In a dedicated manufacturing system, the same number of consecutive modules as consecutive steps will need to be installed. Through reconfigurability, a single module can be used repeatedly to achieve any number of operations.

Finally, increased product regionalization is enabled by reconfigurability. Companies seeking to relocate production to the markets they serve can draw on existing facilities in other markets and easily tune their facilities to the local conditions and market, a key requirement of frugal innovation. As RMSs are uniquely rapidly upgradable the new requirements imposed by the new setting can be rapidly adjusted to.

3 DEFINING A FRUGAL RECONFIGURABLE MANUFACTURING SYSTEM

3.1 Definition

A definition of what constitutes and qualifies as a frugal reconfigurable manufacturing system is essential to be able to design such a manufacturing system. A frugal, reconfigurable manufacturing system is defined by combining the definitions as found in the previous sections to achieve:

A frugal, reconfigurable manufacturing system is designed in a resource-scarce manner at the outset for rapid and cost-effective changes in its configuration, in order to provide production capacity and functionality significantly cheaper than competitive alternatives whilst continually meeting evolving basic needs of its customers and the market

Frugality is ensured by the inclusion of a "resource-scare manner," "providing production capacity and functionality significantly cheaper than competitive alternatives," and "basic needs" of customers. Reconfigurability, in line with the broader definition adopted in section 2, is included through the definition of "design at the outset for ... changes in its configuration" and the continuous meeting of "evolving" basic needs of customers and the market. Already, the inherent overlap of frugal innovation and RMS can be seen by the applicability of (core) functionality towards both.

3.2 Core Characteristics

The core characteristics of frugal manufacturing and RMSs show further overlap. Convertibility of RMSs concerning 'transforming existing functionalities' lies close to the functional characteristics of RMSs by providing the best functionality for customers. Customization allows for user-friendly operations, whilst diagnosability and robustness both increase the reliability of the product or manufacturing system significantly. Similarly, scalability and growing refer to the same concept of product growth whilst integrability is a necessary requirement to convert a global product to a local one. Modularity and affordability are less directly linked. The following 7 core characteristics of a F-RMS can therefore be deduced.

- Modularity
- Affordability
- User-customizability
- Reliability
- Local Integrability
- Scalability
- Core functionality

3.3 Criteria for Success

To determine the success of F-RMSs, evaluation criteria should be established. As for both frugal innovation and RMSs, criteria are largely defined as a method to evaluate the characteristics of F-RMSs and are defined according to the characteristics defined above. As such, whilst the core characteristics define the F-RMS, the criteria provide a measure of how well they are implemented.

The most important and inherent criterion for the success of F-RMSs is substantial cost reduction, based on the characteristic of affordability. A F-RMS must be significantly cheaper than its alternatives, which could range from a similar non-frugal RMS to multiple dedicated manufacturing systems providing the same functionalities. Cost is defined as the cost of the system over the life cycle, defined as (Zhang et al. (2006)). :

$$C_\Sigma = C_d + C_m + C_{rc} + C_{ru} + C_o + C_{rm}, \tag{1}$$

where C_d is the design cost, C_m the manufacturing/ implementation cost, C_{rc} the reconfiguration cost, C_{ru} the ramp-up cost, C_o the operation and support cost, and C_{rm} the remanufacturing cost. As a criteria, the total cost reduction defined by Winkler et al. (2020) for frugal innovation of at least 60% cost reduction is ideally adhered to.

Another criteria is the manufacturing functionality per configuration, used to indicate the core functionality, scalability and modularity of the system. Here manufacturing functionality is defined as the "operational degree of switching from a product to the other with different process requirements" Abdi and Labib (2003). A F-RMS must focus on core requirements. Achieving core functionality within a single configuration whilst also allowing reconfigurations to achieve different functionalities is therefore important for F-RMSs to offer increased flexibility whilst making use of the cost-cutting benefits of frugal functionality limitations. Achieving the correct degree of functionality per configuration is accomplished through the analysis of two metrics. The operational capability (OC) per configuration (p) and machine (q) should be minimized and is mathematically defined as in Goyal and Jain (2016):

$$OC_{p,q} = [(\sum_{k=1}^{K} \delta^q_{p,k}) - 1]^Y, \tag{2}$$

where Y is a power index, K is the set of all operations that machine p in configuration q is able to perform and the binary operator $\delta^q_{p,k}$ is defined as

$$\delta_{p,k}^{q} = \begin{cases} 1 & \text{if machine } p \text{ in configuration } q \text{ is able} \\ & \text{to perform operation } k \\ 0 & \text{otherwise} \end{cases}$$

At the same time, flexibility is ensured through the enabling of reconfigurability. The reconfiguration effort E_{rm}, calculated using the three components reconfiguration time t_{rm}, reconfiguration cost C_{rm} and ramp-up time Napoleone et al. (2023) ($E_{rm} = t_{rm} + C_{rm} + t_{ru}$) must therefore also be as low as possible. A F-RMS must have minimal reconfiguration effort, such that the introduction of product variety is less effort through reconfiguration than through the introduction of system flexibility.

The system usability is a third key criteria and is used for the user-customizability, reliability and local integrability characteristics. F-RMSs must be locally integrable and scalable, user-customizable, and reliable. The system must therefore be usable by those owning, operating, repairing and otherwise interacting with it. This criterion can be split into two parts: operational complexity, and system reliability. Operational complexity consists of the complexity of operational tasks within a configuration. The reliability consists of system robustness, as well as maintainability.

On a component level, the system usability can be judged by qualitatively determining component complexity and maintainability. An integrated qualitative judgement of component complexity leads to an indication of the reliability of the component. Schleinkofer et al. (2019) introduces a matrix juxtaposing maintainability and complexity, which can be seen in Figure 2. As many components

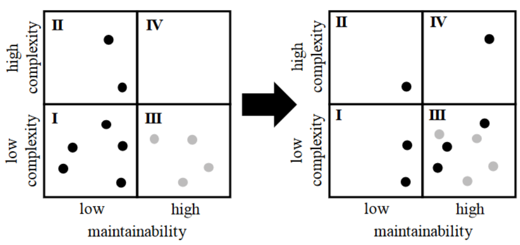


Fig. 2. System reliability optimization matrix (Schleinkofer et al. (2019))

of a F-RMS as possible should be placed in the third quadrant of the matrix seen in Figure 2 to achieve system usability.

A final set of criteria is provided by context-specific KPI's. It can be concluded rather straightforwardly that a manufacturing system must meet the KPI's set by its owners or operators. Nevertheless, this criterion is explicitly mentioned to stress the importance of the F-RMS providing local integrability and user-customizability.

3.4 Enablers

Through the comparison of the ranked lists of enablers of Niroumand et al. (2021) and Pansare et al. (2023) for frugal innovation and RMSs a combined set of enablers is established. Globally, the enablers found can be categorized into the following categories, although overlaps can also be inferred:

- Stakeholder support
- Customer consideration
- Employee involvement
- Organizational factors
- Resource use
- Design process
- System design

4 FRAMEWORK FOR DESIGN

The concept of what constitutes a F-RMS is thus well established. However, the opportunities of F-RMSs outlined in section 2 can only be achieved if manufacturing systems are designed (or redesigned) as an F-RMS from the outset. The comprehensive framework for RMSs as developed by Andersen et al. (2017) is used as a basis for the F-RMS framework. The core characteristics and criteria of F-RMSs are then used for the adaptation of this framework to a comprehensive framework for the design of F-RMSs. The framework is equipped with a number of tools based on the criteria, core characteristics of F-RMS, as well as related concepts such as change drivers and the production life-cycle. Thereby, a directly applicably but generic framework that can be used to design any F-RMS is created. The final framework can be seen in Figure 3.

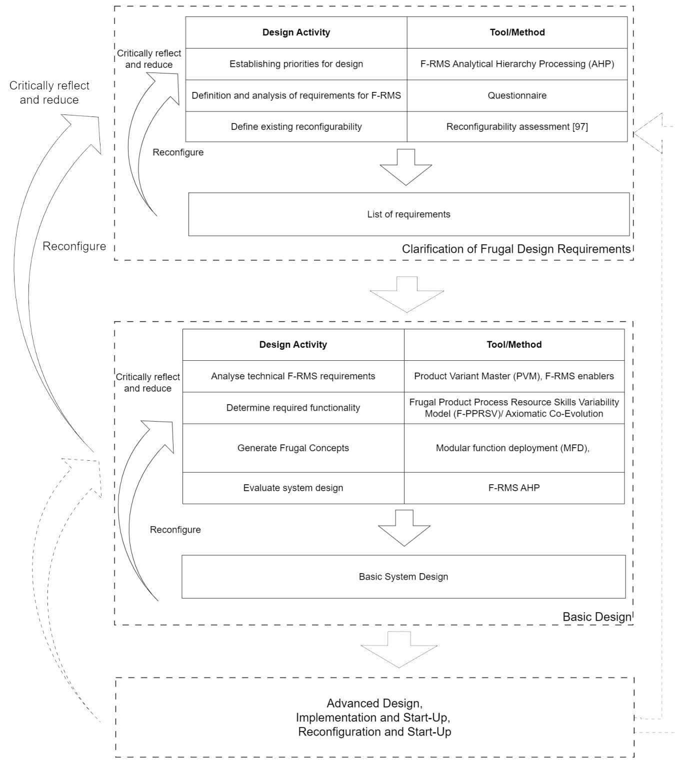


Fig. 3. The consolidated design framework for F-RMSs

4.1 Clarification of Frugal Design Requirements

The clarification of frugal design requirements phase has three activities: establishing priorities for design, definition and analysis of requirements for F-RMS, and defining existing reconfigurability. In the establishing priorities for design activity a analytical hierarchy process (AHP) hierarchy is established based on the F-RMS criteria to explicitly prioritize objectives which can then be used to establish weights for the developed criteria. The AHP is carried out as in Singh et al. (2007). The hierarchy as constructed for the selection of an F-RMS can be seen in

Figure 4. To evaluate the functioning of a future manufacturing system, a distinction is made over its functioning in the short, medium or long term in the third level of the AHP. According to this distinction, possible changes in production may be concerned with product variant changes, volume changes or product changes for the short, medium and long term, respectively (Napoleone et al. (2021a)).

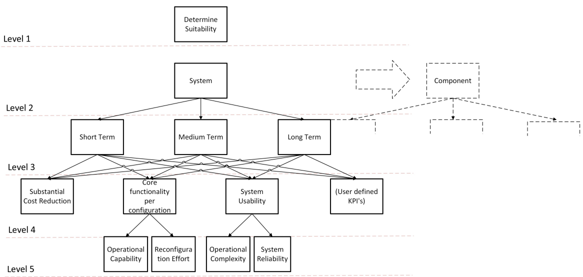


Fig. 4. The hierarchy for determining FRMS suitability

Closely aligning an eventual product with customer requirements lies "at the basis of frugal innovation" (Mourtzis et al. (2017)). Defining the user requirements for the manufacturing system is therefore especially important for F-RMSs. A general requirements questionnaire is developed according to the characteristics defined in section 3. These questions are based on the questionnaire Andersen et al. (2018), which based its questions on change drivers. The change drivers for reconfigurability are classified into the categories: product, volume, technology and strategy. The questionnaire was expanded for suitability for F-RMSs according to the addition of frugality change drivers (Pisoni et al. (2018); Ploeg et al. (2021)): constraint-based change drivers and localized drivers.

The final activity is the definition of existing reconfigurability, especially significant for brownfield projects. An assessment of the reconfigurability is carried out according to the assessment by Boldt et al. (2021). The current level of frugality does not have to be judged in the same way. The potential for frugality should instead be judged according to the current process. Accordingly, the potential for frugality is recognized by determining specific practical improvements in reconfigurability.

4.2 Basic Design

The basic design phase consists of four activities. The first, analysing technical F-RMS requirements, is carried out by completing the product variant master (PVM). The product variant master (PVM) is a tool that is frequently used in industry to determine the production requirements of a product family, as well as its customer requirements and functionalities (Mortensen et al. (2010)). It allows for a comprehensible mapping of the variety of the product to be produced according to two abstraction mechanisms that break down the product into the parts or modules which appear in the entire product family and their possible variants. The variety, changability and modularity of product families determine the (reconfigurable) production capacity and functionality needed Abdi and Labib (2004). The PVM is therefore useful for determining the technical requirements of design.

The second activity is the determining of required functionality. Core functionality is a key characteristic of F-RMSs. Establishing the required operations and resources needed for production is therefore essential. For brownfield projects, the frugal product process resource skill variant (F-PPRSV) model is used for this purpose and can be seen in Figure 5. Here, the operations required to produce different product variants are linked to parts, resources and consequent operations (Fidan et al. (2021)). A truncation step where the models of different variants are combined into a single model gives a clear overview of core functionalities. Properties may be variant specific (outlined in red) or vary per product (green background). A similar process is followed for greenfield projects, where the tool used is axiomatic design. Here, instead of mapping the existing process, the (core) functions of the product are directly related to the operations, resources and parts (AlGeddawy and ElMaraghy (2009)). The relation between functionality and operations is therefore made causal and explicit.

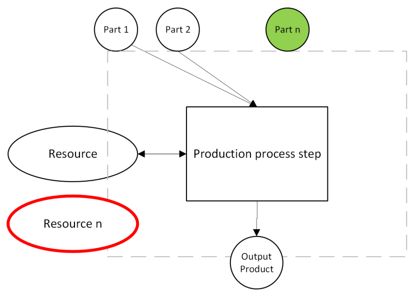


Fig. 5. The basic structure of the F-PPRSV, with green colors and red outlines signifying product variety

After the required product and production functionalities are known, the frugal concept designs can be generated. This is done according to modular function deployment (MFD) as created by Erixon (1998). In this five-step process, modules are identified separately, combined and the total design evaluated. The first step of MFD: 'defining customer requirements' entails linking the requirements defined in the 'clarification of frugal design requirements' phase to the functionalities found in the previous step in a quality function deployment (QFD) matrix. These production properties are ensuingly linked to technical solutions. These are linked to module drivers for RMSs as defined by Brunoe et al. (2021) and modules are formed based on patterns. The modules are finally linked together and a final concept generated by completing an interfacing matrix.

The design(s) are finally evaluated according to the initial AHP prioritization. A Pugh matrix, where concepts are scored as having a positive (+1), neutral (0) or negative (-1) effect on the relevant criteria, allows for an estimation of the performance of the designs when the criteria can not be quantified (Napoleone et al. (2021b)).

5 CASE STUDIES

Case studies are carried out to validate the applicability of the framework and demonstrate the relevance of frugal reconfigurable manufacturing systems (F-RMSs) in general. Two case studies have been carried out at different manufacturing companies to demonstrate the generalizability of the framework.

5.1 Case Study 1

The first case study involves an electronics assembly company in the Netherlands. The company is characterized by a large variety of different products. The company faces a shift in production towards increasing product variability as a client with traditionally high product volumes decreases its demand. It therefore wants to redesign its assembly floor, which is characterized by a legacy structure. A map of the current assembly floor can be seen in Figure 6a and consists of a large number of workstations (desks) with specific tools and machines needed for production placed on these desks.

(a) Current operation (b) Redesign as an F-RMS

Fig. 6. A map of the assembly floor as it currently operates

The company seeks to gather ideas to carry out the redesign of the assembly floor. The focus of the first case study is therefore placed on phase one of the framework and the MFD is not carried out. Nevertheless, a simple redesign is proposed that can be seen in Figure 6b. Workstations are removed from the production floor, enhancing both the frugality and the scalability of the system. This results in extra storage space between workstations. Storage of resources (tools, parts and machines) that are not needed for every product is concentrated around the periphery of the assembly floor. A tool station is available at the end of every production line for tools that are needed more often. Workstations and heavy machines are placed on wheels to enhance mobility. As such, impromptu production and testing lines for high product volumes can be rapidly configured.

The system is expected to be a successful F-RMS, as determined by analysing the performance of the criteria over the production life cycle. Cost reduction is achieved in the long-term. The short term costs will increase slightly as operational costs rise with employees needing to relearn the locations of fixtures. The cost benefits become apparent in the long term as new product introductions are easily integrated and fewer new machines acquired. The total operational capability of the system within a configuration decreases in the short term as machines and tools are removed and implemented only with new products. The reconfiguration effort decreases. Therefore core functionality of the system is achieved. The usability of the system is unaltered in the short term but increases in the mid- and long term. The operational complexity of the system is reduced with the removal of unnecessary machines. The system reliability is likely to decrease, with machines and tools being carried around more often. The maintainability is however improved with machines being easily replaced. Therefore total system reliability stays the same.

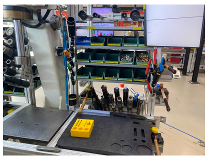
5.2 Case Study 2

The second case study was carried out at a large electronic drive company's plant in the Netherlands. It mainly produces assemblies of gear units and electric motors that are both highly customizable. Motor parts are picked from an inventory warehouse directly beside the motor assembly workstations. After assembly, the motors are transferred to several variant-specific gear unit assembly islands which can be seen in Figure 7. Gear unit parts are stored within these islands and the gear unit is assembled as a standalone unit before being assembled to the motor. The company is well established with continuous improvement operations and was interested in exploring the opportunities of the new concept (of F-RMSs) applied to their production system. The focus of case study 2 was therefore placed on establishing a basic design concept.

Fig. 7. The gear unit work island of company 2

It is decided to focus on the gear unit islands as a suitable sub-system for F-RMSs as a result of the PVM indicating suitable product modularity characteristics for the gear unit. A concept based on six modules is determined according to the MFD, these modules can be seen in Figure 8. The fixture module consists of the main structure of the work island with submodules that do not need to be altered for product variation and technology that is not required to be updated for future products. It is the common unit to which the other modules are attached. The storage closet module includes all parts that are integrably product variant specific. The small parts rack is a module that is similar in function to the storage closet. However, parts stored in the small parts rack may often be needed for multiple products and are needed in larger quantities. The tool rack contains all product specific tools needed for production and is therefore unique per product variant. The screwdriver and oil filling mechanism are needed for every product variant yet have unique features that make them difficult to integrate with other modules.

The cost is not expected to be reduced substantially in the mid-term, the costs of implementation and increased number of reconfigurations required are expected to be offset by the reduced volume ramp-up costs and operation costs. In the long run cost is reduced, as new fixtures



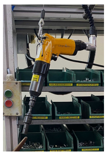
(a) Fixture, with press, tools

(b) Storage closet (housing)

(c) Storage closet (specific parts)

(d) Small parts rack

(e) Tool rack



(f) Screw-driver

(g) Oil filling

Fig. 8. The modules designated by the MFD, as they are implemented in the present state

do not have to be created for new products. The core functionality per configuration is greatly enhanced as the reconfiguration effort is reduced considerably due to the reconfigurable modules (which, due to the high prioritization, greatly improves the overall score). The operational capability of the island per configuration is also reduced, thereby frugalizing it. Usability is reduced in the mid-term as the system becomes more complex due to the reconfigurations and continually changing tools at the fixture. The system reliability can also be expected to decrease as each module and sub-module is replaced as a whole, compounding the reliability of the general system. The design is therefore a somewhat successful F-RMS in terms of the criteria due to the cost reduction and focus on core functionality, achieved through reconfigurability with room for improvement in terms of usability.

6 CONCLUSION

Frugal reconfigurable manufacturing systems (F-RMSs) were conceptualized and designed in this paper. The key opportunities of F-RMSs were identified: reducing required initial capital costs, reducing total costs of ownership by reducing the total number of machines needed, achieving functionality through reconfiguration and specific tuning of a factory to its local needs. These opportunities can be explicitly addressed by designing an F-RMS, which was delineated by its core characteristics: modularity, affordability, user-customisability, scalability, local integrability, core functionality and reliability. A successful F-RMS was furthermore found to rely on the success of three criteria: substantial cost reduction, core functionality per configuration and system usability. Of these, the core functionality per configuration criteria is further subdivided into the sub-criteria operational capability and reconfiguration effort, whilst the system usability is sub-divided into an operational complexity and system reliability aspect.

These criteria, and the defining characteristics of the F-RMS served as a basis for a design framework for F-RMSs. The framework of Andersen et al. (2017) for RMSs was used as a basis for the design frame of F-RMSs. As a tool to explore the general design of F-RMSs, the first two phases of the design framework were adapted: clarification of frugal design requirements and basic design. The framework adopts a cyclical method with a critical reflection and reduction task implemented in every cycle, where requirements and functionalities should be reduced as much as possible at every design step. Tools were suggested that highlight the frugality in design activities and enabled the use of reconfigurability to achieve frugality in manufacturing. Finally, case studies were carried out to validate the applicability of the framework and demonstrate the relevance of frugal, reconfigurable manufacturing systems. The two designs created for the companies studied demonstrated the opportunities of F-RMSs, with cost reduction and core functionality being achieved. System usability was found to be harder to implement in practice through reconfigurability. Nevertheless, the opportunities of F-RMSs largely applied in practice.

It is recommended that a design established according to the principles and framework of the F-RMS is implemented in practice to further demonstrate the validity of the system. For practitioners, the continuation of the design of F-RMSs into the advanced design, implementation and reconfiguration phases according to their own established processes would grant important insights into the further design challenges faced by F-RMSs and any changes of requirements after reconfiguration. The opportunities of designing for any number of functionalities through reconfiguration is recommended to be investigated in an implementation of the F-RMS. For researchers, it is recommended to investigate how the trade-off between reconfigurability and usability that was observed in the case studies can be improved to achieve a truly frugal RMS. In particular, reducing complexity for frugality whilst introducing reconfigurability is a key concern identified.

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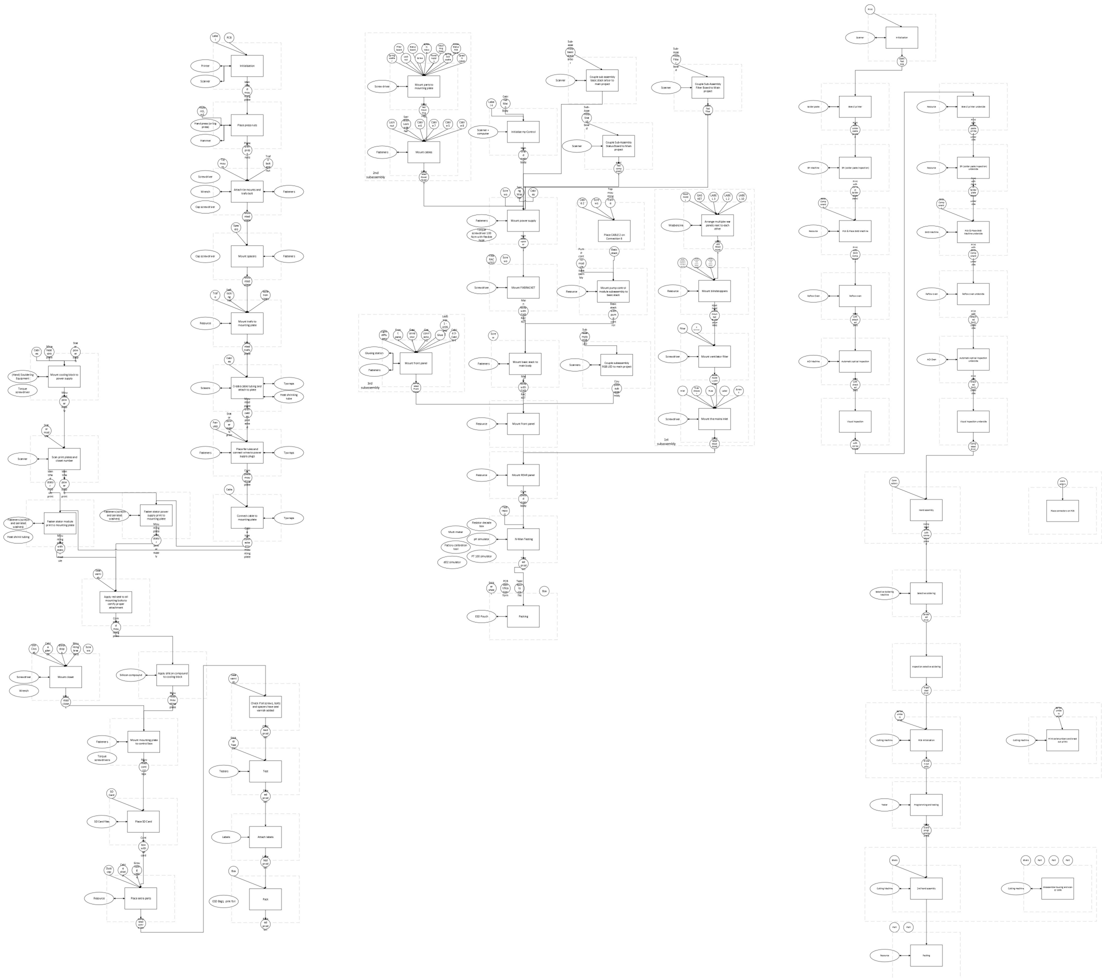
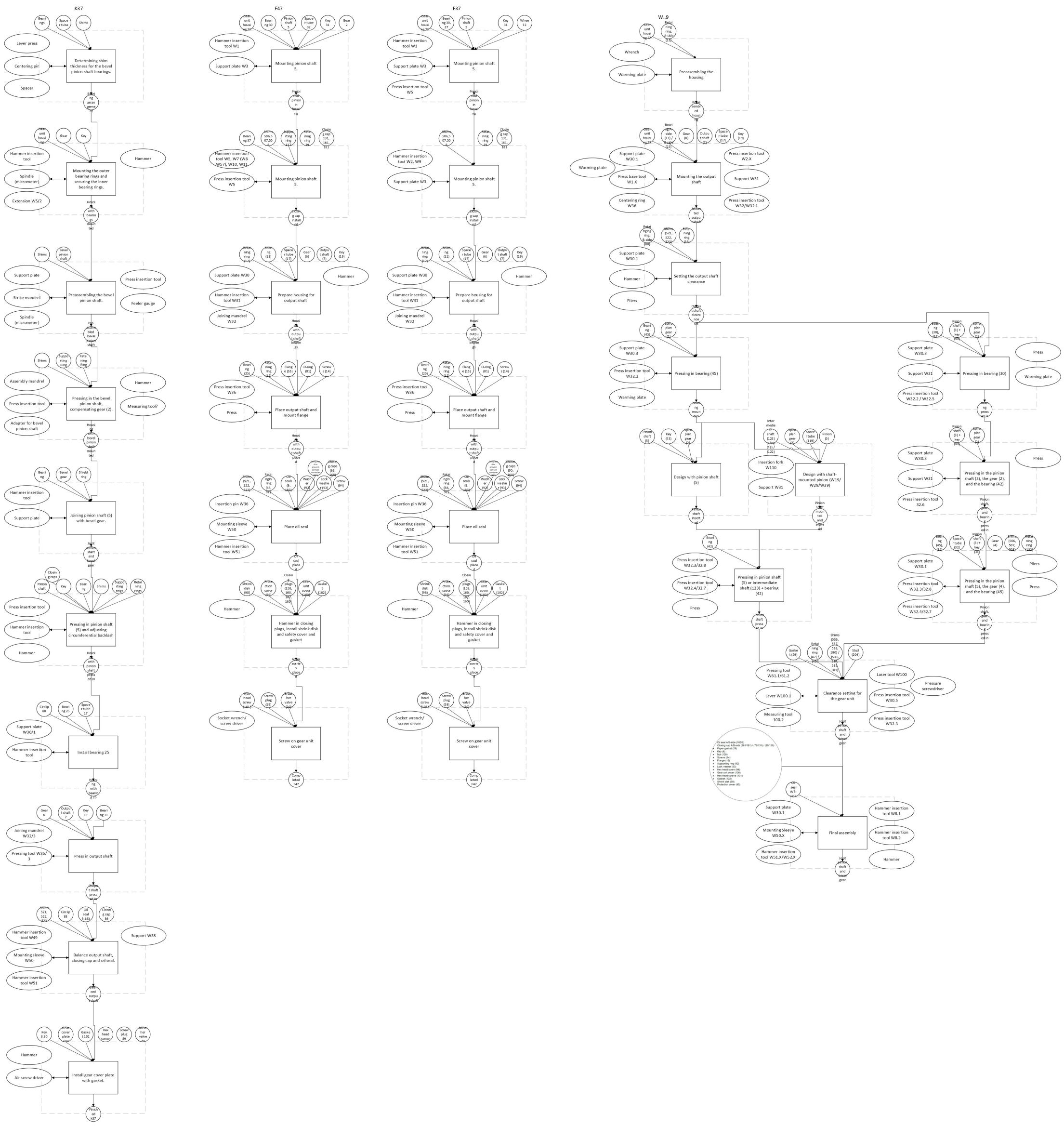
Appendix B: PPRSVs

PPRSV Company 1



PPRSV Company 2



Appendix C: Module indication matrix

Module Drivers	Technical Solutions	Roller Bench	Hydraulic press	Information Screen	Workspace plate	Housing storage closet	Shim containers	Key Containers	Ring Containers	Closing caps containers	Bearings Containers	Spacer Tube Containers	Gear Containers	Specific Part storage (Shafts and bevel gear)	Hammer Insertion Tool	Press Insertion Tool	Assembly mandrel	Strinke mandrel	Spindle (micrometer)	Support Plate	Centering Pin	Adapter for bevel pinion shaft	Extensions W5/2	Spacers	Hammer	Feeler Gauge	Measuring tool?	Hoist	Heating Plate	Drill/screwdriver (pneumatic)	Oil filling mechanism	Barcode scanner	Total
	Module carryover	1													1	1	1	1														1	
Localization of changes	Technology evolution				1																				1				1	1			5
	Regulation & Standards		1																									1		1			3
	Planned System changes	1																									1						2
Variety and Standardization	Common Unit				1		1	1	1	1															1						1		7
	Different Specification		1								1	1	1	1	1	1	1	1									1						10
	Changeability																																0
System Development	Function sharing		1																												1		1
	Geometric integration & Precision														1	1	1	1	1	1	1	1	1	1									10
	Portability of interfaces			1	1	1			1	1	1	1	1																				9
Production of Manufacturing Equipment	Vendor Capabilities												1	1																			2
	Separate testing												1	1																			2
In use	Service and Maintenance														1	1				1	1						1		1	1			8
	Recycling					1	1	1	1	1	1	1	1	1																			10
	Customer Requirements																																0
	Upgrade					1	1	1	1	1	1	1	1	1																			10
	Process and/or organization	1			1																									1			3
	Total	3	3	1	4	3	3	3	4	4	4	4	6	5	4	4	3	3	1	2	2	1	1	1	2	0	3	1	2	4	2	1	

Figure 1: The module indication matrix for company 2

Appendix D:Questionnaire

Question No.	Question
Variety	
q1	How many product/part variants exist? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL) variety?
q2	How is product/part variety expected to evolve in the next 3–5 years? And what is the main driver for change?
q3	How does the physical size/geometrical dimension of the product/part differ across variants?
q4	How do the materials differ across variants?
q5	How does the weight differ across variants?
q6	To which extent is size/geometrical dimension of products/parts expected to differ for new generations and new variants?
q7	To which extent are the materials of products/parts expected to differ for new generations and new variants?
q8	To which extent is the weight of products/parts expected to differ for new generations and new variants?
Customisation	
q9	To which extent are current products/parts customised? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL) customisation?
q10	How is product/part customisation expected to evolve in the next 3–5 years? And what is/are the main driver/s for change?
q11	To which extent is the user/customer involved in designing any customisation? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL) involvement?
q11a	To which extent is the user/customer able to design any customisation independently? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL) customisation?
Processing requirements	
q12	Do product/part designs have in common any modules/subassemblies (i.e. modules/subassemblies of the product/part that are used for multiple variants)?
q13	Which degree of commonality/reuse of modules/subassemblies is expected in future new product/part designs?
q14	To which extent are processing requirements different for product/part variants?
q15	How are processing requirements of new product/part generations and variants expected to differ from existing processing requirements?
	Continued on next page

Table 1 – continued from previous page

Question No.	Question
q16	How often do changes in processing requirements occur after system design has started? (e.g. the process/es need to be adapted because the demand for a specific variant is surprisingly high and this impacts a lot on processing requirements)
q17	To which extent is final product cost considered a processing requirement? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q18	To which extent can processing requirements be reduced for the product to still be satisfactory to the customer? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
New product/part introduction	
q19	How often are new product/part generations currently introduced? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q20	How is introduction of new product/part generations expected to evolve in the next 3–5 years?
q21	Over which timespan are new product/part generations introductions planned within the current strategy? For your specific industry, is that considered Very Long (VH), Long (H), Medium (M), Short (L) or Very Short (VL) Term?
Product/part life-cycle	
q22	What is the current length of a product/part's life cycle in production? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q23	How is the length of product/part life cycles expected to evolve in the next 3–5 years?
PRODUCTION QUESTIONS	
Production volume	
q24	What is the total annual production volume? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q25	How is the production volume expected to evolve in the next 3–5 years?
q26	How much does total production volume currently fluctuate between planning periods?
q27	How are fluctuations of total production volumes expected to evolve in the next 3–5 years?
q28	How unpredictable is total production volume?
q29	How is unpredictability of total production volume expected to evolve in the next 3–5 years?
Production mix	
q30	How much does production volumes for individual product/part variants fluctuate between planning periods?
q31	How are production volume fluctuations for product/part variants expected to evolve in the next 3–5 years?

Continued on next page

Table 1 – continued from previous page

Question No.	Question
New production volume	
q32	How unpredictable are production volumes of new product/part introductions?
q33	How unpredictable is the timing of market launch of expected new products/parts?
Production cost	
q34	What is the average total cost of production of one product? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q35	How is the production cost expected to evolve in the next 3–5 years?
q36	How unpredictable is total production cost?
q37	How much are production costs affected by unforeseen changes after system design has started?
Production quality	
q38	How much does production quality for individual product/part variants fluctuate between planning periods?
q39	To which extent does production quality form a problem to production operation? For your specific industry, is that considered Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL)?
q40	How are production quality fluctuations for product/part variants expected to evolve in the next 3–5 years?
TECHNOLOGY QUESTIONS	
Processing change	
q41	How often is new processing technology upgrading required in production machinery and equipment? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q42	Are disruptive production technologies expected to evolve in the future?
Materials change	
q43	How often are new product/part materials introduced? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q44	How is the number of new product/part material introductions expected to evolve in the next 3–5 years?
ENVIRONMENT QUESTIONS	
Supply Chain	
q45	How often does acquiring the right resources for production (e.g. labor, materials, machinery) form a problem to meeting requirements? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q46	How often do delays of resource delivery delay production? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q47	How are any difficulties in acquiring the right resources for production expected to evolve in the next 3-5 years?
Market Localization	

Continued on next page

Table 1 – continued from previous page

Question No.	Question
q48	To which extent are production requirements provided by the local market? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q49	To which extent do product requirements vary from other markets? For your specific industry, is that extent considered Very High (VH), High (H), Medium (M), Low (L), or Very Low (VL)?
q50	How is the importance of the local market to production expected to evolve in the next 3-5 years?
Geographic Mobility	
q 51	How many separately located facilities has production of the specific product and its variants?
q52	Does the production location change over the product's life cycle?
q53	Is the location of production for the specific product expected to change in the next 3-5 years?