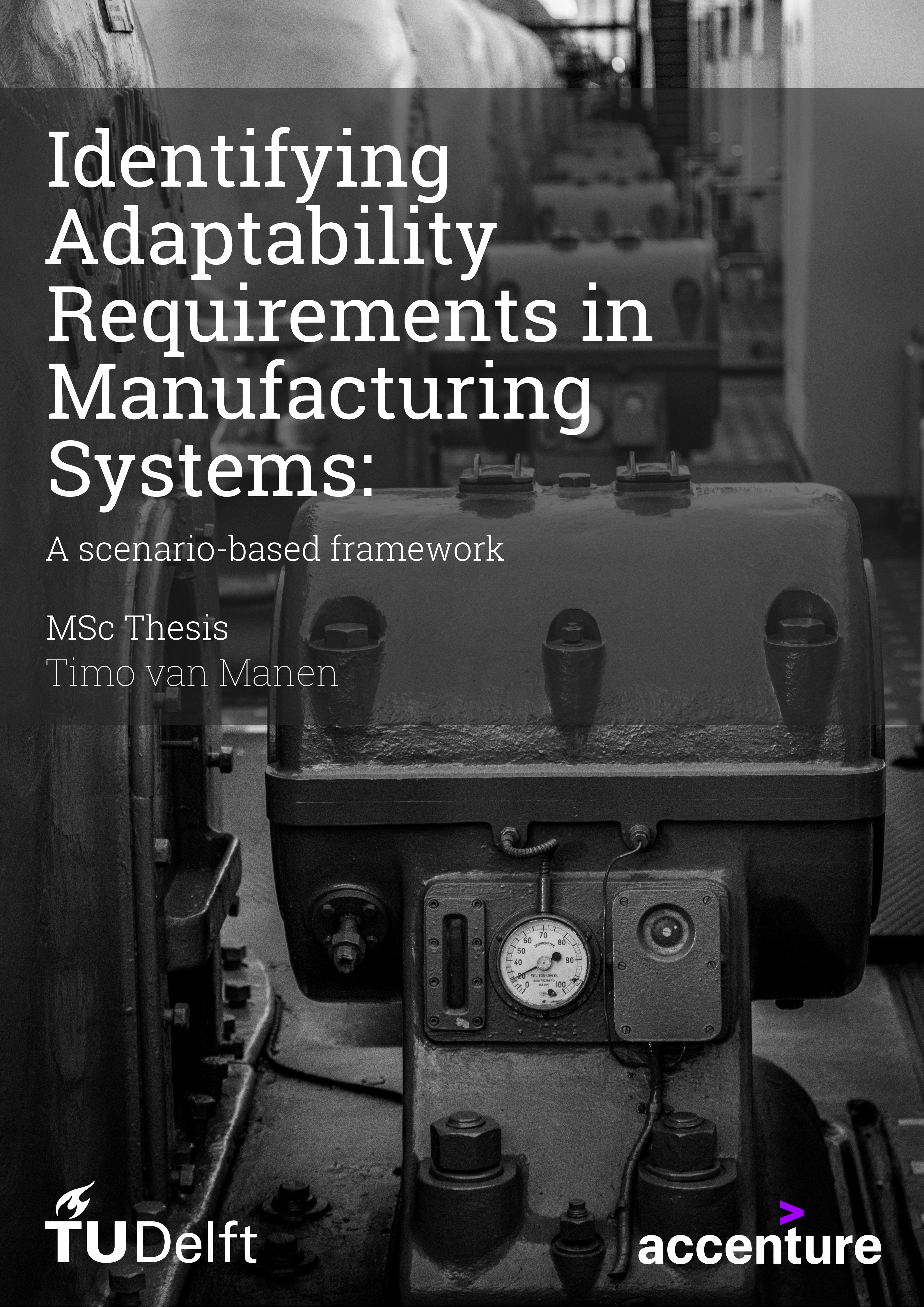

Identifying Adaptability Requirements in Manufacturing Systems:

A scenario-based framework

MSc Thesis
Timo van Manen

TU Delft

accenture

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A scenario-based framework

by

Timo van Manen

Student number:	4869494
Faculty:	Faculty of Civil Engineering and Geosciences
Msc track:	Transport, Infrastructure & Logistics
Specialization:	Logistic Systems
Date:	08/10/2025
Responsible supervisor:	Dr. A. Napoleone
Thesis committee:	
Dr.ir. M. Saeednia	Supervisor TU Delft
Dr.ir. X.L. Jiang	External supervisor TU Delft
Coen-Jan Smits	Supervisor Accenture

TU Delft

Abstract

Globalization, rapid technological progress, and growing product variety expose manufacturing systems to increasingly volatile and uncertain production requirements. To remain competitive, manufacturing systems must be able to adapt to these changes. A critical step towards achieving manufacturing adaptability is the identification of the required levels and types of adaptability. However, the literature lacks structured methodologies to support this process, limiting effective implementation in practice. This paper addresses this methodological gap by developing an integrated framework that unifies flexibility- and reconfigurability-oriented research streams. First, a new theoretical perspective on manufacturing adaptability is proposed, encompassing newly defined concepts and terminology. Building on this foundation, the study develops a methodological framework to support manufacturers in systematically identifying adaptability requirements. The proposed method employs a scenario-based approach to account for both expected volatility and uncertainty of predictions. The framework is applied in a case study in the food processing industry and subsequently evaluated through a series of expert interviews. Results indicate that the framework has the potential to facilitate structured requirement formulation and provides practical guidance for decision-making at both strategic and operational levels. This work contributes both theoretically, by advancing a unified perspective on manufacturing adaptability, and practically, by offering a tool to operationalize the identification of adaptability requirements.

Contents

Nomenclature

Abbreviation	Definition
AI	Artificial intelligence
B1	Branch 1 - Flexibility-oriented perspective
B2	Branch 2 - Reconfigurability-oriented perspective
CD	Change driver
DMS	Dedicated manufacturing system
EU	Environmental uncertainty
FFA	Free fatty acids
FMS	Flexible manufacturing system
IoT	Internet of things
PPR	Primary production requirements
PV	Production variable
RMS	Reconfigurable manufacturing system

1 Introduction

The manufacturing industry is facing increasingly complex market demands due to trends of mass customization, high product variety and market globalization (Weckenborg et al., 2024). In addition, rapidly emerging manufacturing technologies and accelerated product innovation cycles further increase the turbulence in relation to manufacturing processes (Spena et al., 2016). This volatile market environment tends to burden manufacturing systems with quickly changing production requirements that are often difficult to anticipate. To effectively account for these changing requirements, manufacturing systems need to possess a certain degree of adaptability. **Manufacturing adaptability** is in this thesis defined as the ability of a manufacturing system to adapt to changes in manufacturing requirements. **A manufacturing system** can be defined as an input-output transformation, employing human resources, machines, and equipment to convert input materials to products (Radford, 1984). While manufacturing systems by this definition can be distinguished at multiple hierarchical levels, this thesis generally refers to one or multiple connected production lines, bound by a common material and information flow.

Two main strategies to achieve adaptability in manufacturing systems can be distinguished: flexibility and reconfigurability. **Flexibility** is in this thesis defined as the capability of a system to accommodate changes in production requirements without altering its existing configuration. In contrast, **reconfigurability** refers to the system's ability to transition between different configurations. Flexibility and reconfigurability can be implemented simultaneously, together determining the level of adaptability of the manufacturing system. Flexibility and reconfigurability are considered mutually exclusive and collectively exhaustive in relation to manufacturing adaptability. The fundamental relationship between flexibility and reconfigurability is illustrated in Figure 1.1.

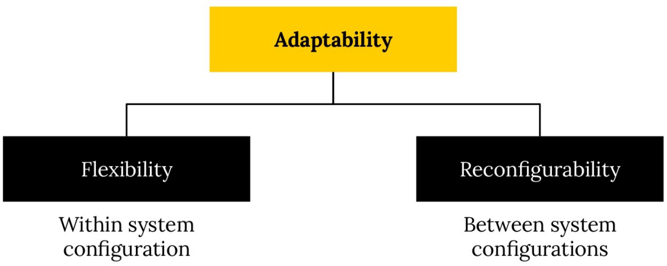

Figure 1.1: Relation between adaptability, flexibility and reconfigurability

While manufacturing adaptability is vital in manufacturing strategy, its implementation does not come without expenses. Both flexibility and reconfigurability need to be accounted for in the manufacturing system's design, often at high initial investment costs (Maganha et al., 2021). Moreover, flexibility often comes at the cost of reduced production efficiency or product quality (Pavel & Stamatescu, 2024). Similarly, performing reconfigurations in a manufacturing system results in downtime and a subsequent ramp-up period, negatively impacting productivity. As such, it is critical for manufacturers assess exactly how much adaptability is required to limit the negative trade-offs, while still ensuring that the continuously changing production requirements are met. If the system fails to meet the production requirmements due to a lack of adaptabiltiy, this can result in negative effects like lost revenue, fines, and dissatisfied customers. Figure 1.2 summarizes the risks of implementing too much or too little manufacturing adaptability.

Figure 1.2: The effects of possessing too much and too little manufacturing adaptability

It is widely acknowledged in the academic literature that a vital part of implementation process of manufacturing adaptability is the identification and formulation of adaptability requirements (Boyle, 2006; Cousens et al., 2009; Slack, 1988; Suarez et al., 1991). However, review of existing research found that methodologies to support manufacturers in identifying adaptability requirements remain limited. While the industry shows a strong interest in adaptable manufacturing (R. Andersen et al., 2024), the absence of structured frameworks for requirement generation hinders the implementation of adaptability, particularly reconfigurability, within manufacturing systems (Pansare et al., 2023). There is, therefore, an evident need for a practitioner-oriented method to support manufacturers in the identification of manufacturing adaptability requirements. To address this methodological gap, this thesis aims to develop a framework to assist manufacturers in the identification of adaptability requirements.

This research aims to contribute to the existing scientific literature in two ways. First, a new theoretical framework for manufacturing adaptability is proposed, integrating the flexibility-based and reconfigurability-based perspectives established in the literature into a unified adaptability-oriented perspective. This theoretical contribution introduces novel terminology and conceptual framing to the existing body of research. Second, based on this theoretical perspective, a methodological framework supporting manufacturers in identifying adaptability requirements is developed, thereby addressing the identified gap in the literature. This method is supplemented by a set of practical tools that facilitate its application.

1.1. Research questions

Due to increasingly volatile and uncertain production environments, manufacturing systems increasingly need to be adaptable. It is recognized throughout the literature that the identification of manufacturing adaptability requirements is a crucial step in the implementation of manufacturing adaptability and design of adaptable manufacturing systems. However, a methodological framework to assist manufacturers in the identification of said requirements is missing in the existing body of scientific research. The main research question this thesis aims to answer therefore becomes:

"How can a methodological framework to identify adaptability requirements for manufacturing systems be designed by integrating concepts from the existing scientific literature?"

The main research question is divided into 4 subquestions:

1) *What are the similarities and differences in concepts and terminology between the existing literature on identification of adaptability requirements from the perspective of flexibility and reconfigurability?*
2) *How can these perspectives from the existing literature be integrated into a new theoretical framework?*
3) *How can a methodological framework be constructed to identify adaptability requirements based on the proposed theoretical perspective?*
4) *How can the proposed methodological framework be illustrated and evaluated?*

The first research question investigates methods for identifying adaptability requirements, considering both flexibility and reconfigurability perspectives. It examines the structure and terminology employed in existing approaches, highlighting their commonalities and differences. The second research question builds upon the first by integrating the structure and linking the terminology between both bodies of literature. This results in an overarching perspective on the concept of adaptability and the identification of adaptability requirements. The third subquestion converts this new perspective to a more practice oriented methodology to identify adaptability requirements. The fourth research question aims to evaluate the proposed methodology to assess its usability. The relationship between the different subquestions is illustrated in Figure 1.3.

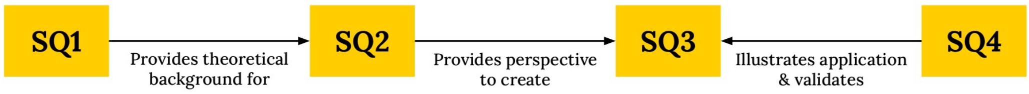

Figure 1.3: Supportive relationships among the research sub-questions

First, the methodology used to answer the subquestions is discussed in Chapter 2. After this, an analysis of the existing literature on this topic is presented in Chapter 3. Chapter 4 proposes a theoretical framework in relation to manufacturing adaptability. Chapter 5 details the methodological framework as designed during this research project. In Chapter 6, the application of the methodological framework is illustrated using a case study, while Chapter 7 presents the result of the evaluation of the framework. The limitations, further research and contribution of this research are discussed in Chapter 8. Ultimately, the main findings of this research are summarized in Chapter 9.

2 Methodology

As discussed in the introduction, the goal of this thesis is to provide a method, or methodological framework, to assist manufacturers in the identification of adaptability requirements in manufacturing systems. In order to develop such a framework, a process corresponding to the three-stage framework development process as described in McMeekin et al. (2020) was used. The three stages in this development process consist of: 1) Identify evidence to inform the methodological framework, 2) Develop the methodological framework, and 3) Evaluate and refine. Table 2.1 shows the research subquestions related to each of the development stages. The research design for each development stage is discussed seperately in this chapter.

SQ	Research subquestions	Development stage
1	What are the similarities and differences in concepts and terminology between the existing literature on identification of adaptability requirements from the perspective of flexibility and reconfigurability?	Identify evidence to inform (1)
2	How can the existing perspectives from the existing literature be integrated into a new theoretical framework?	Identify evidence to inform (1)
3	How can a methodological framework be constructed to identify adaptability requirements based on the proposed theoretical perspective?	Develop framework (2)
4	How can the proposed methodological framework be illustrated and evaluated?	Evaluate and refine (3)

Table 2.1: Research sub-questions in relation to the framework development stages

2.1. Identify evidence to inform the methodological framework

2.1.1. Narrative review

In order to identify evidence to inform the methodological framework, an initial narrative review of the literature was conducted. Narrative reviews aim to map the existing evidence on a research topic in a non-systematic manner (Demiris et al., 2019). The goal of this initial literature review was to create a broad overview of the literature on identification of adaptability requirements, as well as to recognize the main terminology used in this field.

For the purpose of finding relevant literature, the following search procedure was used: First, Google Scholar (scholar.google.com) and Scopus (scopus.com) were used to find a large number of articles potentially relevant to this research. A large diversity of search words related to "identification of adaptability requirements" were used to obtain a general overview of the existing literature. The key word "adaptability" was systematically substituted with "flexibility", "reconfigurability" and "changeability" to prevent exclusion of papers based on their definition of terms. In addition to the academic search engines, the AI tools Elicit (elicit.com), Connectedpapers (connectedpapers.com) and ChatGPT (ChatGPT.com) were used to find relevant literature. Papers with similar relevance were explored using the "cited by" function in Google Scholar. Of the large number of papers collected, the abstract, introduction, discussion and conclusion were read to determine their relevance. The papers that were considered to be relevant were scanned, but not thoroughly read, in order to get an overview of the papers contents.

As a result of the narrative review, two main perspectives were identified in the existing body of literature. Each perspective supports a different theoretical framework in relation to adaptability, using diverging concepts and terminology. The first, or flexibility-oriented, perspective frequently employs the term flexibility as a synonym for adaptability, without taking possible reconfigurations into account. Papers related to the first perspective aim to identify flexibility requirements, deriving these requirements from manufacturing strategy and environmental uncertainty as faced by the system. This perspective is in the remainder of this thesis referred to as **B1** (Branch 1). The second, reconfigurability-oriented, branch of papers tends to focus on reconfigurability requirements, basing these on internal and external CDs affecting the system. Requirements for reconfigurability and flexibility tend to be separated, often using the term changeability to refer to the combination of both. This perspective is in the remainder of the thesis referred to as **B2** (Branch 2). For each branch, the proposed identification methods can be generalized into a high level methodological framework, as shown in Figure 2.1.

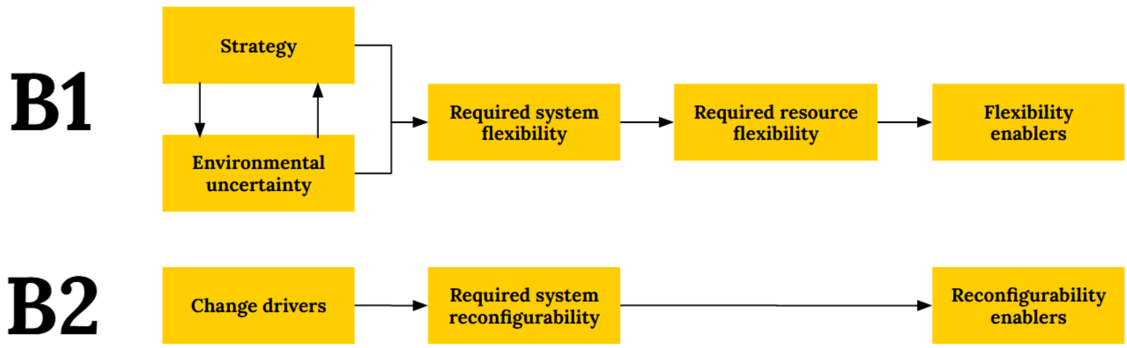

Figure 2.1: Approaches for identifying adaptability requirements as proposed in B1 & B2

2.1.2. Critical review

The structured overview of the literature that was obtained in the narrative review was subsequently used to shape a critical review. A critical literature review is used to provide an interpretative analysis of the literature, revealing important issues with respects to theories or research methods (Anderson et al., 2008). The aim of the review in this research was to thoroughly compare and analyze the methodological frameworks, concepts and terminologies from both perspectives, herein highlighting the main differences and commonalities. The perspectives were thematically compared, the areas of comparison area being based upon the methodological structure as identified in the initial review. The structure of this comparison is expanded upon in more detail in Section 3.2. As a result of the critical review, a new perspective was developed, synthesizing elements from both existing branches into a novel framework. This theoretical framework establishes the conceptual foundation upon which the methodological framework was be built.

In order to perform the critical review, ten scientific articles were selected for each perspective. These articles were selected from the body of literature used in the narrative review based on their representation of the perspective. In selecting the articles, care was taken to avoid including studies that were directly derived from one another with only minor variations in their frameworks, ensuring that each chosen work contributed genuinely new insights. The selected papers were thoroughly analyzed and compared, the results whereof are presented in Chapter 3. Figure 2.2 summarizes the applied methodology in the first framework development stages.

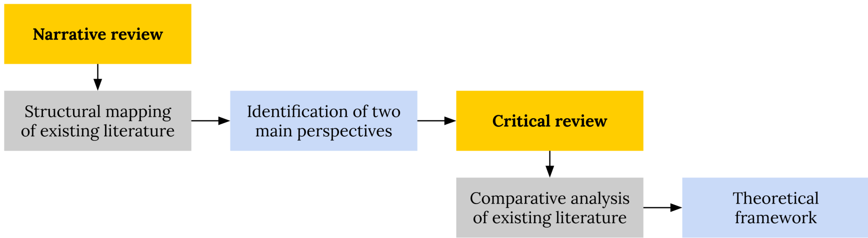

Figure 2.2: Research methodology as used in the first framework development stage

2.2. Developing the methodological framework

The methodological framework was developed using an exploratory case study approach, consistent with established methods of framework building from case studies as described in Yin Robert (2018). An initial concept of the methodological framework was developed based on the theoretical framework resulting from stage 1. Subsequently, this concept was tested on a case involving a factory processing cacao liquor. A general introduction of the case can be found in Section 6.1. The case study being explorative in nature, the pilot applications were used to constantly iterate upon the methodological framework. In this manner, the methodological framework was refined while accounting for practical application. Figure 2.3 shows the development process of the methodological framework in stage 2.

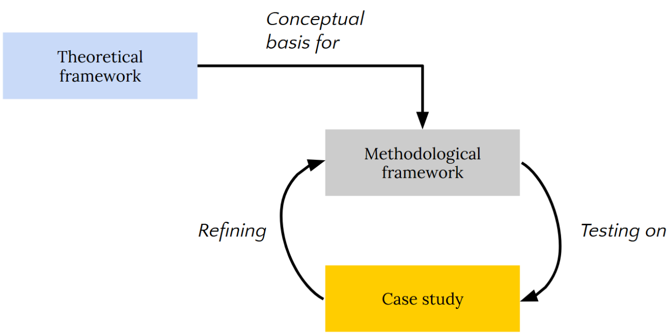

Figure 2.3: Research methodology as used in the second framework development stage

2.3. Evaluating and refining the methodological framework

Once the method had been fully developed, it was applied to the case system in a descriptive case study to demonstrate the framework in practice. The application of the descriptive case study is presented in Chapter 6. The case study served two purposes: to demonstrate the operation of the methodological framework and to evaluate its effectiveness. The evaluation of the framework was further supported by three semi-structured interviews with manufacturing industry experts. A semi-structured interview permits the interview to be focused while still giving freedom to explore ideas that come up during conversation (Adeoye-Olatunde & Olenik, 2021). As such, this approach is very suitable to implement for expert validation (Johansen & Fischer-Hübner, 2023). The interviews were structured to test three main elements: 1) Understanding, 2) Verification, and 3) Validation.

1) **Understanding**: In order to evaluate the methodological framework, it is vital ensure that the respondent understands the reasoning and its functioning. Otherwise, steps or concepts in the framework might be misinterpreted, leading to unreliable results. Therefore, the first part of the interview was dedicated to ensuring the interviewee possesses a proper understanding of the method to be evaluated. In case of unclarity, an additional explanation was provided.

2) **Verification:** During verification, the goal is to ensure that the method is designed and specified correctly, according to its own formal rules and theoretical foundation (Ralyté et al., 2025). In case of the framework as proposed in this paper, the goal is to assess whether the methodological framework correctly acts along the assumptions as stated in the theoretical framework. To ensure comprehensive verification of the method, a general overview was first discussed, focusing on the question: *Does the method correctly identify adaptability requirements in accordance with the theoretical framework?* Subsequently, each methodological phase was examined individually, with particular attention to the question: *Is the phase defined and specified correctly?*
3) **Validation:** In the validation of a method, the aim is to ensure that its procedures and results are correct and valid in real-world context (Ralyté et al., 2025). During the interviews, the main focus point was to assess the practical usability of the methodological framework in industrial context. The discussion was mainly structured around two questions: *1) Can the methodological feasibly be applied in real-word context?*, and 2) *Can application of the framework to real-life situations provide valuable insights for decision-makers in manufacturing companies?*

Finally, general questions were asked about the strengths and weaknesses of the method, as well as any potential improvements the respondent envisioned. The main findings from both case study and expert interviews are discussed in Chapter 7. Figure 2.4 summarizes the third framework development stage.

Figure 2.4: Research methodology as used in the third framework application stage

2.4. Conclusion

In this chapter, the methodology used to answer the main research question was outlined. A three-stage development process was used in this research. First, existing literature was analyzed and compared to create a new theoretical framework. Using the theoretical framework as a foundation, a methodological framework was designed. Finally, the proposed methodological framework was evaluated and refined using a case study and expert interviews. The methodology used to answer each research subquestion is summarized in Table 2.2. Additionally, the chapter in which the subquestion is addressed is indicated.

Subquestion	Methodology	Chapter
Subquestion 1	Narrative literature review Critical literature review	Chapter 3
Subquestion 2	Critical literature review Conceptual synthesis	Chapter 4
Subquestion 3	Explorative case study Framework development	Chapter 5 Chapter 6
Subquestion 4	Expert interviews Descriptive case study	Chapter 7 Chapter 6

Table 2.2: Overview of methodologies and corresponding chapters.

3

Literature Review

In this section, the existing literature on identification of manufacturing adaptability requirements or closely related topics is discussed. The analysis of the current body of research applied in this thesis consists of two stages. In the initial stage, a narrative review was conducted in order to create an overview of the current body of research. A number of research gaps were identified in the available evidence. One of the identified gaps was subsequently selected as the focus of this thesis. Two main perspectives (B1 & B2) were observed, both taking different approaches towards identification of adaptability requirements. Subsequently, a critical review was performed on the literature comprising these branches, resulting in a in-depth comparison of perspectives. The results from both reviews as shown in Figure 3.1 are discussed sequentially in this chapter. More information on the manner on the methodological design of the literature review can be found in Chapter 2.

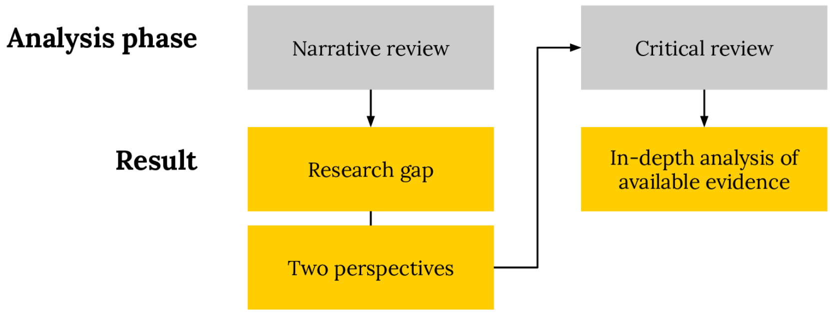

Figure 3.1: Overview of the stages in the literature review

3.1. Narrative review

The narrative review as performed in this thesis resulted in the identification of two main perspectives towards manufacturing adaptability in the published research. While both perspectives offer a high-level framework for identification of adaptability requirements, these frameworks reflect diversities in terminology and conceptual framing. These differences mainly stem from the articles being rooted in different manufacturing system paradigms. A concise background on the manufacturing system paradigms as encountered in the literature is provided in the section down below.

3.1.1. Manufacturing system paradigms

At the beginning of the 20th century, Dedicated Manufacturing Systems (DMSs), together with mass manufacturing, arose as the dominant paradigm for manufacturing systems (Jovane et al., 2003). DMSs aim to optimize production efficiency using task specialization, standardized components and fixed

production sequences. DMSs are optimized to produce a single type of product at maximum efficiency, often by using tools and equipment specifically designed or the task. The high throughput and relatively low cost of DMSs results in a low cost per part if operating at full capacity. However, due to the shortening life cycle of products and market diversification, DSM became too rigid in a lot of cases, prompting the need for more adaptive systems (Handfield & Pagell, 1995).
As a reaction to this need, the paradigm of Flexible Manufacturing Systems (FMSs) arose in the eighties (Elmaraghy, 2006). Where DMSs are specifically designed to produce one product or very small product family, FMSs enable production of a wide range of parts without extensive manual intervention. This is enabled by the deployment of general-purpose machines that are able to handle and produce a large range of products. As a consequence, FMSs are more robust towards environmental changes, but this comes at the cost of high initial investments (Elmaraghy, 2006). The high investment cost in combination with the typically low throughput often results in a high manufacturing cost per product (Koren et al., 1999).
In an attempt to combine the benefits of DMS and FMS, the paradigm of Reconfigurable Manufacturing Systems (RMS) was introduced by Koren (Koren et al., 1999). RMSs are characterized by their modularity and integrated control structure, enabling reconfiguration of both machines and system structure. While FMSs offer a predefined flexibility, the flexibility of RMSs can be adjusted according to the situation, resulting in customized flexibility. Presently, a large body of literature on RMS has accumulated, exploring research areas such as configuration design and production planning. Although the literature on RMSs is extensive, actual industry implementation of remains limited to date (Pansare et al., 2023).

The first perspective as identified in the literature (B1) stems from the paradigm of FMS and thus frequently employs the term flexibility as a synonym for adaptability, disregarding reconfigurability as a system characteristic. The identification of adaptability requirements is typically regarded as a step in the implementation of manufacturing flexibility. The second perspective (B2) stems from the paradigm of RMS and does distinguish between flexibility and reconfigurability, often using the term "changeability" to refer to a combination of both. The identification of adaptability requirements here is typically incorporated in frameworks for the design of reconfigurable or changeable manufacturing systems.

3.1.2. B1 - Flexibility

From the studies adopting the B1 perspective, a common structure for identifying adaptability requirements can be derived. This structure consists of two main stages that are largely consistent across existing frameworks(see Figure 3.2). In the first stage, the required system flexibility is determined by two factors: a strategic component defined by the company, and the environmental uncertainty encountered by the manufacturing system. The system flexibility is used to indicate aggregate types of flexibility that describe the performance of the system as a whole. In the second stage, the required flexibility of the system is converted into resource flexibility requirements. Resource flexibility are internal flexibility types that enable flexibility on a system level. The required resource flexibility types are typically linked to operational flexibility enablers, which are left out of scope for this review.

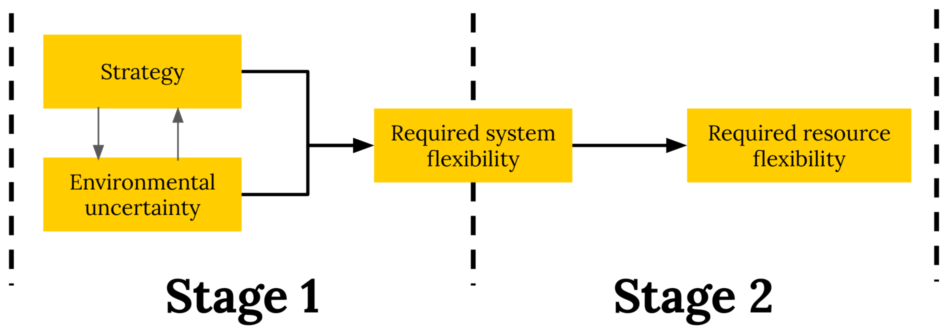

Figure 3.2: General structure of the B1 approach for identifying adaptability requirements

The exact steps to be taken and terminology used in each of the frameworks differ slightly, but the general structure remains the same. The approaches to typically follow a top-down approach, in which the required flexibility is determined based on the competitive or manufacturing strategy.

3.1.3. B2 – Reconfigurability/Changeability

In the same way, a common structure can be derived for papers employing the B2 perspective. In the first stage, required reconfigurability and flexibility are identified on a system level based on change drivers (CDs) affecting the manufacturing system. Reconfigurability and flexibility requirements are typically differentiated according to whether the underlying CDs act over a short- or long-term time frame. B2 tends to focus more on the reconfigurability, in stage 2 identifying the reconfigurability characteristics required to support the changeability requirements. Reconfigurability characteristics are specific properties of a system that enable the system to adapt to changing system requirements (Koren et al., 1999).

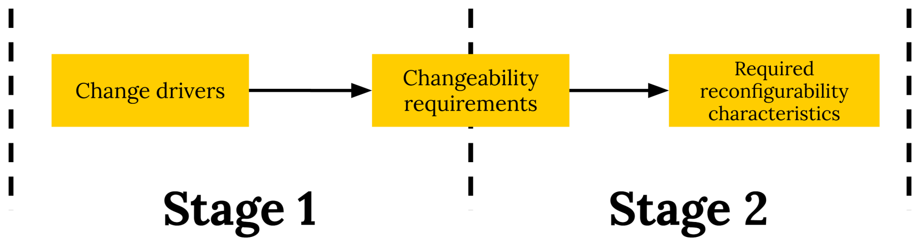

Figure 3.3: General structure of the B2 approach for identifying adaptability requirements

3.1.4. Research gap

As explained in Chapter 1, manufacturing systems need to be increasingly adaptable due to volatile and uncertain production environments. The identification of adaptability requirements is a crucial step in the implementation and design of adaptable manufacturing systems. Although this identification process is acknowledged within broader frameworks, the narrative review revealed a lack of practical methods to carry it out.

Scholarly publications taking the flexibility perspective (B1) often mention the identification of adaptability requirements as a step in a larger framework to implement manufacturing flexibility (Boyle, 2006; Narain et al., 2000; Slack, 1988; Suarez et al., 1991). However, no practical approaches are presented. Mishra et al. (2014) and Gerwin (1993) describe links between sources of environmental uncertainty and required types of flexibility to cope with these, but do not mention how these requirements should be formulated.Narain et al. (2000) suggests utilizing a quantitative alternative by articulating requirements based on range and response of mix and volume flexibility, but do not specify how this should be performed.

Academic literature adopting the reconfigurability/changeability perspective (B2) often mention the requirement generation as a step in the development of reconfigurable or changeable manufacturing systems (R. Andersen et al., 2024; Deif & ElMaraghy, 2006; Heisel & Meitzner, 2006; Rösiö, 2012). A number of methods to generate requirements are mentioned. Methods such as brainstorming or scenario generation have been proposed, yet the literature provides little guidance on how these should be implemented in practice (Tracht & Hogreve, 2012). Schou et al. (2020) and Kjeldgaard et al. (2023) describe a method in which required adaptability of the system is based on expected changes in the product design. However, this method focuses solely on adaptations arising from product variant changes and does not offer a means to identify projections of such changes. Some papers such as Rösiö (2012), A. L. Andersen, ElMaraghy, et al. (2018) and A.-L. ; Andersen et al. (2023) do propose questionnaires to identify required levels of reconfigurability or changeability. While these questionnaires certainly provide practical guidance to manufacturers, the requirements are expressed in generalized levels of change and related reconfigurability characteristics. While these requirements provide a general overview of the necessary level of adaptability, they often lack the specificity needed to effectively support decision-making in manufacturing systems. In conclusion, the literature lacks a structured methodology for formulating the full range of adaptability requirements in a manner that provides practical support for decision-making in manufacturing systems.

3.2. Critical review

As explained in Chapter 2, ten scientific articles representing each perspective were selected for the critical review. The papers that were selected for analysis are shown in Table 3.1 and Table 3.2 for B1 and B2 respectively.

Author	**Title**
Vokurka and O'Leary-Kelly (2000)	A review of empirical research on manufacturing flexibility
Boyle (2006)	Towards best management practices for implementing manufacturing flexibility
Slack (1988)	Manufacturing systems flexibility – an assessment procedure
Suarez et al. (1991)	Flexibility and performance: A literature critique and strategic framework
Gerwin (1993)	Manufacturing flexibility: A strategic perspective
Nilsson and Nordahl (1995a) & Nilsson and Nordahl (1995b)	Making manufacturing flexibility operational – part 1: A framework & - part 2: Distinctions and an example
Narain et al. (2000)	The strategic implications of flexibility in manufacturing systems
Mishra et al. (2014)	Assessment of manufacturing flexibility: A review of research and conceptual framework
Olhager and West (2002)	The house of flexibility: Using the QFD approach to deploy manufacturing flexibility
Cousens et al. (2009)	A process for managing manufacturing flexibility

Table 3.1: The B1 papers selected for the critical literature review

Author(s) & Year	Title
Rösiö (2012)	Supporting the design of reconfigurable production systems
A.-L. ; Andersen et al. (2023)	Paving the way for changeable and reconfigurable production: Fundamental principles, development method & examples
Tracht and Hogreve (2012)	Decision making during design and reconfiguration of modular assembly lines
Deif and ElMaraghy (2006)	A systematic design approach for reconfigurable manufacturing systems
Heisel and Meitzner (2006)	Progress in reconfigurable manufacturing systems
Schuh et al. (2009)	Design for changeability
Francalanza et al. (2014)	Deriving a systematic approach to changeable manufacturing system design
R. Andersen et al. (2024)	A systematic methodology for changeable and reconfigurable manufacturing systems development
Dit Eynaud et al. (2019)	Identification of reconfigurability enablers and weighting of reconfigurability characteristics based on a case study
Benkamoun et al. (2015)	An intelligent design environment for changeability management – application to manufacturing systems

Table 3.2: The B2 papers selected for the critical literature review

The critical review is structured thematically in three sections, corresponding to the framework structure as identified in the narrative review (see Figure 3.4). First, the nature of manufacturing adaptability is covered. Second, the origins of the need for manufacturing adaptability are addressed. Third, the manner of formulation for adaptability requirements is analyzed.

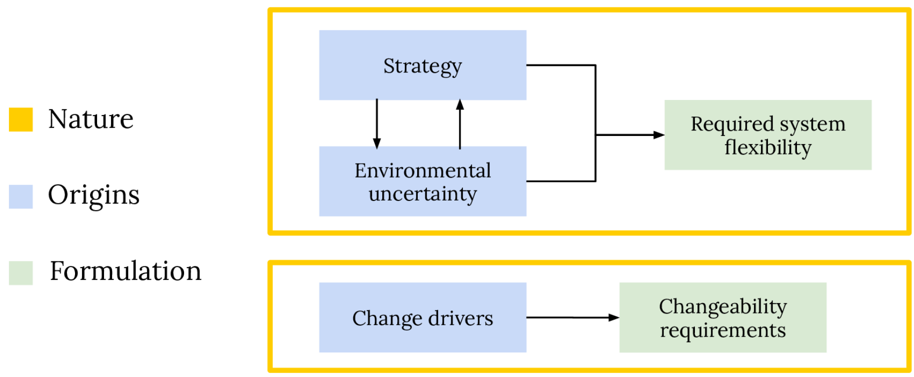

Figure 3.4: Thematic areas of comparison for the critical review

3.2.1. The nature of manufacturing adaptability

Both B1 and B2 do not directly use the term adaptability, or for that matter refer to the identification of adaptability requirements. Papers in B1 commonly use the term *"flexibility"*, while the papers in B2 tend to use *"reconfigurability"*, *"flexibility"*, and *"changeability"*.

It is important to realize that flexibility is not inherently different from adaptability. Flexibility is a subset, or strategy by which adaptability can be achieved. In this thesis, manufacturing flexibility and reconfigurability are considered collectively exhaustive in relation to manufacturing adaptability. Since the literature in B1 does not explicitly address the possibility of reconfiguration, or at least does not see it as conceptually separated from flexibility, flexibility is effectively treated as equivalent to adaptability. Therefore, the frameworks in B1 that focus on identifying flexibility requirements can be interpreted as addressing adaptability requirements, though within a more specific scope of interest.

Papers in B2 often employ the term *"changeability"* as an umbrella concept that covers both flexibility and reconfigurability. In the context of B2, changeability is closely aligned with the notion of adaptability as defined in this paper. However, in other literature, changeability is sometimes extended to include broader, more strategic concepts such as *"transformability"* and *"agility"* (Wiendahl et al., 2007). By contrast, the definition of adaptability adopted here is limited to the direct combination of flexibility and reconfigurability.

Although the terminological differences between the two branches are evident, the distinctions in meaning remain ambiguous. The distinction between flexibility and reconfigurability is not well-defined in the existing body of literature. Flexibility is often associated with phrases like "fast adaptation" and "narrow corridor of change", while reconfigurability is linked to expressions such as "structural changes" and "tactical adaptation" (Azab et al., 2013; Napoleone et al., 2021, 2022). ElMaraghy and Wiendahl (2009) seems to hint at a distinction based on whether physical changes are made to the system. If an adaptation requires physical intervention, it is classified as a reconfiguration. If not, it is considered to remain within the realm of flexibility. However, this distinction is not made explicit, and the notion of non-physical reconfiguration is occasionally mentioned. Napoleone et al. (2021) specifies the distinction between flexibility and reconfigurability to rely on the timing, cost and number of steps necessary to implement modifications. According to Napoleone et al. (2022), flexibility is suitable for addressing shorter-term requirements, while reconfigurability is more appropriate for coping with long-term changes.

Similarly, the distinction between reconfiguring and completely restructuring a manufacturing system remains vague. Mehrabi et al. (2000) defines reconfigurability as "the ability of a system to adjust its production resources by rearranging or changing components quickly and economically in response to new products or volume changes". Dissecting this definition, reconfigurability is to be enabled by "rearranging or changing components". This seems to be generally supported in the literature with other sources defining reconfigurability based on the ability of a manufacturing system to "modify or rearrange its structure or components" (A. L. Andersen, Larsen, et al., 2018).

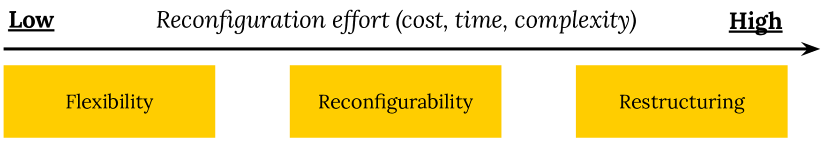

Figure 3.5: Reconfiguration effort for different adaptation strategies

3.2.2. Origins of the need for manufacturing adaptability

This section aims to compare and relate the perspectives from B1 and B2 concerning the perceived origins of the need for adaptability. First, the theoretical perspective of B1 towards this topic is elaborated upon, after which the same is done for B2. Subsequently, an attempt to compare and related both perspectives is made.

B1 - Enviromental uncertainty & Manufacturing strategy

In B1, most frameworks analyzed agree on the fact that the required system flexibility is determined by **1) environmental uncertainty** and **2) the strategic role of flexibility**. The manufacturing strategy is defined in an interplay by the competitive strategy of the company and environmental uncertainty as faced by the system (Boyle, 2006; Cousens et al., 2009). In turn, the manufacturing strategy determines how the system is to cope with this environmental uncertainty. Uncertainty can even be reduced by changing the manufacturing strategy, thereby also reducing the required level of flexibility. As such, these elements are in most frameworks assumed to be interdependent and should always be considered in relation to each other. The environmental uncertainty as faced by the system and manufacturing strategy that is chosen to cope with this uncertainty define the level of flexibility that is needed in the system. If interpreted with a focus on the consumer side, such as in Nilsson and Nordahl (1995a), system flexibility is seen as required to change the system requirements with the market in accordance with the chosen manufacturing strategy.

Environmental uncertainty
Environmental uncertainty (EU) can be defined as the unpredictability in factors that influence manufacturing operations (Moin et al., 2022). However, EU is often ill-defined throughout the frameworks and consists of different classifications. EU can be regarded from two perspectives: The marketing function and the manufacturing function (Narain et al., 2000). Uncertainty in relation to the marketing function (**external uncertainty**) describes dynamic market change, caused by factors external to the production process. On the other hand, uncertainty related to the manufacturing function (**internal uncertainty**) originates from the manufacturing resources and production management system. Table 3.3 lists sources of environmental uncertainty related to the marketing function (external) and to the manufacturing function (internal) as gathered by combining the results from Mishra et al. (2014) and Moin et al. (2022).

Sources of external uncertainty	**Sources of internal uncertainty**
Competitors	Machine downtime
Consumers	Material characteristics
Technology	Departmental coordination
Economic policies	Resource acquisition and distributor problems
Product market and demand	Queuing delays
Customization	Material shortages
Short delivery time	Variable task times
Society	Rejects & reworks
Uncertain regulations	Manpower change

Table 3.3: Sources of internal and external uncertainty as gathered from Mishra et al. (2014) and Moin et al. (2022)

The focus with regard to uncertainty seems to be on the manufacturing function in most frameworks, such as Nilsson and Nordahl (1995a) and Cousens et al. (2009). Nilsson and Nordahl (1995a) argue that the dynamics of the market are described by changing of qualifying- and order winning criteria. They state that foreseeing these changes should be based on analysis of trends and events rather than subjective assessment by company managers, but do not further detail how this should be performed. Opposite to the "internal realm" in Suarez et al. (1991) is the "external realm". The external realm includes four factors: demand characteristics, competitor behavior, stage in product life cycle, and end-product characteristics. As these factors fall into the external realm, they are subject to environmental uncertainty. Slack (1988) does not use the term environmental uncertainty, but refers to changes in the environment as determinants for the required flexibility. Specifically, Slack states that the likelihood and predictability of environmental changes are the major determinants of the range and response characteristics as required by the manufacturing system. Interestingly, the paper also names possible changes in competitive strategy as a cause for flexibility need. Some papers such as Cousens et al. (2009), Mishra et al. (2014), Olhager and West (2002) and Slack (1988) do not use the term uncertainty, but directly refer to projections of the future environmental conditions the company might face. For example, Olhager and West (2002) base the non-strategic component purely on the needs of the customer.

The literature distinguishes different types of EU. Table 3.4 lists a number of EU types as gathered from the literature by Moin et al. (2022). Especially the first three types (Demand uncertainty, Supplier uncertainty, Technology uncertainty) are widely recognized in the literature.

N	Type of environmental uncertainty
1	Supplier uncertainty
2	Demand uncertainty
3	Technological uncertainty
4	Internal uncertainty
5	Competitor uncertainty
6	Customer uncertainty
7	Financial resource endeavor
8	Sourcing uncertainty
9	Government regulations
10	Macroeconomic fluctuation
11	Macro-environment uncertainty
12	Delivery uncertainty
13	Commercial uncertainty
14	Earnings uncertainty

Table 3.4: EU types used in the literature as adopted from Moin et al. (2022)

The role of flexibility in manufacturing strategy
According to the B1 papers, the required flexibility is not only determined by the environmental uncertainty, but also by the role of flexibility in the manufacturing strategy. Flexibility can proactively be used as a strategic asset to ensure shorter lead times and frequent product introductions, thereby claiming a competitive advantage. In this way, flexibility can become part of the competitive strategy of a company, exceeding the flexibility as required by the market.

The influential paper by Gerwin (1993) distinguishes four generic strategies towards flexibility in manufacturing:

- **Adaptation:** Flexibility is considered as a reactive mechanism to accommodate environmental uncertainty. This is the most traditionally recognized approach, both in scientific literature as in industrial application. When utilizing this strategy, the required level of flexibility requirements are directly dependent on the environmental uncertainty as faced by the system.
- **Redefinition:** Flexibility is regarded as a strategic lever for reshaping the extent of environmental uncertainty present in the market. The idea is to redefine industry norms and customer expectations through accelerating product cycles and shorter lead times. Redefinition requires a high level of manufacturing flexibility, providing room for redefining environmental uncertainty.
- **Banking:** Flexibility is considered a capability that should be accumulated to prevent problems during future contingencies, or to later enable strategic repositioning. As such, the banked flexibility can both be used reactively or proactively. Implementing a banking strategy entails investing in things like surge capacity or reserve equipment, thereby also increasing cost. Banking requires a high level of flexibility, exceeding the flexibility as required to cope with current environmental uncertainty.
- **Reduction:** This strategy focuses on reducing the need for flexibility by reducing sources of environmental uncertainty. Actions to be performed in a reduction strategy include pursuing long-term supplier contracts or performing preventive maintenance. Flexibility is still regarded as a reactive mechanism, but the focus is now on the environmental uncertainty itself.

A general indication of the level of flexibility required for each strategy for the same initial uncertainty is provided in Table 3.5.

Strategy	Strategic posture	Required level of flexibility
Adaptation	Defensive	Medium
Redefinition	Proactive	High
Banking	Defensive / Proactive	High
Reduction	Proactive	Low

Table 3.5: Summary of the four generic strategies as proposed by Gerwin (1993)

While most papers take the manufacturing strategy as a starting point, Boyle (2006) and Narain et al. (2000) start with determining the competitive strategy first. Narain et al. (2000) even suggest the use of a SWOT analysis in establishing this competitive strategy. The manufacturing strategy is subsequently derived from the competitive strategy. The manufacturing strategy is argued to be highly influenced by the uncertainty as faced by the system, and vice versa. As such, these elements of the frameworks are interdependent and should not be considered separate. Vokurka and O'Leary-Kelly (2000) does not explicitly make a distinction between competitive and manufacturing strategy, but simply states that there is a strategic component. Mishra et al. (2014) simply refers to "the role of flexibility in manufacturing". This role of flexibility in manufacturing is defined in terms of dependability, availability and productivity in the paper by Slack (1988). Suarez et al. (1991) refers to the strategic component as the "internal realm" of the "need factors" and only considers strategy in relation to the products to be produced, not addressing other strategic applications of flexibility. In addition to the manufacturing strategy, Narain et al. (2000) also takes the marketing strategy into account.

A comparison of both environmental uncertainty and the strategic components as adopted by the analyzed papers in B1 can be found in Table 3.6.

Paper	Environmental uncertainty types	Strategic component
Boyle (2006)	Current uncertainty Expected uncertainty	Competitive strategy Manufacturing strategy
Cousens et al. (2009)	Unpredictability of production output Predicted range of mix/volume	Manufacturing strategy
Gerwin (1993)	Classification on nature of uncertainty	Manufacturing strategy
Mishra et al. (2014)	Internal & external uncertainty types	-
Narain et al. (2000)	Internal & external uncertainty	Competitive strategy Manufacturing strategy Marketing strategy
Nilsson and Nordahl (1995a) & Nilsson and Nordahl (1995b)	Changing quality- and order winning criteria	Manufacturing strategy
Olhager and West (2002)	Customer needs and expectations	Manufacturing strategy
Slack (1988)	Likelihood and predictability of changes in competitive stance and environment	Manufacturing strategy
Suarez et al. (1991)	Demand characteristics Competitor behavior Product life cycle End-product characteristics	Product strategy
Vokurka and O'Leary-Kelly (2000)	Perceived uncertainty	Strategy

Table 3.6: Comparison of strategic and environmental uncertainty components across analyzed papers in B1.

B2 - Change drivers

Instead of environmental uncertainty, papers in B2 often attribute the need for adaptability to CDs, generally regarding the identification of CDs as the first step in the identification of adaptability requirements (A. L. Andersen, ElMaraghy, et al., 2018; A.-L. ; Andersen et al., 2023; Rösiö, 2012; Schuh et al., 2009).

In the context of adaptable manufacturing, a CD can be defined as any factor that will cause or require changes in the production system (A.-L. ; Andersen et al., 2023). Exact definitions vary throughout the literature but tend to refer to the same on a conceptual level. A CD does not directly cause a change in a manufacturing system; rather, it is the *change of the CD* that triggers the system's transformation. For example, the it is not the dimensions of a output product that require a manufacturing system to adapt, rather it is the *change in product dimensions* that induces need for transformation. CDs are characteristic of a specific manufacturing situation and can therefore not be generalized over different systems (Schuh et al., 2009). Similarly to EU, CDs can be characterized into internal and external categories (Azab et al., 2013). External CDs are outside of the direct influence of the company, while internal CDs are designed by actions of the manufacturing company itself.

Different types of CDs are recognized throughout the literature. **Strategy-related drivers** are internal change factors that stem from the company's own manufacturing strategy. **Product-related drivers** arise from changes in the product portfolio, whether through the introduction of new products or variations in existing ones. **Volume-related drivers** reflect shifts in production volumes for specific product types. **Technology-related drivers** are triggered by the introduction or availability of new production technologies, having the potential to impact the production process.

R. Andersen et al. (2024), A.-L. ; Andersen et al. (2023), and Tracht and Hogreve (2012) classify CDs into variant changes, volume changes, and product changes. These classes are directly linked to short-, mid- and long-term time horizons respectively. Not all analyzed papers use the term CDs, however, other terms referring to expected changes are at the base of every approach. Heisel and Meitzner (2006) uses trends in product development and expected variability in structure and output, Deif and ElMaraghy (2006) market demand profiles and Al-Zaher et al. (2013) bases requirements on engineering changes. Francalanza et al. (2014) and Dit Eynaud et al. (2019) skip over the drivers of change and directly looks at the change in general system requirements that are to be expected. Interestingly, Dit Eynaud et al. (2019) specifically indicates to take historical system requirements into account as well. Table 3.7 summarizes the CD classifications as used throughout the analyzed papers in B2.

Author	CD classification
A.-L. ; Andersen et al. (2023)	Variant changes (short-term) Volume changes (mid-term) Product changes (long-term)
Benkamoun et al. (2015)	Product change Process change Technology or standard change Environment change Strategic change
Deif and ElMaraghy (2006)	Market demand
Dit Eynaud et al. (2019)	Changes in general system requirements
Francalanza et al. (2014)	Changes in general system requirements
Heisel and Meitzner (2006)	Trends in product development Variabilitiy of structure and output
R. Andersen et al. (2024)	Variant changes (short-term) Volume changes (mid-term) Product changes (long-term)
Rösiö (2012)	Product-related drivers Volume-related drivers Technology-related drivers Strategy-related drivers
Schuh et al. (2009)	Product-related drivers Volume-related drivers Technology-related drivers
Tracht and Hogreve (2012)	Variant changes (short-term) Volume changes (mid-term) Product changes (long-term)

Table 3.7: Comparison of CD classifications in the analyzed papers in B2.

Comparing B1 & B2

In this section, the author aims to compare and relate the perspectives from B1 and B2 as explored in this chapter previously. Where B1 employs the term environmental uncertainty (EU), B2 attributes the need for adaptability to CDs. B1 generally takes the role of adaptability in the manufacturing into account, while B2 does not explicitly consider such a dimension. First, the relationship between environmental uncertainty and CDs is examined. Next, the role of adaptability in the manufacturing strategy is compared between both branches.

Change drivers and environmental uncertainty

According to the definitions in the literature environmental uncertainty refers to the unpredictability in factors that influence the manufacturing system (Moin et al., 2022), while CDs refers to any factor that causes change in the same system (A.-L. ; Andersen et al., 2023). As such EU could be interpreted as the unpredictability in CDs affecting the system.

The key distinction between B1 and B2 lies in how required adaptability is determined: in B1, it depends on the extent of expected change in the CD, whereas in B2, it depends on the degree of uncertainty in the CD's projection. This distinction is visualized in Figure 3.6. However, the uncertainty of a CD cannot be completely regarded as separate from its expected changes. Extensive expected change amounts to a highly dynamic environment and a high corresponding level of uncertainty. Nevertheless, it is important to note that a high coefficient of variation in future events or trends does not necessarily mean they are unpredictable. What matters for uncertainty is the deviation from what is expected, not the overall range or scale of the events or trends.

In the literature, both CD and EU are categorized into internal and external types. Nonetheless, the basis for this classification differs significantly between the two concepts. In the case of EU, the difference is based on whether the origin of the uncertainty is within the manufacturing process. For CD, the

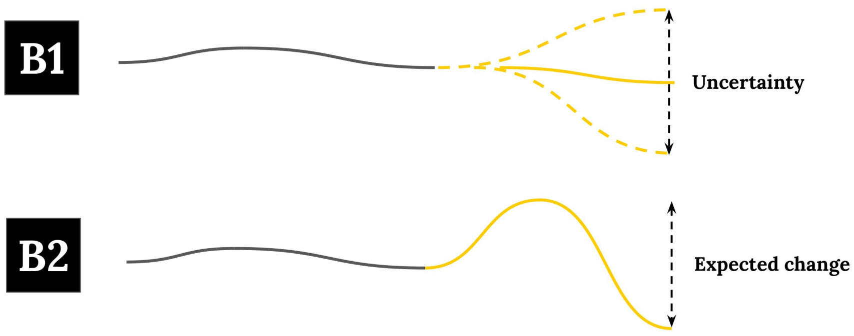

Figure 3.6: Factors driving the need for adaptability as approached by B1 & B2

difference is based on whether the driver is within or outside the direct control of the manufacturing firm. As such, the internal and external dimension of these concepts can not directly be compared. As the EU describes uncertainty originating from a CD, the sources of EU as listed in Table 3.3 can directly be compared to the classes of CDs in **??**. Table 3.8 relates the sources of EU to the CD categories. As the granularity of categorization in Table 3.3 matches best to the classifications by Karl and Reinhart (2015) and Hingst et al. (2021), these are used for comparison.

Sources of EU (adopted from Figure 3.3)	CD categories
External	
Competitors	Global organization (Hingst et al., 2021)
Consumers	Market demands (Karl & Reinhart, 2015), New markets and consumer patterns (Hingst et al., 2021)
Technology	Production technology (Karl & Reinhart, 2015), Product & Technology cycles (Hingst et al., 2021)
Economic policies	Economy (Karl & Reinhart, 2015), Legal environment (Hingst et al., 2021)
Product market and demand	Market demands (Karl & Reinhart, 2015), New markets and consumer patterns
Customization	Product design (Karl & Reinhart, 2015), New markets and consumer patterns (Hingst et al., 2021)
Short delivery time	Market demands (Karl & Reinhart, 2015), New markets and consumer patterns
Society	Social/political factors (Karl & Reinhart, 2015), Environment and social impact (Hingst et al., 2021)
Uncertain regulations	Social/political factors (Karl & Reinhart, 2015), Legal environment (Hingst et al., 2021)
Internal	
Machine downtime	-
Material characteristics	-
Departmental coordination	Methods of organization (Karl & Reinhart, 2015)
Resource acquisition and distributor problems	Global organization (Hingst et al., 2021)
Variable task times	-
Rejects & reworks	-
Manpower change	Human resources (Karl & Reinhart, 2015), Working environment (Hingst et al., 2021)

Table 3.8: Comparing EU sources to CD categories

Table 3.8 shows the internal sources of EU to be easily classifiable under the CD categories. In contrast, he external sources of EU are less easily matched. The EU sources and corresponding CD classifications in the table were selectively chosen and may not fully represent all possible categorizations. However, the table is illustrative of a general pattern: B2 tends to emphasize CDs external to the internal production process, while B1 also accounts for internal production-related factors.

The role of adaptability in manufacturing strategy
Although adaptability is frequently addressed in the context of manufacturing strategy within B1, it appears to be largely absent from the discussions in B2. However, if interpreting the role of flexibility to B2, the same four strategies as discussed in Section 3.2.2 can be distinguished in relation to CDs. It is important to recognize that implementing a proactive strategy in regards to manufacturing adaptability is only possible when the CDs concerned are internal. External CD by definition are outside the direct influence of the manufacturing company and can thus not be adjusted to create a competitive advantage in a strategy of redefinition. Similarly, a reduction policy is difficult to apply since the CD can not be mitigated at will. Of course, when considering external CD able to be indirectly influenced rather than directly, it is possible to use them in proactive strategies. Naturally, when external CDs can be indirectly influenced rather than directly controlled, they may still be incorporated into proactive strategies.
Most frameworks in B2 seem to inherently assume a strategy of adaptation, which may explain why

strategic application of adaptability is seldom discussed. Nevertheless, the role of adaptability in manufacturing strategy remains an crucial element when evaluating adaptability requirements for manufacturing systems.

Conclusion
In this section, the perspectives of B1 and B2 towards the origins of the need for adaptability in manufacturing systems were compared and related. While B1 focuses on adaptability as a response to uncertainties internal and external to the system, B2 places greater emphasis on external CDs, seldom considering the effects of uncertainty. Most papers in B1 consider adaptability requirements the outcome of the interplay between EU as faced by the system and the manufacturing strategy selected to cope with this uncertainty. B2 tends to omit the strategic component, inherently assuming a reactive approach to expected change. A summary of the comparison between B1 and B2 is presented in Table 3.9.

B1	**B2**
Environmental uncertainty • Internal: Originates in the production process • External: Originates from outside the production process	Change drivers • Internal: Under direct influence of company • External: Outside direct influence of company
Discusses role of adaptability in manufacturing strategy	Assumes a strategy of adaptation

Table 3.9: Comparison of the most important concepts from B1 & B2.

3.2.3. Formulation of adaptability requirements

This section explores how each branch approaches the formulation of manufacturing adaptability requirements. First two distinct taxonomies of flexibility types as adopted in B1 are examined, followed by the approach used in B2. Finally, an attempt is made to integrate both perspectives.

B1 - Flexibility types

As discussed in Section 3.2.1, B1 does not explicitly distinguish reconfigurability as separate from flexibility. Therefore, adaptability requirements are expressed in terms of flexibility. Flexibility is a multi-dimensional concept and encompasses various forms in relation to manufacturing. The various forms of flexibility are expressed in so-called flexibility types and related flexibility dimensions.
The classification of flexibility types differs considerably across the literature, with individual types often defined or interpreted in varying ways by different authors. The same flexibility type may carry distinct meanings depending on the paper it was used in, complicating efforts toward establishing a common taxonomy. Even within a single classification, the interrelations between flexibility types can be complex, with causal relationships being common. Moreover, the inherently abstract nature of the flexibility concept often results in flexibility types that are open to subjective interpretation. This section seeks to provide a structured overview of key concepts as represented in the literature associated with B1. The section is structured around two general perspectives, each as a guiding example supported by an influential classification. The perspectives are used to illustrate the concepts and terminology originating from B1. Variations of these perspectives form the basis for a large number of frameworks in B1, allowing for a somewhat coherent overview.

First, the taxonomy as proposed by Browne et al. (1984) is discussed. This taxonomy (B1.1) encompasses a relatively large number of flexibility types, which are often linked through causal relationships. Secondly, the types and dimensions as proposed by Slack (1988) are examined. This taxonomy (B1.2) is more externally focused and includes the notion of flexibility dimensions for each flexibility type. Subsequently, the distinction between internally and externally focused flexibility types is made.

Taxonomy B1.1 - Interrelated flexibility types

The classification as proposed by Browne et al. in this section functions as backbone to explore taxonomy B1.1. Browne et al. (1984) recognizes eight flexibility types, many of which are connected via causal relationships. Similar classifications of flexibility are widespread in the literature, such as those proposed by Sethi and Sethi (1990) or Gerwin (1993), including 11 and 7 flexibility types respectively. The flexibility types as proposed by Browne et al. (1984) are widely used throughout the literature, albeit in slight variations.

- **Machine flexibility** indicates the ease with which a machine can be adapted to produce a given set of part types. Measurements of machine flexibility include the time it takes to change machine components or load new programs.
- **Process flexibility** refers to the ability to produce a mix of different jobs simultaneously. Process flexibility is achieved by implementing multi-purpose machines. A measurement of process flexibility is the number of part types that can be processed at the same time.
- **Product flexibility** is the ability to switch quickly and economically between producing a new product or product mix. As such, product flexibility is measured by the time and cost of switching from one product (mix) to another.
- **Routing flexibility** indicates the ease to which a product can be produced over multiple routes throughout the system. Routing flexibility is essential in case of machine breakdowns, as defective sections of the system can be avoided by rerouting the production process.
- **Volume flexibility** refers to the ability of the system to handle varying levels of production volume. This can be interpreted as an economical measurement to indicate the range of profitable production levels, but is also used purely operational.
- **Expansion flexibility** refers to the ease with which the capability and capacity of a manufacturing system can be extended. Expansion flexibility is enabled by modular design and flexible layout of the full system.
- **Operation flexibility** indicates the ability of the system to switch up the order of operations for producing a product. While referring to a system property, it is apparent that operation flexibility is only appropriate for certain product types.
- **Production flexibility** refers to the complete universe of product types that the manufacturing system can produce.

Similar to most classifications as found in B1, there exists hierarchical relationships between the flexibility types as classified Browne et al. (1984). This taxonomy suggests that machine flexibility and process flexibility are the fundamental building blocks upon which routing, volume, expansion and operation flexibility are based. Production flexibility is put forward as the culmination of the other flexibility types, indicating a form of total system flexibility.

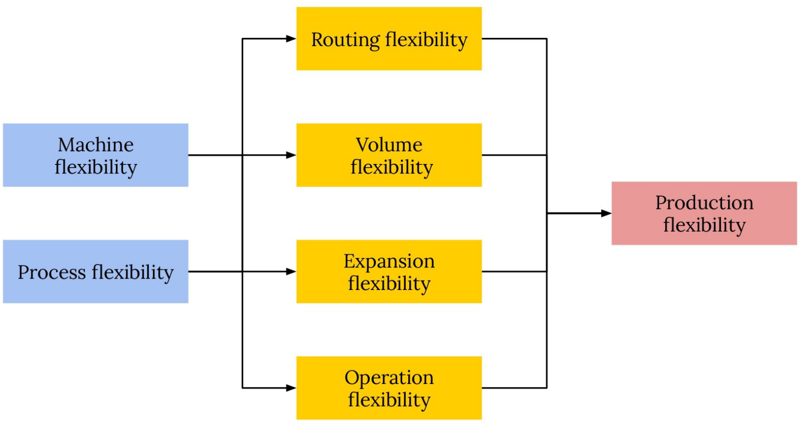

Figure 3.7: Flexibility types and their relations

It is important to note that machine flexibility is not a characteristic of the system, but instead is a machine property. Even so, the machine flexibilities of the components in the manufacturing system together are an important enabler of flexibility type on system level. In the existing literature, classifications of flexibility are often proposed as hierarchical multi-level schemes in which flexibility on one level enables flexibility on the level above. Different levels in this context include the individual machine, manufacturing cell, manufacturing system, factory or multifactory level (Gerwin, 1993).

Methods for identification of adaptability requirement that employ taxonomy B1.1 tend to approach the formulation of requirements on a more strategic and qualitative basis. For instance, frameworks as developed by Vokurka and O'Leary-Kelly (2000), Gerwin (1993) or Suarez et al. (1991) focus on selecting the right types of flexibility to cope with the EU as confronted by the system. To this end, many of these papers provide guidance on which types of flexibility are suitable for which type of EU. Sometimes direct linkages are provided, while sometimes the relations are established in a more indirect and descriptive manner. As a consequence of the higher-level approach, the adaptability requirements are formulated in terms of flexibility types to be implemented, without further quantifying or even qualitatively describing the level that is required. A limited number of studies do suggest that identified flexibility types should be prioritized, yet concrete methodologies for establishing such prioritization are rarely addressed in the literature.

Taxonomy B1.2 - System flexibilities and flexibility dimensions
To explore this classification, the framework as proposed by Slack (1988) functions as a guiding example. Slack (1988) distinguishes between two main categories: system flexibility, which reflects the overall ability of the manufacturing system to adapt to change, and resource flexibility, which indicates the ability of the resources to enable these flexibility types. System flexibility includes **product flexibility**, or the ability to introduce new or modified products into production; **mix flexibility**, which refers to adjusting the range of products being made; **volume flexibility**, which reflects the system's capacity to vary production levels; and **delivery flexibility**, or the extent to which delivery schedules can be adjusted to meet changing customer demands. These system flexibilities are enabled by four resource flexibilities that are characteristic of the infrastructure and workforce. **Process flexibility** refers to the range of tasks that a manufacturing process can perform and the speed with which it can switch between them. **Labour flexibility** describes the variety of tasks that workers are capable of handling and how easily they can move between roles. Similarly, **supply system flexibility** deals with how readily the company can adjust the quantity and type of input materials. **Control system flexibility** is about how easily the organization's planning and control systems can reconfigure operations in response to change.

Slack (1988) further argues that every type of flexibility can be expressed in the dimensions of range and response. The **range** refers to the ability of the system to adapt to different states. The **response** indicates the ability to move between these states. For example, the range of product flexibility refers to the total set of products that can be produced by the system, while the response indicates the effort it takes to transition between producing different products. Similar classifications are found throughout B1, sometimes using different terminology, such as range and responsiveness (Gerwin, 1993) or capability and capacity (Evans, 1991). Table 3.10 provides an overview of the classification of system flexibilities as proposed by Slack (1988). While some terms align with the classification proposed by Browne et al. (1984), they may be used to refer to different underlying concepts.

	Range	Response
Product flexibility	The range of products which the manufacturing system is able to produce	The time necessary to adjust the manufacturing system for regular production of a different product
Mix flexibility	The range of products which the company is able to produce within a given time period	The time necessary to adjust the mix of products being manufactured
Volume flexibility	The absolute level of aggregated output which the company can achieve for a given product mix.	The time taken to change the aggregated level of output
Delivery flexibility	The extent to which delivery dates can be brought forward or backward	The time taken to reorganize the manufacturing system so as to replan for the new delivery date

Table 3.10: Classification of system flexibilities as proposed by Slack (1988).

Olhager and West (2002) extends on this by adding the dimension of distension. If flexibility range represents the action space the flexibility type spans, distention refers to the time and cost needed to change the action space. Some authors in addition consider the **uniformity** an important dimension of flexibility. The uniformity describes how indifferent the performance of the system is under varying states within the flexibility corridor. For instance, a high volume flexibility range would enable increasing production volumes to a high level, yet this this adaptation might come at the expense of average product quality or production efficiency. Such a correlation would indicate an imperfect volume flexibility uniformity, as the performance of the system depends on its current state within the flexibility corridor.

Comparing B1.1 & B1.2
Taxonomy B1.1 formulates adaptability requirements exclusively in terms of the types of flexibility to be employed, without considering the required level of these flexibility types. While some studies adopting this taxonomy do advocate for a prioritization among selected flexibility types, the methodology for such prioritization is typically not elaborated. In contrast, Taxonomy B1.2 adopts a more quantitative and tangible approach to formulating adaptability requirements, although mostly focusing on externally-driven flexibility types. Table 3.11 provides a side-to-side example of formulation of adaptability requirements for both perspectives. The different types of flexibility as used in the analyzed papers are shown in Table 3.12.

Taxonomy	Formulation of adaptability requirements
Taxonomy B1.1	• Routing flexibility • Operation flexibility
Taxonomy B1.2	• Capability to shift from 250 to 300 items/day in one month • Capability to accommodate production of product A within 3 hours

Table 3.11: Example of difference in formulation of adaptability requirements between B1.1 and B1.2

Paper	Flexibility types	Flexibility dimensions
Boyle (2006)	• Product • Process • Routing • Volume • Expansion	-
Cousens et al. (2009)	• Volume • Mix	-
Gerwin (1993)	• Changeover • Mix • Rerouting • Responsiveness	• Range • Time
Mishra et al. (2014)	Does not propose own typology	
Narain et al. (2000)	• Necessary • Sufficient • Competitive	-
Nilsson and Nordahl (1995a) & Nilsson and Nordahl (1995b)	• Product • Mix • Volume • Delivery	• External / characteristic • Strategic / System / Resource
Olhager and West (2002)	• New product • Mix • Volume	• Range / Response / Distension • Output / System / Resource
Slack (1988)	• 4 types of resource • 4 types of system	• Range / Response
Suarez et al. (1991)	• Product • Process • Routing • Volume • Expansion	-
Vokurka and O'Leary-Kelly (2000)	Does not propose own typology	

Table 3.12: Comparison of flexibility types and dimensions across analyzed papers in B1.

Externally- vs internally-driven flexibility
D'Souza and Williams (2000) argue that flexibility types can be classified as either externally- or internally-driven. **Externally-driven flexibility types** are concerned with meeting the market needs, or production requirements. **Internally-driven flexibility types** are related to concerned with flexibility in the operational activities of the manufacturing functions. Similarly, Buzacott (1982) names these classes job type flexibility, which is the ability of the system to cope with changes in the jobs to be processed by the system, and machine type flexibility, which is the ability to cope with changes internal to the manufacturing system.

In this section, the formulation of adaptability requirements was discussed through the lens of B1. Table 3.13 compares flexibility types as distinguished by Browne et al. (1984) to the interpretation by Slack (1988) and links them to flexibility characteristics as introduced in this section. Some of the flexibility types by Browne et al. can be interpreted as expressing only the range or response dimension.

Type (Browne et al., 1984)	Type (Slack, 1988)	Internally or externally focused	Hierarchical level
Machine flexibility	-	Internally	Machine
Process flexibility	Mix	Externally	System
Product flexibility	Product (response)	Externally	System
Routing flexibility	-	Internally	System
Volume flexibility	Volume	Externally	System
Expansion flexibility	-	Internally	System
Operation flexibility	-	Internally	System
Production flexibility	Product (range)	Externally	System

Table 3.13: The flexibility types as proposed by Browne et al. (1984) in relation to flexibility dimensions.

B2 - Reconfigurability characteristics

Whereas the level of flexibility is characterized by the flexibility types, the level of reconfigurability is in B2 typically expressed in reconfigurability characteristics (Rösiö, 2012). Koren et al. (1999) distinguishes five key characteristics for reconfigurable manufacturing systems: Modularity, Integrability, Customization, Convertibility and Diagnosability. Later, scalability was introduced as an additional frequently used characteristic (Guo et al., 2021).

- **Modularity** is the extent to which the components of the system are designed to be modular. These components include machine tools, software and structural elements.
- **Integrability** indicates the extent to which system and components are able to integrate new components and technologies
- **Convertibility** refers to the extent or ease of the restructuring between different configurations to account for difference in product mix and new product introductions.
- **Scalability** is the extent or ease to which the system is able to use reconfigurations to account for changes in capacity.
- **Diagnosability** is the extent to which the system is able to detect production failures or irregularities. This is a characteristic of reconfigurability since reconfigurations require retuning of the production processes, making diagnosability crucial
- **Customization** refers to the fact that the system can be customized to the specifications that are needed at each point in time. This again links to the term of customizable flexibility as explained earlier.

Reconfigurability characteristics might differ between different papers in B2. Table 3.14 shows a comparison of reconfigurability characteristics used in the analyzed papers. Rösiö (2012) and Dit Eynaud et al. (2019) propose a categorization in which critical characteristics are made possible by supporting characteristics. **Critical characteristics**, such as convertibility and scalability, directly result in changes to system capacity or functionality. **Supporting characteristics**, including integrability, diagnosability, and modularity, do not directly alter functionality or capacity, but they reduce configuration and ramp-up effort and time, thereby enabling the critical characteristics.

Author	Reconfigurability characteristics mentioned
A.-L. ; Andersen et al. (2023)	Modularity, Integrability, Diagnosability, Convertibility, Scalability, Customisation
Benkamoun et al. (2015)	Modularity, Interfaceability
Deif and ElMaraghy (2006)	Scalability, Integrability, Modularity
Dit Eynaud et al. (2019)	Modularity, Integrability, Diagnosability, Convertibility, Scalability, Customisation
Francalanza et al. (2014)	Modularity, Integrability, Diagnosability, Convertibility, Scalability, Customisation
Heisel and Meitzner (2006)	-
R. Andersen et al. (2024)	Modularity, Integrability, Diagnosability, Convertibility, Scalability, Customisation
Rösiö (2012)	Convertibility, Scalability, Automatibility, Mobility, Modularity, Integrability, and Diagnosability
Schuh et al. (2009)	-
Tracht and Hogreve (2012)	Modularity, Scalability, Convertibility, Mobility and Automatibility

Table 3.14: Comparison of CD classifications in the analyzed papers in B2.

Comparing B1 & B2

Both flexibility types and reconfigurability characteristics represent system properties that enable adaptation to internal and external changes within a manufacturing environment. The key distinction lies in their perspective on how such adaptations are achieved. Even so, some flexibility types and reconfigurability characteristics are conceptually closely related. Table 3.15 shows links that can be identified between the flexibility types and reconfigurability characteristics as discussed in this chapter.

Reconfigurability characteristics (Dit Eynaud et al. (2019)	Flexibility types (B1.1) Browne et al. (1984)
Modularity	-
Integrability	-
Diagnosability	-
Convertibility	Product flexibility
Scalability	Expansion flexibility
Customization	Production flexibility

Table 3.15: Relating reconfigurability characteristics and flexibility types.

The supporting reconfigurability characteristics describe system properties that enable reconfigurations, and as such do not find a counterpart in flexibility. The critical characteristics, however, can all be related to flexibility types. Convertibility and product flexibility both describe the ease of converting between production of different products or product mixes. Scalability and expansion flexibility both describe the capability of the system to account for changes in production capacity. Customization and production flexibility both summarize the effect of all characteristics and flexibility types respectively: the ability of the system to adapt to specific production requirements over time.
The B1 dimensions of range and response can be applied to reconfigurability in a similar fashion. However, the range of reconfigurability is harder to determine as repeated reconfigurations can infinitely change the structure of a manufacturing system. Zhang et al. (2006) argues that the response consists of both reconfiguration time and ramp-up time. The reconfiguration time is the time it takes to execute a reconfiguration, the ramp-up time is the subsequent time that is required to bring the system to full operation (Huang et al., 2018). The concept of distention can be interpreted as being similar to reconfigurability. The action space spanned by flexibility is at all times dependent on the configuration of the manufacturing system. The ease of changing this action space, or distention, is conceptually the

same as the ease of reconfiguring.

3.2.4. Conclusion

In this literature review, a narrative synthesis was used to identify two main perspectives on manufacturing adaptability, from which ten articles per perspective were selected for critical analysis. Although a wide range of papers was considered during the narrative review, the body of scientific evidence on this topic is extensive, and it remains possible that some highly relevant contributions were overlooked in the selection for critical analysis. Nevertheless, the review offers a useful overview of the key contrasts between B1 and B2.
It should be noted that terminology and conceptualizations may vary even within a single branch. As such, not all statements attributed to a branch apply uniformly to every individual paper. Still, the synthesized statements are intended to represent the conceptual framing within each branch as accurately as possible.

The two branches of literature approach adaptability from different conceptual angles. B1 interprets adaptability as being solely rooted in flexibility, giving little consideration to reconfigurability as an alternative. B2 on the other hand, recognizes both flexibility and reconfigurability, frequently framing their combination within the broader concept of changeability. The assumed sources of the need for adaptability also differ. In B2, this is largely linked to volatility in CDs, whereas B1 associates it with the interaction between environmental uncertainty and manufacturing strategy. Regarding the formulation of adaptability requirements, B1 focuses on categorizing various flexibility types. B2 expands the scope by describing the extent of reconfigurability in reconfigurability characteristics. Specifically, B2 distinguishes between short-, medium-, and long-term changes, assigning them either to flexibility or to reconfigurability. B1 offers only limited means of translating environmental uncertainty into concrete adaptability requirements, sometimes mentioning a link between types of environmental uncertainty and specific flexibility types. By contrast, B2 suggests several tools, such as questionnaires, to determine the necessary level of adaptability. Yet these methods typically yield only broad, generalized estimates rather than precise evaluations of adaptability needs. Table 3.16 summarizes the comparison between B1 & B2 as resulting from the literature review.

	B1	**B2**
Nature of adaptability	Flexibility	Reconfigurability & flexibility
Origin of need for adaptability	Environmental Uncertainty & Manufacturing strategy	Change drivers
Formulation of adaptability requirements	Flexibility types & Flexibility dimensions	Reconfigurability characteristics & short/mid/long-term changes
Methodological contribution	Links Environmental Uncertainty to Flexibility types	Varying methodology

Table 3.16: Comparison of concepts and terminology.

4

Theoretical framework

This chapter outlines the theoretical framework derived from the critical review of the literature. The framework synthesizes the two principal perspectives discussed in the critical literature review, while also incorporating complementary concepts from adjacent fields. By doing so, it enables a novel interpretation of the underlying theory. Since the framework is grounded in the critical literature review, its presentation in this chapter follows the same thematic structure as the comparison outlined in Section 3.2. First, the conceptualization of the nature of adaptability is examined, after which the origins of adaptability are addressed. Finally, the manner of formulation for the adaptability requirements are discussed.

4.1. The nature of manufacturing adaptability

A manufacturing system may be regarded as an input-output transformation , possessing a certain transformative capability to convert components or materials into a desired set of products. This transformative capability determines the rate and characteristics of the input that the system is able to process, as well as the rate and characteristics of the output it is capable of producing. As such, the transformative capability required of a system, defined by the **primary production requirements (PPR)**, is determined by the characteristics of its inputs and outputs. A change in the characteristics of the input to be processed or output to be produced results in a change in the PPR. The ability of a manufacturing system to adapt its manufacturing capability to meet changing PPR is in this thesis defined as **"manufacturing adaptability"**.

Figure 4.1: Input-output representation of a manufacturing system

Adaptability refers to the ability of a manufacturing system to respond to changes in PPR. Accordingly, the required level of adaptability is characterized by the changes in PPR to which the system must be capable of adapting. The PPR of a manufacturing system is defined by the characteristics of the input to be processed and output to be produced. These characteristics can be expressed by **production variables (PVs)**, which can be either quantitatively or qualitatively defined. Table 4.1 shows an example of a PV and related PPRs.

Production variable (PV)	Primary production requirements (PPRs)
Product portfolio = (Product A, Product B, Product C)	• System needs to be able to produce product A • System needs to be able to produce product B • System needs to be able to produce product C

Table 4.1: Example of a PV and related PPR

Adaptability is a multidimensional concept that may manifest in various forms. For each PV, a related type of adaptability expressing the ability of the system to adapt to changes in this PV exists. For example, for the PV product size, a related adaptability type exists expressing how well the system is able to adapt to producing different product sizes.

Abbreviation	Name	Used to describe
PV	Production variables	Describe characteristics of the input or output stream to the manufacturing process
PPR	Primary production requirements	Describe the required production capability of the manufacturing system

Table 4.2: Overview of concepts as introduced in Section 4.1.

As discussed in Section 3.2.1, flexibility and reconfigurability are in the existing literature distinguished as two important concepts in relation to manufacturing adaptability. In the theoretical interpretation presented in this chapter, flexibility and reconfigurability are regarded as operational strategies through which manufacturing adaptability can be achieved. This thesis aims to develop a methodological framework for identifying adaptability requirements in manufacturing systems. The choice of strategy, whether flexibility or reconfigurability, through which these requirements are fulfilled lies beyond the scope of this work. The requirements to which a manufacturing system should adhere are therefore only expressed in terms of adaptability, rather than in terms of flexibility or reconfigurability.

4.2. Origins of the need for manufacturing adaptability

As explained in previous section, adaptability refers to the ability of a manufacturing system to respond to changes in PVs. As such, adaptability is required only when PVs are changing, or expected to change. Figure 4.2 visualizes how a change in a PV causes a need for adaptability in the corresponding adaptability type. In the white boxes, an illustrative example for the PV "output volume" is shown.

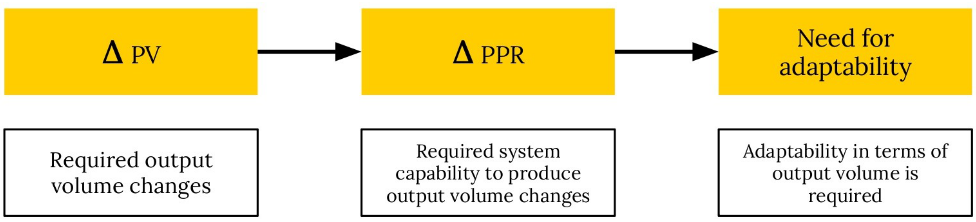

Figure 4.2: The need for adaptability as caused by a change in PV value

The extent of the need for manufacturing adaptability in a system is determined on two factors. The first factor is the extent of change that is expected in the PV. If the size of a product to be manufactured within a system is expected to double over the next year, the system must exhibit sufficient adaptability to ensure that its transformative capability is able to adapt. This factor is in this thesis referred to as the **expected volatility**. The second factor is the uncertainty regarding projections of the PV in the future.

For example, consider a system operating under uncertainty regarding whether product A or product B will be required next week. This system requires adaptability in order to adjust its transformative capability to production of either product within a week. This factor is in this thesis referred to as the **uncertainty of predictions**. Figure 4.3 visualizes how the need for adaptability can arise from both of these factors.

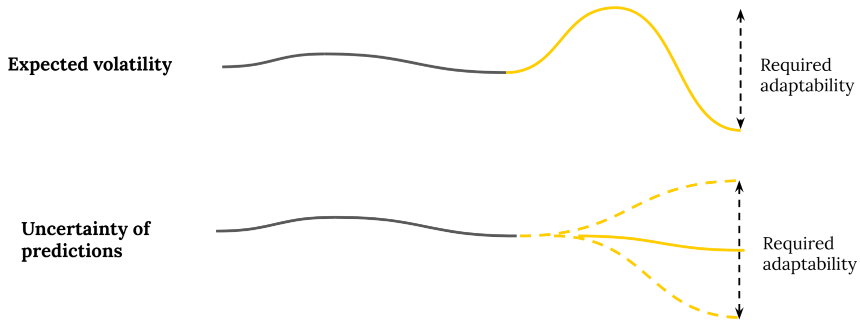

Figure 4.3: Expected volatility and uncertainty of predictions as origins of the need for adaptability

4.2.1. Expected volatility

External factors such as increasing market demand or new suppliers constantly influence the available production resources and required production output, thereby affecting the systems PVs. Any factor that brings about a shift in the value of a PV is referred to as a **change driver** (**CD**). As such, the volatility of a PV depends only on the CDs affecting this variable.

This theoretical framework distinguishes two types of CDs: 1) events and 2) trends. **Events** are CDs that trigger a sudden shift in PV value. An example would be the decision of a manufacturing company to start producing a new product type. The effect of this decision causes an instantaneous shift in the product portfolio being produced by the system. On the contrary, **trends** are gradual developments affecting the PV over time. An example would be rising popularity of oat milk, potentially increasing the production volume of an oat milk factory over the next year. Figure 4.4 illustrates the difference between an event and a trend.

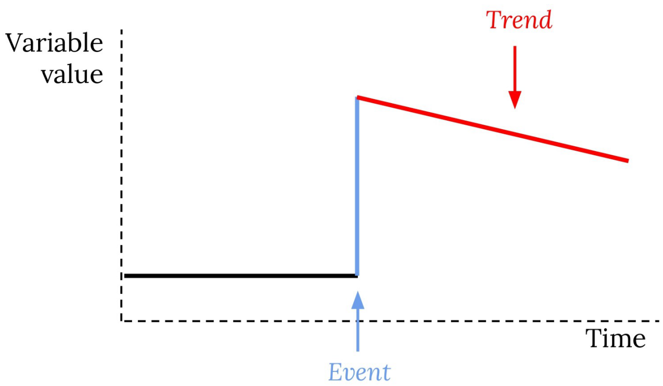

Figure 4.4: The effect of a trend and event on the value of a PV over time

If the current value of a PV is known, a complete projection of the future can be established based on the trends and events that are expected to affect the PV value.

Variability & Shift of mean

In manufacturing systems, volatility may occur on varying timescales. Assessing volatility across different time scales can yield very different perspectives. For example, production volume may fluctuate on an hourly basis throughout the day, while appearing constant when expressed in units per week. Although both perspectives reveal aspects of production volatility, they give rise to distinct adaptability requirements, which decision-makers may need to address in different ways. It therefore is meaningful to make a distinction between short-term variations and long-term changes when assessing expected volatility ,in turn resulting in short-term and long-term adaptability requirements (Napoleone et al., 2021). In this thesis, short-term variations are referred to as **"variability"**, while a long-term change is called a **"shift of the mean"**. The difference between both is visualized in Figure 4.5. The distinction between long-term and short-term is inherently relative, and its meaningful application depends on the specific characteristics of the manufacturing system and its surrounding environment.

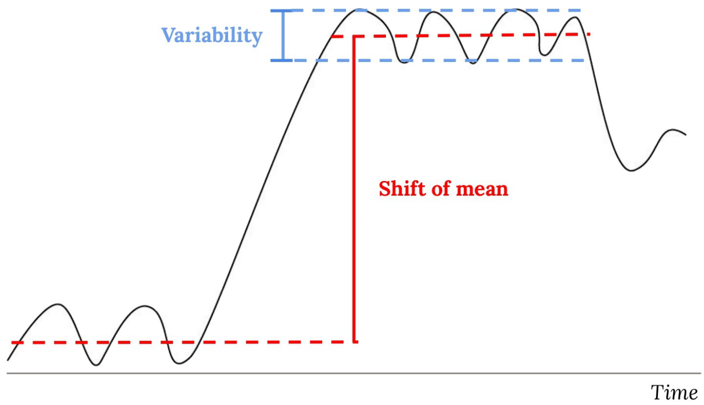

Figure 4.5: The difference between variability and shift of mean

Variability can be characterized by amplitude and frequency of the fluctuations (Echsler Minguillon et al., 2019). The amplitude indicates how far the fluctuations deviate from the average. The frequency indicates how often the fluctuations occur. Figure 4.6 shows how frequency and amplitude can be used to describe variability.

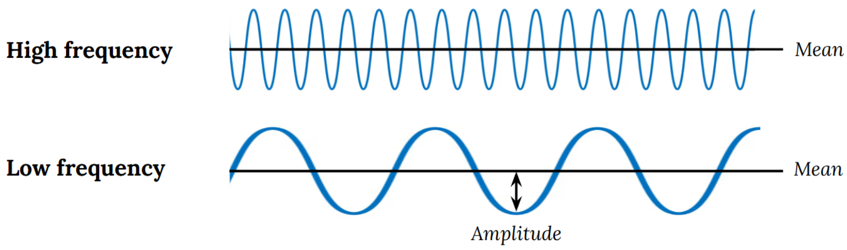

Figure 4.6: Frequency and amplitude as characteristics of variability

Throughout the literature, flexibility is often associated with handling short-term variability, while reconfigurability is assumed to cope with long-term shifts of mean. However, the methodological framework developed in this thesis is explicitly limited to identifying the requirements for adaptability. It does not prescribe whether these requirements should be fulfilled through flexibility or reconfigurability. Nevertheless, the distinction between long-term and short-term adaptability requirements is helpful for manufacturers in assessing whether flexibility or reconfigurability is needed.

4.2.2. Uncertainty of predictions

As the manifestation of CDs and their effects on PVs can never be fully known in advance, future projections of production variables inevitably involve a degree of uncertainty. Consequently, the future of a PV cannot be captured by a single deterministic forecast but must instead be represented as a range of potential developments. This range can be delineated through the use of extreme scenarios, which serve to reflect the boundaries of the range of possible futures (Schoemaker, 1995). The purpose of

these scenarios is not to accurately predict a specific future, but to explore the boundaries of feasibility. This is especially relevant in relation to manufacturing adaptability, as the required level of adaptability for a system hinges on the possible futures it should be able to accommodate.
In this context, the extreme scenarios should reflect the most extreme realizations of each PV, thereby delineating the extremes in terms of transformative capability that the system should adapt to.

An important consideration in using extreme scenarios to explore the future boundaries of feasibility is to determine how extreme these scenarios should be. This **degree of extremity** depends on the level of probability one aims to represent, indicating how likely it is that the actual realization of the future is part of the range of futures captured by the extreme scenarios. A low degree of extremity reflects only the most likely developments, thereby offering limited robustness when unexpected disruptions occur. This might result in an underestimation of adaptability requirements, possibly resulting in operational problems. On the other hand, a high degree of extremity is very robust, but might not be functional in practice. An excessively high level of extremity in defining manufacturing adaptability requirements would imply that a system must be capable of adapting to virtually any circumstance. Such an approach is unlikely to be economically feasible and offers little practical insight for the manufacturer.

4.3. Formulation of adaptability requirements

In this section, the way in which adaptability requirements are to be formulated is discussed. First, the types of adaptability for which requirements should be composed are analyzed. Second, the dimensions and corresponding representation in which these requirements can be meaningfully expressed are addressed.

4.3.1. Types of required adaptability

To capture adaptability within formal requirements, it is necessary to specify the types of adaptability for which requirements are to be constructed. For each PV, a related type of adaptability expressing the ability of the system to adapt to changes in this PV exists. To holistically capture the adaptability required by the system, requirements must encompass adaptability types in relation to all relevant characteristics of the manufacturing system's input and output streams. The relevant requirements should therefore originate from one of these two categories of PVs:

- PVs describing the input into the production process
- PVs describing the output requirements of the production process

To holistically capture the adaptability required by the system, requirements must encompass adaptability types in relation to all relevant characteristics of the manufacturing system's input and output streams. Table 4.3 proposes a classification of adaptability types with examples of corresponding PVs. These classes apply to each separate input and output of the manufacturing system, representing distinct types of adaptability. The classification of adaptability types is a variation of system flexibility taxonomy as used in the existing literature, such as Olhager and West (2002), Narain et al. (2000) and Mishra et al. (2014). Whereas these flexibility types are typically used to describe the characteristics of production output, the present classification applies them to both the input and output of the production process. In the description of the subcategories "input product" refers to a component or material entering the production process in order to be processed. The term "output product" refers to the output of the production process.

Subcategory	Description	PV examples
Product adaptability	Adaptability towards the characteristics of the products being processed or produced.	• Density of input product A • Shape of output product B
Volume adaptability	Adaptability towards the volume of products being processed or produced.	• Production input of product A per hour • Total production output per day
Mix adaptability	Adaptability towards the mix of product types being processed or produced.	• # of product types processed at the same time • Relative share of product A in production output
Portfolio adaptability	Adaptability towards the total set of products that should be able to be processed or produced.	• Maximum product size in production portfolio • List of input product types

Table 4.3: Proposed classification of adaptability types with corresponding PV

4.3.2. Dimensions of required adaptability

Required levels of manufacturing adaptability can be measured across the dimensions of range and response (Upton, 1994). The **range** refers to the ability of the system to adapt to different states. The **response** indicates the ability to move between these states. For example, the range of product flexibility refers to the total set of products that can be produced by the system, while the response indicates the time it takes to transition between producing different products. The dimensions of range and response are interdependent, as the time it takes to adapt to a new capability level is generally tied to the extent of change required. Conversely, the feasible range of capability levels is determined by the available time or effort. Consequently, adaptability requirements need to be represented in two-dimensional space, capturing the required level of response across the entire adaptability range. Adaptability requirements can effectively be visualized in two-dimensional space by means of a **range-response graph** (Slack, 1988). If looking at the example in Figure 4.7, it can be seen that System II requires a larger adaptability range than System I. However, System I, up until a certain level of system capability, requires a faster response. It is important to consider that this specific graph interprets response as the equivalent to time required to implement the change. As such, the graphs represent the states that are possible to reach, not the cost or effort associated with changing to these states. It is entirely possible that a system is technically able to reach a certain state, but this is economically infeasible.

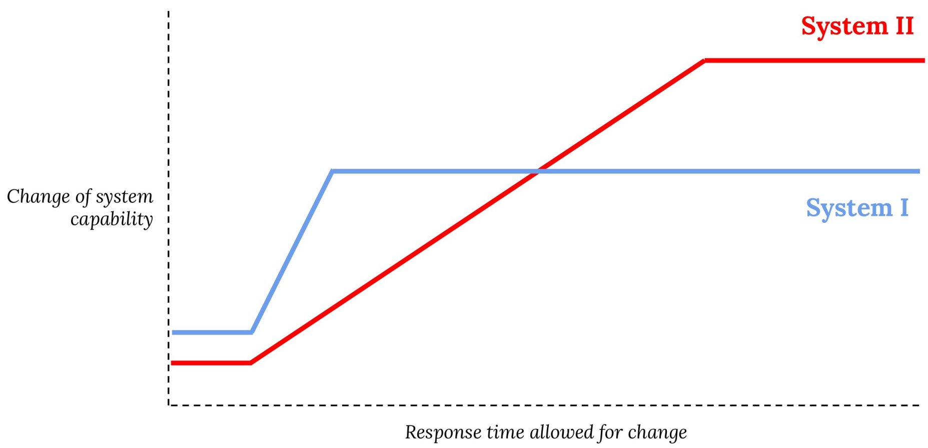

Figure 4.7: Adaptability requirements expressed as range-response graphs

4.4. Conclusion

In this chapter, a theoretical framework regarding manufacturing adaptability was presented. This framework forms the conceptual foundation for the methodological framework introduced in Chapter 5. The theoretical framework was structured around three thematic areas.

First, the nature of manufacturing adaptability was examined. A new definition of manufacturing adaptability was presented based on the interpretation of manufacturing systems as input-output transformations. Furthermore, the concepts of primary production requirements (PPR) and production variables (PVs) were introduced. In addition, the relation of manufacturing adaptability to flexibility and reconfigurability was clarified.
Second, the origins of the need for manufacturing adaptability were discussed. The need for manufacturing adaptablity was found to depend on two factors: 1) Expected volatility, and 2) uncertainty of predictions. The concept of change drivers (CDs) was introduced to explain changes in PV value. Furthermore, a number of distinctions were proposed in the interpretation of these concepts, which are visualized in Figure 4.8. The use of extreme scenarios was suggested as a means to capture both expected volatility and uncertainty.

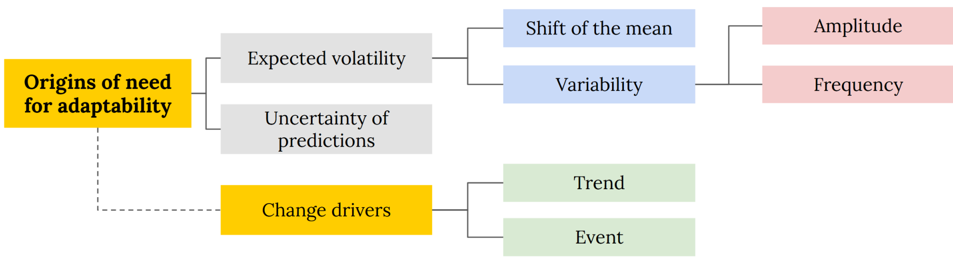

Figure 4.8: Origins of the need for adaptability in the theoretical framework

Third, a way of formulating adaptability requirements was proposed. A classification of adaptability types which can be applied to both input and output of a manufacturing system was presented. Adaptability requirements were characterized along the dimensions of range and response. Range-response graphs were put forward as a method to visualize the requirements in two dimensions. An overview of the above is shown in Figure 4.9.

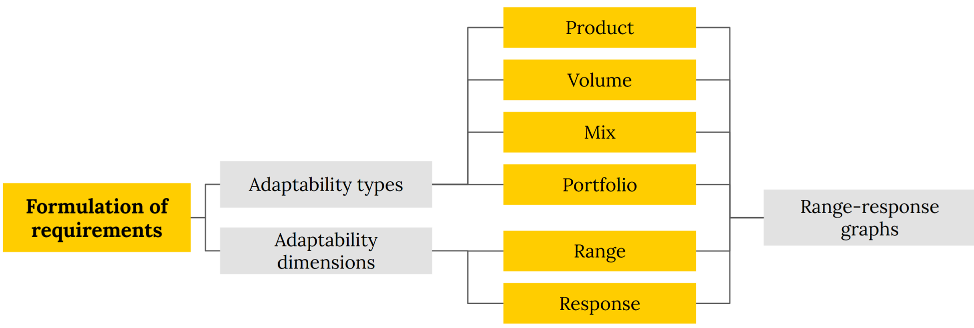

Figure 4.9: Formulation of adaptability requirements in the theoretical framework

5

Methodological framework

In this section, the proposed methodological framework for identification of adaptability requirements is presented. The framework is based on the theoretical perspective as proposed in Chapter 4. On a high level, the framework consists of a preparatory phase and three main phases. The preparatory phase determines the scope and timeframe for which the analysis is conducted. In first phase of the analysis itself, the relevant PVs directly affecting the operation of the production system are identified. In the second main phase, scenarios are constructed for each PV. The third phase is concerned with interpreting these scenarios as range-response graphs expressing adaptability requirements. The framework is summarized in Figure 5.1. Although the phases are presented sequentially, in practice the process is often iterative, with earlier phases being refined in light of insights gained from later phases.

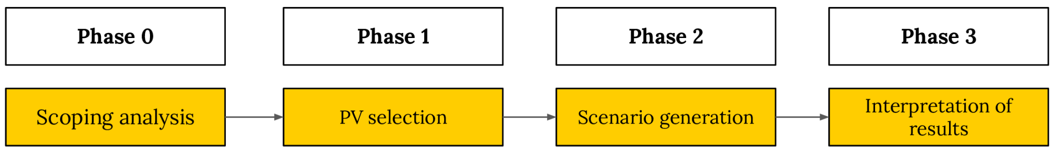

Figure 5.1: Phases of the methodological framework

The framework requires collaboration with company experts in order to perform the analysis in a comprehensive and reliable manner. These experts should be involved in each step in the framework, as they possess the industry knowledge needed to perform and interpret the analysis. Phase 0 and Phase 3 are conducted as an open discussions with the group of experts, whereas Phase 1 and Phase 2 involve individually conducted semi-structured interviews. At the end of Phases 1 and Phase 2, the inputs from the individual interviews are compared and consolidated into a single outcome, which then serves as the basis for the subsequent phase. This iterative divergence-convergence nature of the method is visualized in Figure 5.2.

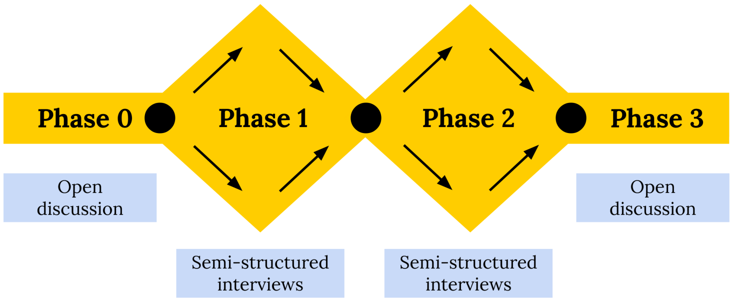

Figure 5.2: The diverging-converging nature of the methodological framework

It is recommended to perform the analysis with at least three different experts from within the company, preferably coming from different departments to ensure a range of perspectives. The experts should be knowledgeable on the functioning of the production process and most importantly should have knowledge on possible trends and events affecting the production process in the future. Ideally, the experts have knowledge on future projections on different hierarchical levels within the company, ranging from operational to more strategic. An example of a suitable combination of functions to approach for interviews are a supply chain manager, production planner and factory floor manager. Each of these functions is knowledgeable about future projections of the production process on a different hierarchical level. Repetition of interviews enables both the validation of findings and the identification of PVs that may be implicit or unobservable from certain stakeholder perspectives.

5.1. Phase 0 - Scoping analysis

In the preparatory phase, or phase 0, the scope and granularity of the analysis are set. There are two main elements that need to be determined in order to fully define the analysis: 1) *the structure and scope of the manufacturing system*, and 2) *the prediction horizon of the analysis*.

5.1.1. Structure and scope of the manufacturing system

In order to conduct a meaningful analysis, it is critical to define the manufacturing system on which the analysis is to be conducted. The framework proposed in this paper addresses adaptability exclusively at the system level and does not consider the internal resources or enablers that underpin it. For the purposes of analysis, the system may therefore be simplified to an input–output transformation, in line with the theoretical perspective outlined in Section 4.1. The system as such represents a manufacturing function, the capability of which may change over time as a result of activation of manufacturing adaptability. A manufacturing system can be defined on multiple hierarchical levels, ranging from single manufacturing stations to entire factories. This analysis was intended for use on the level of production lines, but with can with modifications be used for analysis on other hierarchical levels of production.
When setting the scope of the analysis, the input and output streams are considered to be exogeneous. This means that the changes in these streams are assumed to originate from factors outside of the system. As such, rather than being explained or predicted by the analysis, these variables function as a given input.

The scoping of a manufacturing system should result in a input-output transformation with a number of distinguished inputs and outputs. Figure 5.3 shows a visual representation of manufacturing system represented as an input-output transformation.

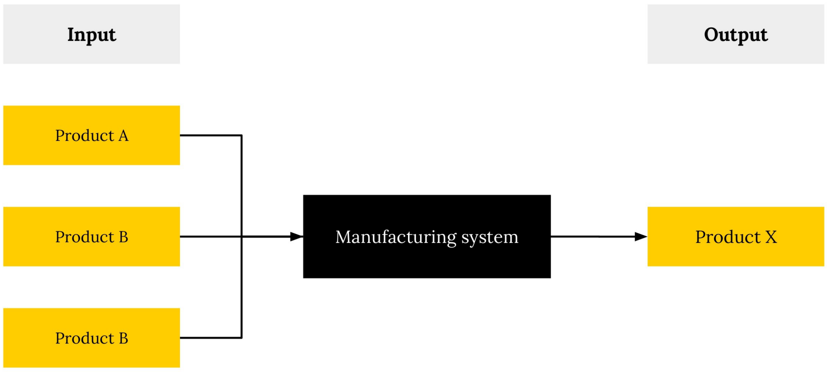

Figure 5.3: Examplary scoping of a manufacturing system

5.1.2. Prediction horizon

The prediction horizon or temporal scope of the analysis specifies how far into the future adaptability requirements will be projected. It is important to set this timeframe in advance as it influences the PVs that are relevant to the manufacturing system, and is essential in the construction of scenarios. Selecting an adequate horizon depends on the aim of the analysis and the availability of information. Long-term timeframes may reveal adaptability requirements well into the future, but their credibility diminishes if they are founded on inadequately defined scenarios.

In order to be useable as a tool for reconfiguration decision making, the time horizon should at least consist of the time it takes to execute reconfigurations (Karl & Reinhart, 2015). If the need for structural modifications is being assessed, the timeframe selected for the analysis should at minimum encompass the period it takes to make structural modifications to the system in order to increase adaptability. This ensures that, if the adaptability capability of the system does not match the required adaptability as found in the analysis, sufficient time to take action remains. Opting for a large prediction horizon tends to significantly increase the uncertainty of information regarding future circumstances, as events further in the future are typically more uncertain. This results in scenarios that are very uncertain to occur, preparing for which might be a waste of resources. In this case it might be more wise to adopt a smaller horizon and repeat the analysis at a later stage, when uncertainty might have reduced. Figure 5.4 shows how this approach can reduce uncertainty for a time horizon of 2 years.

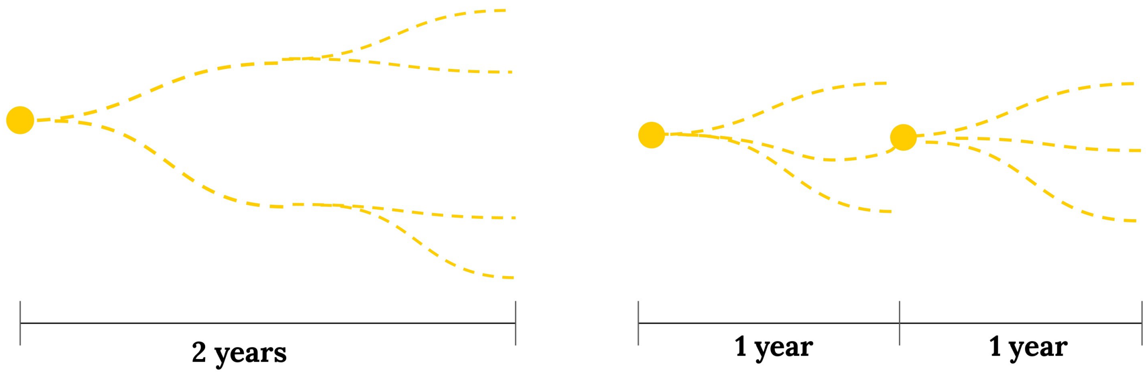

Figure 5.4: Uncertainty for a large prediction horizon (left) and the same period split into two analyses with smaller time horizons (right)

The exact prediction horizon should be determined in correspondence with the stakeholders in the analysis using explorative discussions before performing the main phases.

5.2. Phase 1 - PV selection

The goal of Phase 1 is to identify the PVs that are of importance to the required adaptability of the manufacturing system. As outlined in the theoretical framework, each PV is associated with a related type of adaptability. To further determine the requirements in relations to these adaptability types, the most relevant PVs are selected for further analysis. As outlined in Section 4.2, the need for adaptability originates from two main factors:

1) The **expected volatility** of the PV
2) The degree of **uncertainty** associated with the PV

The need for adaptability arising from these factors is only relevant for decision making if a change in the PV actually exerts influence on the manufacturing system. If the PV in question has little or no impact, even large or frequent changes may not warrant any operational response. As such, an uncertain or volatile PV should only be selected if its change actually impacts the manufacturing system. FFor example, consider a factory that produces plastic bottles. A potential PV in this context could be the type of plastic used in production. Introducing an entirely new type of plastic would represent a major change in the PV. However, if this new plastic does not in any way affect the production process, the PV can be disregarded in terms of required adaptability, as it does not necessitate any modifications to the manufacturing system. On the contrary, a small change in PV value could require significant adaptations if it exerts a large effect on the production process.

On an abstract level, the way in which the expected volatility, uncertainty and impact of change contribute to the relevance of the PV can be captured in the following equation:

$$PV\ Relevance = (Expected\ volatility + Uncertainty) \times Impact\ of\ change$$

5.2.1. Phase workflow

In order to identify the PVs relevant for further analysis, this paper proposes a workflow using semi-structured interviews (see Figure 5.5). The semi-structured interviews should be performed separately for each of the company experts involved in the analysis.

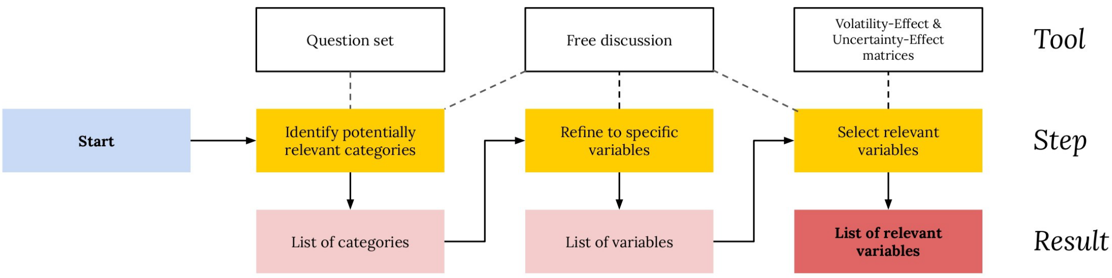

Figure 5.5: The proposed workflow in phase 1

As a starting point for conducting the semi-structured interviews, this thesis proposes Question set A, which can be found in Appendix A. The question set is based on the classification of adaptability types as proposed in the theoretical framework. The questions can be used as a guideline to systematically explore potentially relevant PVs. The actual realization of the PVs in each category is dependent on the industry and should as such be treated differently in each case. It is possible that a relevant PV exists which does not fit in one of presented categories. The classification system should therefore not be seen as an exhaustive method, but rather as a supportive tool, intended to inspire further exploration in free conversation during the interview.
Using the Question set A, categories can be identified in which either a) a change is expected within the prediction horizon or b) projections are highly uncertain. The interviewer subsequently engages in open conversation to explore which specific PVs within these categories may be relevant. For instance,

the question set may reveal that the characteristics of the steel entering a production process are expected to change over the next month. A follow-up discussion is then required to determine *which specific characteristics* are expected to change.

Volatility- and Uncertainty-Impact matrices

After the PV has been specified, it should be decided wether it should be selected for further analysis based on its relevance. At this point in the analysis, estimations of relevance are qualitative and may be very rough. The **Volatility-Impact** and **Uncertainty-Impact matrices**, as shown in Figure 5.6, are tools that can be used to estimate the relevance of PVs towards required adaptability. To use these matrices, plot each PV that is being considered in both matrices. The impact, uncertainty and volatility can be qualitatively estimated using rough indication of the interviewee. If preferred, a rating system from 1-10 can be used to plot the PVs, but since the information at this point in the analysis is limited, accuracy remains low. If a PV is placed in the dark green (upper right) quadrant, it is awarded 2 points. If a PV is placed in a light green (bottom right or upper left) quadrant, it is awarded 1 point. A PV placed in the grey (bottom left) quadrant is rewarded no points. Adding the scores from both matrices together awards each PV a total score. A selection can now be made based on the following rule-of-thumb.

- Total score $\geq 2 \Rightarrow$ The PV is relevant and should be selected
- Total score $= 1 \Rightarrow$ The PV may or may not be selected
- Total score $< 1 \Rightarrow$ The PV is not relevant and should not be selected

This results of the matrix evaluation should be interpreted with care, as results might depend on the interviewee. Even so, the total scores provide a rough guidance when selecting relevant PVs. Larger versions of the matrices can be found in Appendix C.

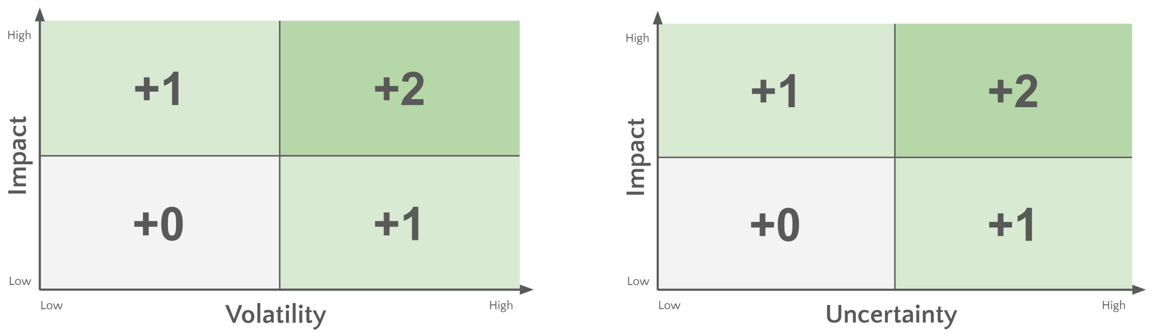

Figure 5.6: The Volatility-Impact matrix (left) and Uncertainty-Impact matrix (right)

The result of phase 1 is a list of selected PVs that is further investigated in subsequent phases. This list is not definitive and can be altered based on insights obtained in later stages of the analysis.

5.2.2. PV definition

Each PV should be defined based on *1*) its unit of measurement , *2*) its aggregation window, and *3*) its present state. The **unit of measurement** ensures that the PV is interpreted the same across all respondents in Phase 2. If a PV is measured in a certain unit throughout the company, it is often sensible to adopt this unit of measurement in the analysis. In cases where expressing the PV quantitatively is not feasible or not desirable, a qualitative description can be used. Even so, it is still important to clearly define the PV in order to avoid confusion when communicating to respondents. For instance, in the case of an output product portfolio, the PV may be defined qualitatively as the full range of products the system should be able to produce.

As outlined in the theoretical framework, a change in PV value can be classified as either variability or shifting of the mean. To define this distinction, an aggregation window needs to be determined. The **aggregation window** is the period of time on which the mean value for each PV is determined.

Changes within this window are considered to be variability around this mean. For example, suppose the chosen aggregation window is one week. The mean PV for production volume is then calculated as the average production over that week. If this weekly average changes from week 1 to week 2, the PV is said to have shifted. In contrast, day-to-day fluctuations—such as differences in production volume between Monday and Tuesday—are considered variability. Thus, the aggregation window determines whether changes in PV values are interpreted as variability or as shifts in the mean. The appropriate length of the aggregation window depends on the characteristics of the production process, its scheduling practices, and the objectives of the analysis.

The unit of measurement of a PV must be smaller than its aggregation window. Otherwise, it is inherently impossible to estimate any variability in the PV. To exemplify: If a unit of measurement is chosen as tonnes per week, it is inherently impossible to identify variability within this week.

PV	Unit of Measurement	Aggregation window
Carbon content iron ingots	Average Carbon% per day	Month
Sugar volume	Produced tonnes per day	Month

Table 5.1: Example of unit of measurement and aggregation window for two PVs.

The present state of a PV needs to be determined in terms of mean value and current variability. As explained in Section4.2.1, the present state of variability can be described in amplitude and frequency of fluctuations. If the variability cannot be adequately captured by these parameters, more descriptive methods of characterization may be used. Table 5.2 exemplifies how the present state of a PV may be described.

PV	Mean	Variability
Carbon content iron ingots	3% Carbon	• Amplitude: +/-1% • Frequency: Daily
Sugar volume	600 tonnes per day	• Amplitude: +/-100 tonnes • Frequency: Daily

Table 5.2: Example of present state description for two PVs.

5.3. Phase 2 - Scenario generation

The objective of Phase 2 is to construct, for each PV, two boundary scenarios that collectively encompass the full range of plausible future states. As outlined in Section 4.2.2 of the theoretical framework, this approach enables the mapping of both expected volatility and the uncertainty of projections. The potentially complex PV scenarios are constructed by combining individually generated CD scenarios. This approach reduces the cognitive load on participants while preserving transparency regarding the derivation of the complete scenarios. The workflow for generating a full PV scenario consists of two subphases, as is shown in Figure 5.7. This process needs to be performed for each PV as selected in Phase 1. First, CDs affecting the PV are identified, and extreme scenarios for these CDs are generated. Second, these CD scenarios are consolidated into two extreme scenarios for the PV.

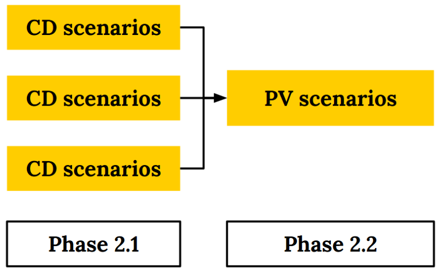

Figure 5.7: Scenario generation process for a single PV

5.3.1. Phase 2.1 - Generating CD scenarios

First, the CDs that potentially impact the PV in the future should be identified. This research proposes a Question set B that assists manufacturers in the identification of these CDs in semi-structured interviews. This question set is presented in Appendix B. To help respondents envision the CDs more clearly, each CD is reduced to a trend or an event, following the distinctions established in the theoretical framework. In reality, the effect of a CD is seldom completely instantaneous. However, if it occurs within a time span that is negligible relative to the prediction horizon adopted in the analysis, it might be treated as an event for the sake of simplification. In the same way, the projection of trends can often be simplified to make further analysis more practical. While the Question set B provides a structure to approach the interview, free discussion further detailing the CDs that arise is encouraged. For each CD that was found using the question set, two extreme scenarios are generated.

The degree of extremity that is applied when generating these scenarios depends on the goal of the analysis and should be equal across all participants. In order for the analysis to lead to meaningful results, overly improbable scenarios should be avoided. The dimensions of the extremes for the CD should align with the scenarios resulting in extreme values of the respective PV the CD belongs to. This means that if a PV is defined in a single quantitative value, the extremes correspond to the scenarios assumed to minimize and maximize the PV value. In the event that the extremes are not so apparent, it is important to include the scenarios that are assumed to challenge the limits of the production resources the most.

The output of Phase 2.1 is a comprehensive list of CDs for each PV, with each CD characterized by two extreme scenarios describing its potential effects. An example of Phase 2.1 output for a single PV is presented in Table 5.3. The effect of a CD should be defined on both timing and extent of the effect. For a CD classified as an event, the timing can be described by a single point in time. In case of a trend, the development of the effect over time should be described textually. A CD may also influence the variability of a PV. In this case, the effect should be expressed in terms of its impact on the amplitude or frequency of fluctuations.

Change driver	**Description scenario #1**	**Effect scenario #1**	**Description scenario #2**	**Effect scenario #2**
Increasing political unrest in source country	No unrest increase	0%	Significant unrest increase	-5% purity decrease over next two years
New supplier contract	Great new supplier	+5% purity increase start October	Bad new supplier	-5% purity increase start October
Decreasing iron price	No price decrease	0%	Significant price decrease	-20% over the next year

Table 5.3: Phase 2.1 output for iron ingot purity in a fictional manufacturing process

5.3.2. Phase 2.2 - PV scenario generation

In order to create extreme scenarios for each PV, the CD scenarios are combined using an morphological chart. A morphological chart is a systematic tool that is typically used in system or product design to combine options for subfunctions into an overall concept (Boeijen & Daalhuizen, 2013). Applying the tool in this context, the chart is used to combine CD scenarios into a full PV scenario. The aim of this morphological analysis is twofold: 1) The analysis is used to combine the proposed CD extremes into two scenarios that represent the extremes in projection for the entire PV, and 2) The morphological analysis ensures consistency across the CD scenarios in order to retain feasibility of these projections. If this consistency is not ensured, it is possible for CD scenarios to be combined into PV scenarios that are infeasible in the real world. For example, a PV scenario could depend on the acquisition of both factory A and factory B, while in reality only one of both factories would be acquired at the same time.

In order to perform a full morphological analysis of a PV, a morphological table is created, each row being dedicated to one CD as identified in step 1. In the next columns, both extreme scenarios as articulated in Phase 2.1 are listed. Table 5.4 gives an example of what such a table could look like. A template for a morphological chart can be found in Appendix D.

Change driver	Option #1	Option #2
CD #1	-5% begin September	+5% begin September
CD #2	+10% over the next year	-5% over the next year
CD #3	+0%	+10.000 units/week begin August
CD #4	+5% variability range begin April	+0% variability range

Table 5.4: An example of a morphological table for production volume of fictional product X

The company expert is now asked to select one of the scenarios for each CD, together creating a whole scenario for the respective PV. This process is to be repeated twice, with the goal of capturing the extreme scenarios for the whole PV. The CD scenarios should be chosen in such a way that all extremes are aligned in the same direction. In the example of Table 5.4, all CD scenarios minimizing the production volume should be selected together (Table 5.5). In the next iteration, all CD scenarios maximizing the production volume should be selected (Table 5.6). This results in two extreme scenarios for the production volume of product X (see Table 5.7). In case of CDs impacting the variability of the PV, the option maximizing the variability should be chosen in both scenarios, as this maximizes the degree of extremity on both sides.

Change driver	Option #1	Option #2
CD #1	-5% begin September	+5% begin September
CD #2	+10% over the next year	-5% over the next year
CD #3	+0%	+10.000 units/week begin August
CD #4	+5% variability range begin April	+0% variability range

Table 5.5: Morphological analysis for production volume of product X – scenario 1.

Change driver	Option #1	Option #2
CD #1	-5% begin September	+5% begin September
CD #2	+10% over the next year	-5% over the next year
CD #3	+0%	+10.000 units/week begin August
CD #4	+5% variability range begin April	+0% variability range

Table 5.6: Morphological analysis for production volume of product X – scenario 2.

Scenario	CD #1	CD #2	CD #3	CD #4
Scenario 1	+0% 20th December	+10% 1st October	+0% begin August	+5% var. range begin April
Scenario 2	+20% 20th December	+20% 1st September	+10.000 units/week begin August	+5% var. range begin April

Table 5.7: Results of the morphological analysis for production volume of product X.

While combining the scenarios of each CD, it is important to constantly check if it is feasible that these scenarios manifest at the same time. If this is not the case, one of the conflicting scenarios should be adjusted. The adjustment should aim to keep the scenario as extreme as possible while ensuring overall feasibility.

5.4. Phase 3 - Interpretation of results

In phase 3, the scenarios resulting from phase 2 are translated into range-response graphs, as were introduced in the theoretical framework. These graphs facilitate visual representation of the requirements for each selected adaptability type. The exact procedure of generating the range-response graph depends on the nature of the PV being quantitative or qualitative. The procedures for both are discussed separately in this section.

5.4.1. Quantitative PVs

In order to create a range-response graph for a quantitative PV, a plotting area should be established, the value of the PV indicated on the Y-axis and the time plotted on the X-axis. The X-axis should be chosen to represent the full prediction horizon as defined in phase 0. The unit of the X-axis should be equal to the aggregation window of the PV. The Y-axis should be large enough to accommodate the full range of variable values as encountered in the PV scenarios. The unit on the Y-axis should be equal to the measuring unit of the PV.

Extreme PV scenarios are plotted as projection lines, starting from the present PV value on the Y-axis. The future projections of the PV can be determined using the events and trends as listed in the PV scenarios resulting from Phase 2. The variability of the PV reflects its fluctuations around the mean value of the projection. As such, it can be represented by a band around the projection lines, as shown in Figure 5.8). The width of this band is determined by the amplitude of the variability, which can be impacted by CDs over time.

Taking the example in Figure 5.8, the projection lines now represent the predicted value of the production volume per day, averaged over every week. However, due to variability, this amount fluctuates on a day-to-day basis. A band surrounds this projection line to visualize the variability, the width determined by the amplitude of the day-to-day variation in production volume. As such, the upper border of the band linked to scenario 1 represents the highest possible daily production volume. In the same way, the lower border of the band around scenario 2 represents the lowest possible daily production volume. These upper and lower bounds are visualized in Figure 5.9. Consequently, the area in between these two lines encompass all possible states of the PV over time (see Figure 5.10). In order to account for all PPR, the system should be able to adapt to each of these possible realizations. The plotted area therefore represents the adaptability requirements in relation to the respective PV. Each point within the area indicates a separate requirement for adaptability, defined based on the value the system should adapt to and the time it is allowed to do so. For example, a point (500, 4) on a range-response graph representing the adaptability requirements for maximum input product size indicates that the system should be able to adapt to processing input products of maximum size 500mm within 4 days.

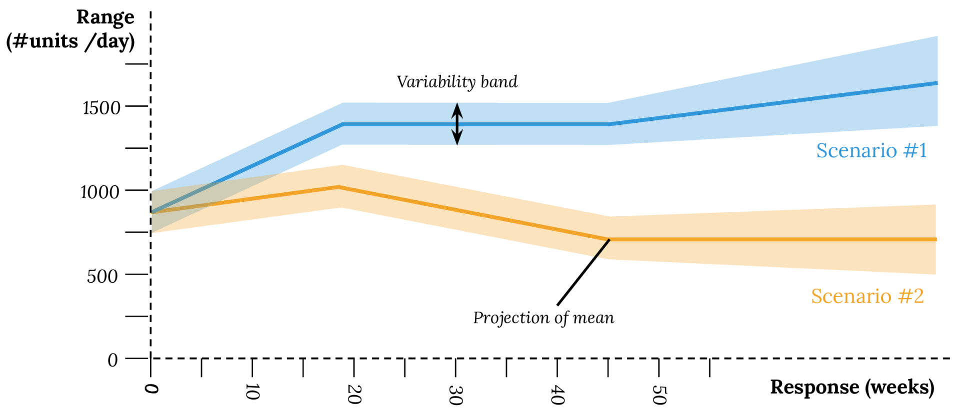

Figure 5.8: Extreme quantitative PV scenarios plotted in a range-response graph

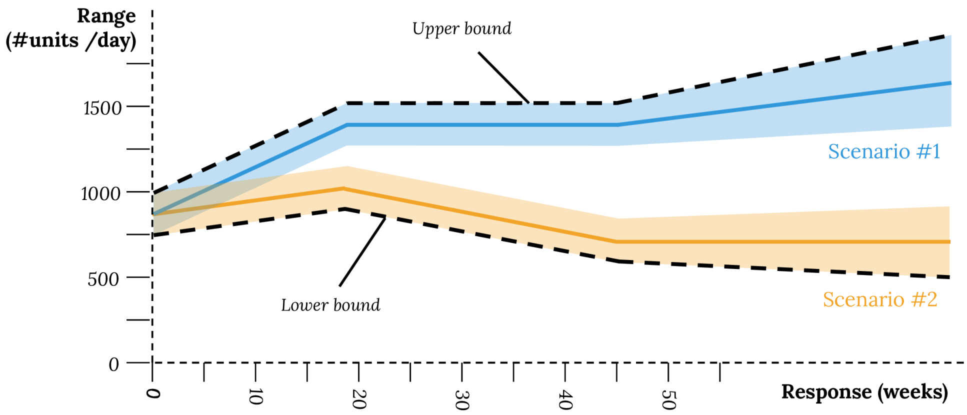

Figure 5.9: Upper and lower bound of the PV over time

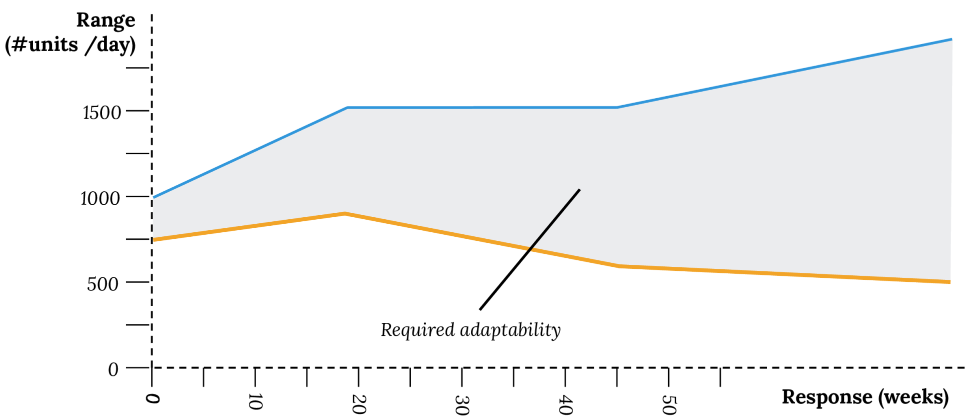

Figure 5.10: Adaptability requirements represented as a range-response graph for a quantitative PV

The procedure as described above is based on quantitatively described PVs. However, not all relevant variables might be easily quantifiable. In the case of qualitative PVs, the adaptability requirements need to be represented in a different manner. For PVs that are ordinal, or can be interpreted to be ordinal in relation to required adaptability, the quantitative intervals on the Y-axis can simply be replaced by categories. The projections of the scenarios and corresponding area of feasible PV values can be handled in the exact same way as for quantitative variables. Figure 5.11 and Figure 5.12 show an example of the adaptability requirements plotting of an ordinal PV.

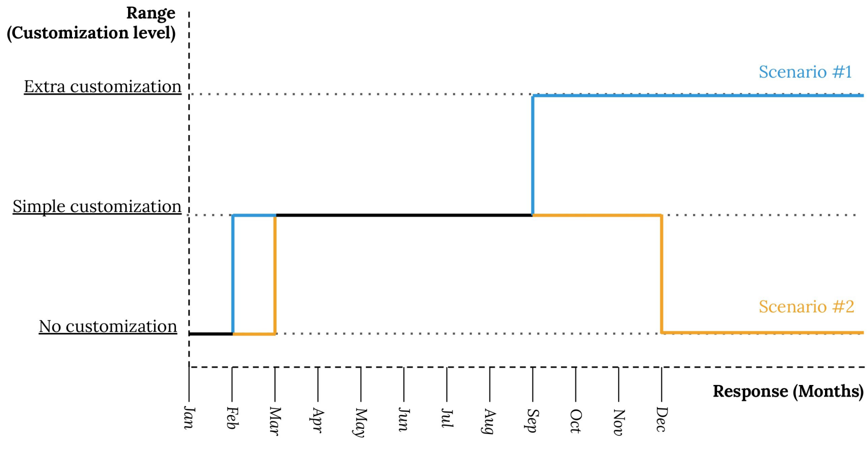

Figure 5.11: Plotting extreme ordinal PV scenarios in a range-response graph

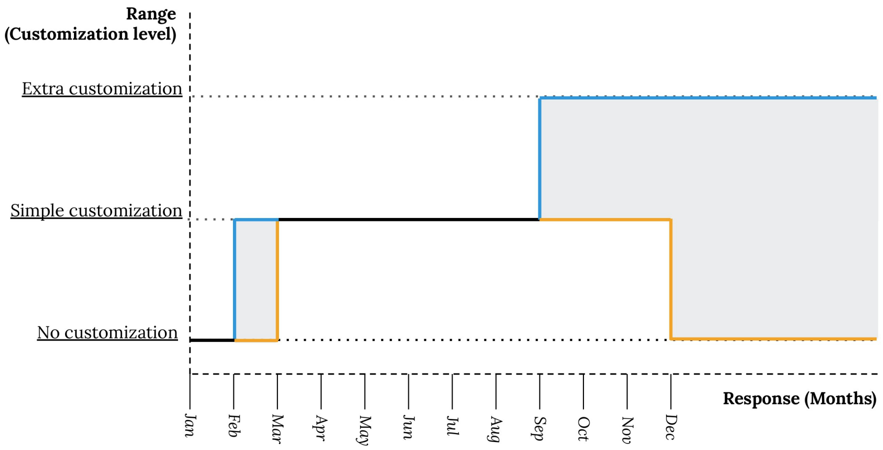

Figure 5.12: Adaptability requirements represented as a range-response graph for an ordinal PV

When assessing adaptability requirements for nominal PVs, a similar plotting area can be used. The PV categories are listed along the Y-axis, preferably in an intuitive order. By plotting the time periods the categories are predicted to realize, each scenario can be fully described on the graph (see Figure 5.13). The area of adaptability requirements in this case simply consists of all feasible realizations of the different product portfolios as determined in both scenarios.

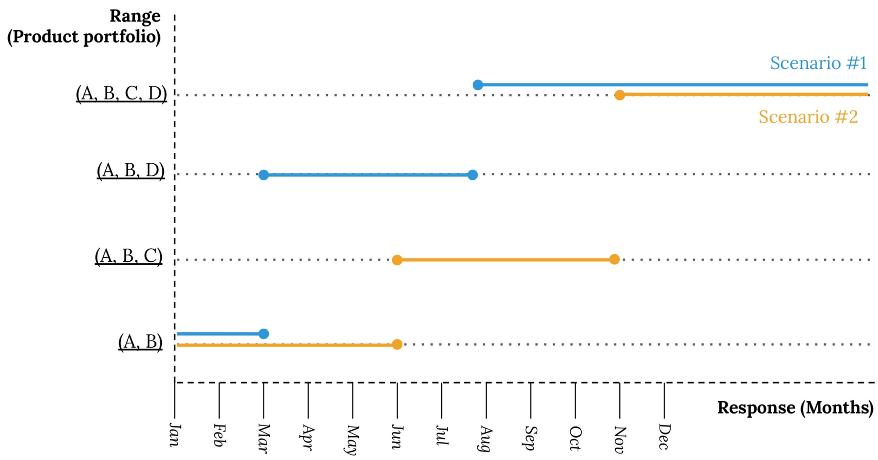

Figure 5.13: Plotting extreme nominal PV scenarios in a range-response graph

After completing the mapping process, the range-response graphs should be reviewed with company experts to assess their realism. If the results appear unrealistic, earlier phases may be revisited to adjust the graphs accordingly. The graphs themselves carry limited meaning; their value lies in the interpretation provided by company experts, who can evaluate how they influence the manufacturing system. Consequently, discussing and iterating on the results in open discussion with these experts is essential for ensuring that the graphs become a meaningful decision-making tool.

5.5. Framework application

The methodological framework finds an application on two levels of decision making. If used on a more strategic level, the framework can iteratively be used to test the effect of strategic decisions on the required levels of adaptability. As the strategic decisions function as input to the analysis, the application of the framework represents a feedback loop, as is shown in Figure 5.14. The decision maker evaluates the capability of the system against the adaptability requirements as resulting from the analysis in order to make strategic decisions related to the supplier and consumer market. Section 5.5.1 describes how the requirements can be evaluated against the systems capabilities.

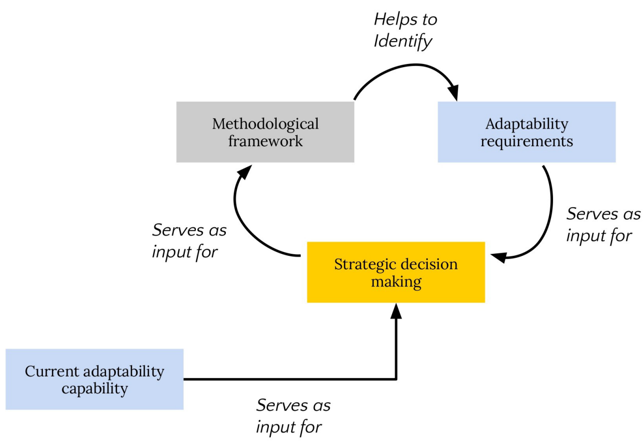

Figure 5.14: The methodological framework as applied in strategic decision making

If used on a operational level, the framework can be applied more sequentially, as depicted in Figure 5.15. The strategic decisions for the future are assumed to be fixed, and the resulting requirements are evaluated against the current system capability. The insights resulting from the analysis can be used to make more operational decisions like reconfiguration plans or working schedules. Section 5.5.2 elaborates on how the framework can be used as a tool in reconfiguration plan design.

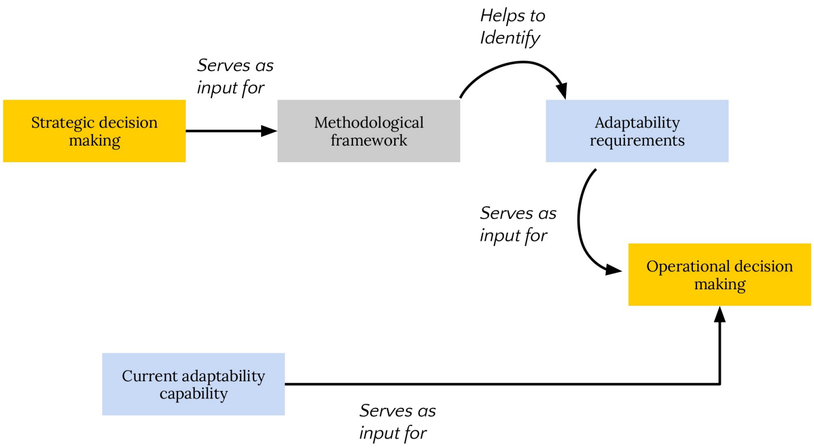

Figure 5.15: The methodological framework as applied in operational decision making

5.5.1. Evaluation against system capability

In the same way as for adaptability requirements, range-response graphs can also be used to express the capability of the system in regards to manufacturing adaptability (see Figure 5.16). Instead of the response time allowed for change, the X-axis now represents the response time that is needed to realize the change in system capability. Taking the example in Figure 5.16, it can be seen that System II requires some time before adapting, but then is able to adapt to a large range quickly. On the contrary, System I is able to start adapting immediately, but has a limited range and slower response.

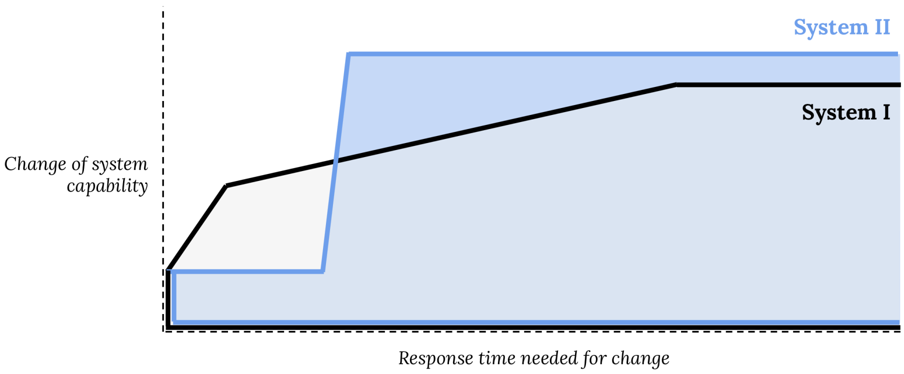

Figure 5.16: Adaptability capability expressed as a range-response graph for two fictional manufacturing systems

The adaptability capability of the system can be evaluated against the required adaptability by overlaying the graphs. Figure 5.17 evaluates the adaptability capability against the adaptability requirements of system I. The area in red shows the area where the required adaptability exceeds the adaptability capability, predicting a potential problem in future operation of the manufacturing system. In this example, the adaptability range of the system is sufficient, but the response is inadequate.

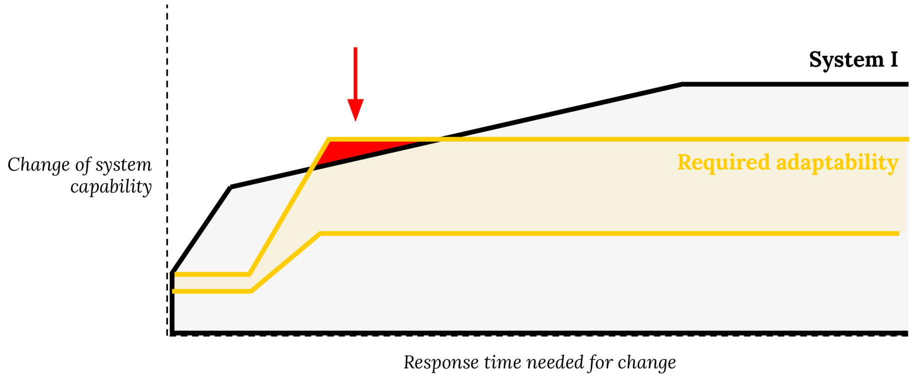

Figure 5.17: Evaluating the adaptability requirements against the capability of the system

5.5.2. Reconfiguration decision making

While RMS has to potential to the be the solution to cope with the unpredictable market changes in a cost-effective way, large scale industrial implementation is still limited (Koren et al., 2018). One of the barriers faced in implementation of RMSs are the current difficulties in identifying long-term requirements. The methodological framework as proposed in this paper has the potential to be used as a tool in the reconfiguration decision making process. While the range of flexibility, or "flexibility corridor", is constant within a certain system configuration, reconfiguration can lead to a shifted range of flexibility, see Figure 5.18.

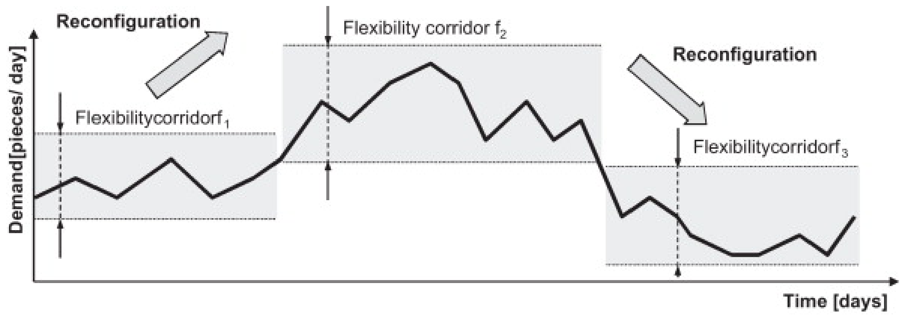

Figure 5.18: Impact of reconfiguration on flexibility (Azab et al., 2013)

As such, reconfiguration of a manufacturing system can shift the capability of a manufacturing system to fit the production requirements as needed. As reconfiguring takes effort and induces (partial) system downtime, reconfigurations are always connected to monetary and temporal expenses (Kurniadi & Ryu, 2017). It is therefore crucial to schedule reconfigurations efficiently and only when needed. By overlaying the flexibility corridor on the required adaptability of the system, the point where the available flexibility is potentially exceeded in becomes apparent (Figure 5.19). The required adaptability can thus be used to design a reconfiguration plan to counter future changes (Figure 5.20).

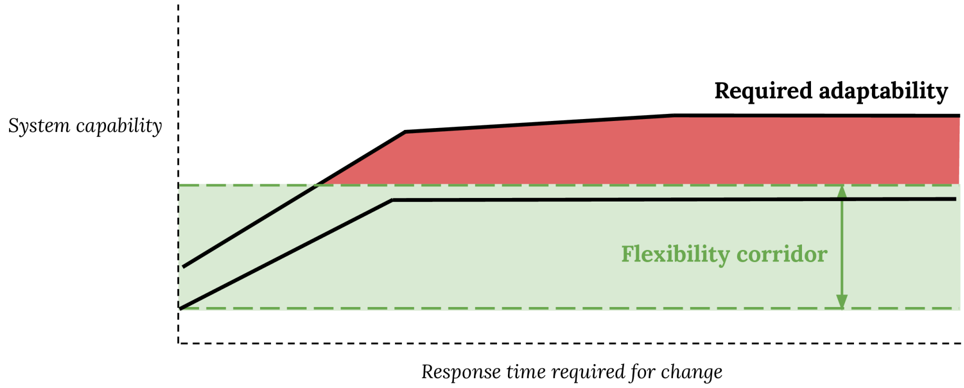

Figure 5.19: Evaluating the required capability against the current flexibility corridor

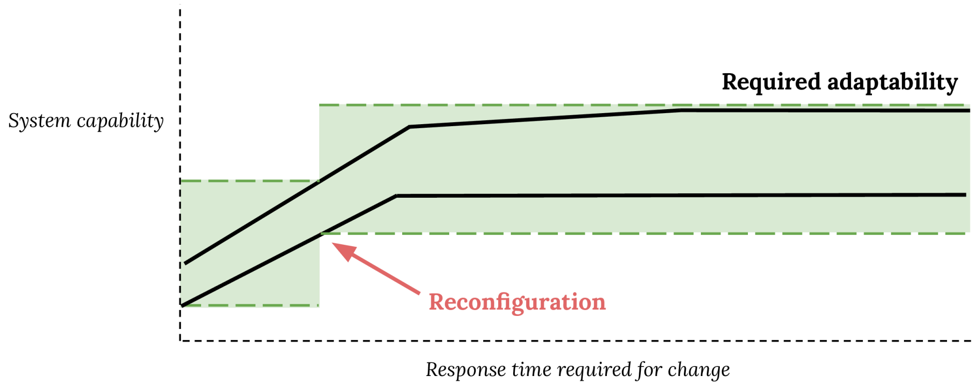

Figure 5.20: The range-response graph as tool for reconfiguration decision making

5.6. Link to theoretical framework

The methodological framework was directly based on the theoretical framework as presented in Chapter 4 . This is reflected in the fact that the theoretical framework conceptualizes the manufacturing system as an input–output transformation, which is similar to the representation underlying the method. The recognition that the need for adaptability arises from volatility and uncertainty is brought into practice through the scenario-based approach, which was adopted specifically to capture both of these factors. In addition, the Uncertainty–Impact and Volatility–Impact matrices, providing a systematic tool for selecting relevant PVs, are directly based on these two elements.

The theoretical link between PVs and adaptability types is used in the methodological framework to define the set of adaptability requirements that need to be generated. Question set A is directly based on the classification of adaptability types as proposed in the theoretical framework. Similarly, the theoretical distinction between trends and events forms the basis for Question set B. By proposing the use of an aggregation window, the differentiation between variability and shifting of mean is brought into practice. Finally, the introduction of range–response graphs as a way to visually express adaptability is directly adopted as a way to generate requirements in the practical method. An overview of the theoretical assumptions as posed in Chapter 4 and corresponding implications for the methodological framework as presented in this chapter is provided in Table 5.8.

Theoretical assumption	Methodological implication
Manufacturing system can be interpreted as an input–output transformation	Manufacturing system is simplified to an input–output transformation
The need for manufacturing adaptability arises from expected volatility and uncertainty of predictions	Scenario generation as a way to capture uncertainty in projections Uncertainty–Impact and Volatility–Impact matrices as tools to select relevant PVs
Proposed classification of adaptability types	Classification used in Question set A, determining the final set of requirement types
Change drivers can be classified as either a trend or an event	Distinction used in Question set B
PV changes can be classified as either variability or shifts of the mean	Implications for the generation of range–response graphs Distinction used in Question set B Definition of an aggregation window
Variability can be described in terms of frequency and amplitude	Variability is described in terms of frequency and amplitude
Range–response graphs can be used to represent adaptability in two dimensions	Adaptability requirements are represented in the form of range–response graphs

Table 5.8: Overview of theoretical assumptions and corresponding methodological implications.

6
Case study

This chapter presents the case study in which the methodological framework was applied. First a general introduction of the case is provided. Subsequently, the application of the methodological framework is presented. Finally, the results of the analysis are discussed. The case serves two purposes in this research. First, case was employed in an explorative manner, providing guidance while developing the methodological framework . Second, the case was used to illustrate and evaluate the application of the proposed method. In Section 6.2, the application of the method on the case system is demonstrated. The insights gained from the case study regarding the functioning and applicability of the framework are discussed in Chapter 7.

6.1. Case introduction

The case was performed at a factory dedicated to the processing of cacao liquor, to be referred to as Factory X. Cacao liquor, also known as cocoa mass, is produced by grinding roasted cacao beans into a thick, smooth paste. It serves as the foundational ingredient for various chocolate products. The cacao liquor is converted into two main streams of output products: Cacao butter and cacao powder. The factory is owned by a large multinational corporations headquartered in the US, active in the agricultural and food sector, from now on referred to as Company X. Given the companies extensive vertical integration in the cacao supply chain, it is relevant to note that the preceding production step, the processing of raw cacao beans, is also managed by Company X. Factory X has two main factories that supply cacao liquor, which are referred to as Factory B and Factory S. Aside from cacao liquor, Factory X sometimes also requires cacao butter and cake used as additives in production, both of which are sourced from external suppliers. The majority of Factory X's production is destined for further processing in facilities operated by Company X. The remaining goods are intended for other clients or the market of the respective commodity. Figure 6.1 shows the direct supplier and consumer relations affecting Factory X.

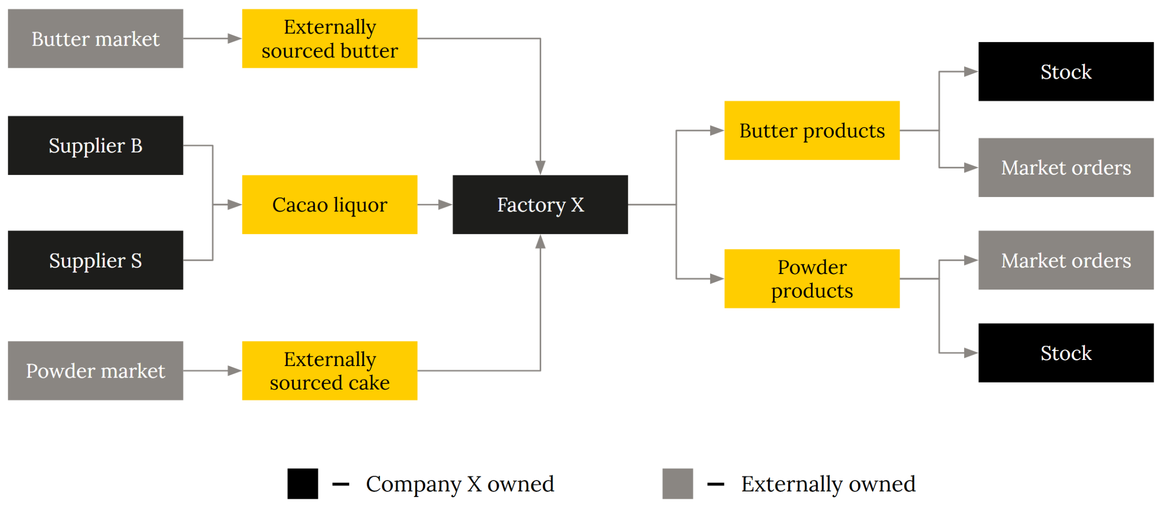

Figure 6.1: Suppliers and customers of Factory X

6.1.1. The production process

Before entering the production process, the cacao liquor is being stored in mass tanks, kept at a temperature of 85-90 °C. When first entering the production process, the cacao liquor is being brought to a temperature of 155 °C in conditioning tanks. This preheating lowers its viscosity and makes it easier to handle during pressing. The warm liquor is then in batches fed into hydraulic presses, which apply extremely high pressure to extract the fat content: the cacao butter. What remains in the press is a firm cacao cake, used to produce cacao powder. The presses typically handle batches of around 180 to 200 kg of cacao liquor, which is converted approximately half-half to cacao butter and cacao cake.

The extracted cacao butter is collected in liquid form and sent to the butter refinery, which consists of filtration and conditioning tanks, where any remaining solid particles are removed. In some cases, externally source butter need to be introduced in the production process, depending on the desired characteristics of the output product. After filtration, it's cooled down in a controlled manner to produce solid cacao butter blocks or chips that can be used to produce numerous products. These blocks are then sent to the packing stations, where they are made ready for shipment.
What remains after in the press after pressing is a firm cocoa cake. This is broken down and transferred to a section of grinding units, where it's milled into a fine, dark powder. After milling, the powders can be mixed with other cacao powders in order to achieve the desired characteristics for the output product. The added powder can either be produced in-house or imported from other factories. The cacao powder finally proceeds to the packing lines, where it is made ready for shipment. The production process in Factory X is schematically visualized in Figure 6.2.

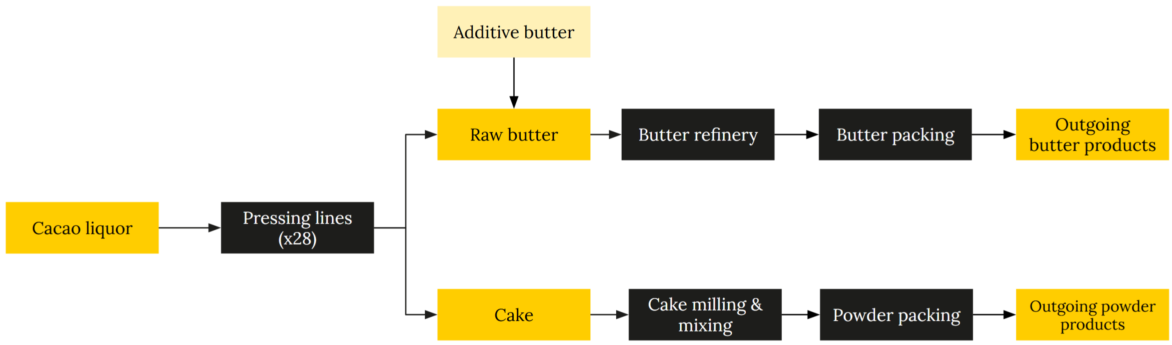

Figure 6.2: The production process at Factory X

6.1.2. Production planning

Within the scope of this case study, the production planning process consists of four hierarchical levels. On the most strategic of the levels, a three monthly planning is constructed for Factory X. This planning is not constructed at the factory itself, but is made at the national headquarters. This is part long-term supply chain planning and incorporates activities at instances further upstream in the supply chain. Based on this long-term strategic planning, a tactical mid-term planning is created. Whereas the long-term planning focuses on contracts, the mid-term planning focuses on actual sales orders, spanning a time scope of 3-4 weeks.

Based on the mid-term planning, a short-term, factory-specific planning is made. This planning is revised daily, and comprises a horizon of 3-4 days. The planning is based on the output requirements, often encompassing around 120 orders for butter products along with a similar number of powder orders. This schedule includes planned maintenance, the schedule of which is determined each Friday for the next week. The production planner creates a schedule for each of the pressing groups, determining which cacao liquor type is to be processed at what time. A production run of products of the same type is referred to as a “bucket”. Similarly, the production planner schedules the buckets for the processing operations specific to butter and cake. Such a bucket typically runs for 1 to 3 days before a changeover to another product type is required. A changeover from bucket to bucket on the pressing line typically takes around 45 minutes.

Based on this schedule, the factories shift manager makes the operational planning for the day. This includes the exact assignments and operation schedules of each machine and is constantly updated based on disruptions or other unforeseen events.

Planning	**Planning horizon**	**Planning level**	**Planning based on**
Long-term planning	3 months	Supply chain	• Sales forecast • Customer contracts • Supplier contracts
Mid-term planning	3–4 weeks	Supply chain	• Long-term planning • Actual sales orders
Short-term planning	3–4 days	Factory X	• Mid-term planning • Planned downtime/-maintenance
Operational planning	1 day	Factory X	• Short-term planning • Disruptions • Machine schedules

Table 6.1: The four levels of production planning for Factory X.

6.2. Application of methodological framework

The methodological framework was applied in collaboration with a number of different company experts. Not all stakeholders collaborated on each phase of the methodological framework. Figure 6.3 highlights the company experts that were consulted in each of the phases of the methodology.

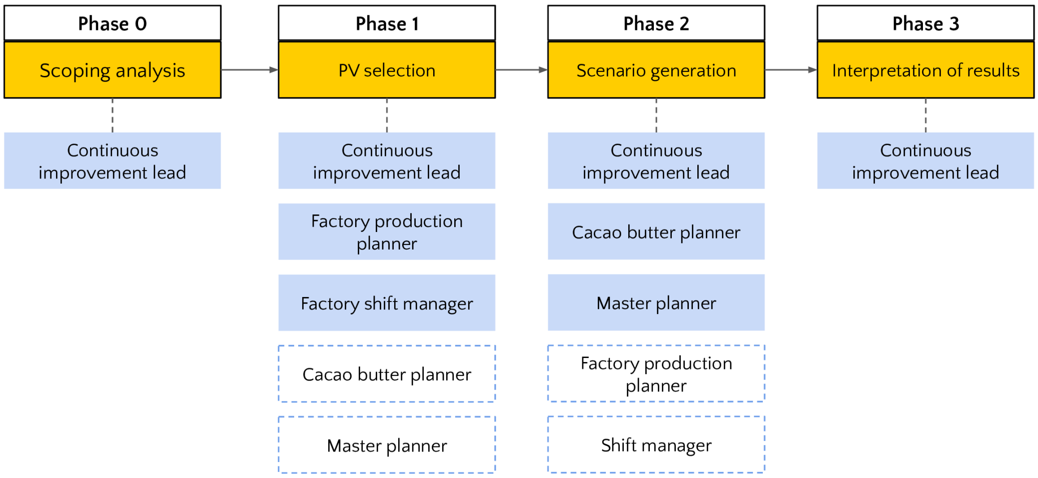

Figure 6.3: The company experts consulted in each phase of the case study

The continuous improvement lead was the commissioner and direct contact person for the analysis. As such, it was important that this person was involved in each phase, especially the scoping of the analysis and interpretation of results.

For the identification of PVs, Question set A was conducted fully on three individuals. The cacao butter supply chain planner and master planner were only asked if they agreed with the selected list of PVs and if they did have any additions. This decision was made to reduce discussion time for these individuals, allowing one interviewing session to be sufficient. The factory production planner and shift manager did participate in scenario generation, but at this time phase 2 of the methodological framework was still in the pilot stage. As such, the results were gathered non-systematically and cannot be used in the final analysis. In total, seven interview sessions were conducted to fully perform the methodological framework. The role of each company expert will now shortly be detailed.

- **Continuous improvement lead Factory X**
  As an improvement lead, this individual is informed on the functioning of all facets of the production system. In addition this person is very knowledgeable about the existing potential of adaptability and possible bottlenecks that need to be kept into consideration.
- **Production planner Factory X**
  As discussed in the case introduction, the production planner is responsible for making the tactical planning of the factory. Therefore, this person is directly impacted by the changing production requirements and available input. As such, this is the most knowledgeable individual within the factory in relation to the volatility of these two categories. In addition, this specific production planner also had experience as a planner in the related supply chain team, further increasing his knowledge.
- **Shift manager Factory X**
  The shift manager oversees the day-to-day operations on the factory floor and is in control of the production planning on an operational level. As such, this person is an expert on short term disruptions and technical characteristics of the manufacturing process.
- **Master planner cacao beans & butter**
  The master planner plans the throughput of cacao liquor to Factory X based on the cacao butter

contracts and information about the cacao beans coming into factory -1. As such, this person is knowledgeable long-term projections for characteristics of both cacao liquor and cacao butter.

- **Cacao butter planner**
  The cacao butter planner plans the production of cacao butter on a mid-term basis, this being a scope of 3–4 weeks. Whereas the master planner mostly looks at projections on a contract level, the cacao butter planner looks at actual sales orders. As such, this person is very knowledgeable on the characteristics of cacao butter on a mid-term scale.

Each of the participating company experts was responsible for the production planning of Factory X on different hierarchical levels. Table 6.2 shows the role of each of the company experts linked to the levels of planning that were distinguished in previous section. The continuous improvement lead is not directly responsible for a planning, but instead is involved in streamlining the factories performance, ranging from an operational to mid-term scope.

Planning	**Responsible employee**
Long-term planning	Master planner cacao beans & butter
Mid-term planning	Cacao butter planner
Short-term planning	Factory X production planner
Operational planning	Factory X shift manager

Table 6.2: The responsible planner on each level of decision making.

6.2.1. Phase 0 - Scoping analysis

In collaboration with the continuous improvement lead, the scope and prediction horizon for the analysis were defined. First, the case company was simplified to an input-output transformation, as shown in Figure 6.4.The additives in the production process were left out as they were assumed to be redundant in relation to adaptability of the system. The simplified system takes cacao liquor as the single input stream into the system. The output of the system consists of cacao butter and cacao powder. All inputs and outputs were considered to be exogeneous, as prescribed in the methodological framework. Strategic decision making impacting the realizations of these variables are assumed to be outside of the scope of the case study. In the case of Factory X, this implies that the demand requirements as provided by the national supply chain team are the start of the decision making process. How these demand requirements originated on supply chain level is outside of the scope of the analysis. Similarly, the input component is simply determined by the supply of cacao liquor being processed. How this cacao liquor originated from upstream in the production chain is not of primary interest.

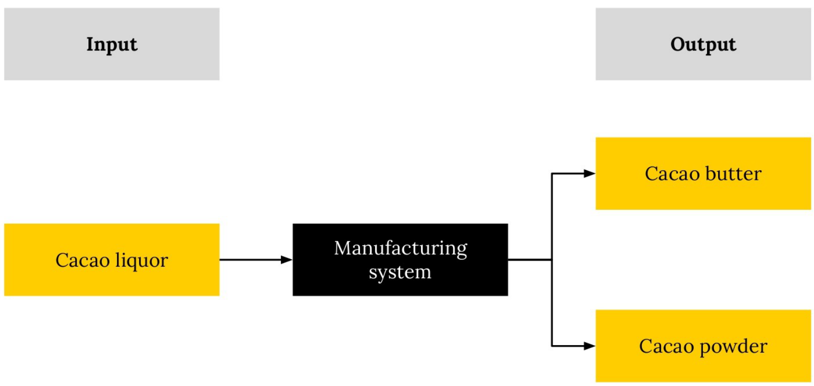

Figure 6.4: System scope as defined for the case study

The prediction horizon was defined to be twelve months, or one year. It was estimated that this is long enough to capture relevant developments, while not so long that future events become entirely unpredictable. Moreover, a one-year horizon provides sufficient time to take corrective action should the system's adaptability prove inadequate.

6.2.2. Phase 1 - PV selection

The identification of relevant PVs was performed using Question set A in three semi-structured interviews. The interviews were conducted in collaboration with the continuous improvement lead, the factories production planner and the factories shift lead. These individuals were selected because each possesses expertise at a different level of manufacturing system operations. This ensured that PVs across all levels could be captured, resulting in a more comprehensive overview.
The three interviews led to the following PVs being identified as relevant to the required adaptability of the system:

PV	Measurement	Aggregation window
Cacao liquor FFA content	Average FFA % per batch	Month
Cacao liquor volume	Processed tonnes per day	Month
Cacao liquor mix	Number of different types processed per week	Month
Cacao butter portfolio	Main type groups in portfolio	Month
Cacao powder portfolio	Main type groups in portfolio	Month
Cacao liquor contaminants	Average contaminant % per batch	Month
Cacao liquor color	Average level of alkalization per batch	Month

Table 6.3: The selected PVs along with their unit of measurement and aggregation window.

While cacao liquor contaminants is listed as a single PV, in reality, there are multiple contaminants that are measured in the cacao liquor. For the simplicity of description, the contaminants are here represented by a single PV. Due to the limited time and information available for this case study, it was decided to select only the PVs cacao liquor FFA content, cacao liquor volume and cacao butter portfolio for further analysis.

6.2.3. Phase 2 - Scenario generation

Phase 2 was performed in three semi-structured interviews with the continuous improvement lead, the master planner and the cacao butter supply chain planner. For the scenario generation, interview participants were primarily drawn from the planning side, as they were expected to have more accurate insights into future developments than individuals in operational roles, such as factory shift managers. Appendix E presents the PV statuses gathered from the different interviews. For each selected PV, the present value and variability were determined to be as presented in Table 6.4.

PV	Present value	Present variability
Cacao liquor FFA content	2.1% FFA percentage	• Amplitude: 0.5% • Frequency: Daily
Cacao liquor volume	580 tonnes per day	• Amplitude: 50 • Frequency: Daily
Cacao butter portfolio	(Standard / Mainstream RFA / Low alk / High alk)	–

Table 6.4: Present value and variability of the selected PVs.

The initial identification of CDs was performed for each PV using Question set B. For each CD, two extreme scenarios were constructed. Subsequently, a morphological analysis was performed to combine the CD scenarios in complete PV projections. Appendix F shows the identified CDs and the corresponding generated extreme scenarios for each respondent. The CD scenarios for each respondent were synthesized and subsequently subjected to a morphological analysis. The scenarios for each PV generated in the morphological analyses are shown in Figure 6.5, Figure 6.6 and Figure 6.7.

Cacao liquor FFA content		
CD	**Scenario #1**	**Scenario #2**
Mid-crop arrival	-1% over September to December	-0.5% over September to December
Main-crop arrival	-0.3% over February	-0.3% over February
Monthly crop deterioration	+0.13% monthly	+0.17% monthly
Strategic blending choices	No change	No change
Bean supplier change	-1% over 12 months	+1% over 12 months
Better sampling implementation	Var. Amplitude +0.25% over 12 months	Var. Amplitude +0.25% over 12 months

Table 6.5: Extreme scenarios constructed for cacao liquor FFA content.

Cacao liquor volume		
CD	**Scenario #1**	**Scenario #2**
Change in quality of harvest	-15% over next year	+10% over next year
EUDR enactment	-5% from January	-2% from January
New contamination regulation	-5% from December	No change
Seasonality	No change	+15% during September – November
Factory X takeover	+90 from September	+110 from September
New contract acquisition	-30 tonnes over 12 months	+30 tonnes over 12 months

Table 6.6: Extreme scenarios constructed for cacao liquor volume.

Cacao butter portfolio		
CD	**Scenario #1**	**Scenario #2**
Rouen takeover	+ Organic butter type from start September	+ Organic butter type from start November
Unconsolidated segregated streams	+ Segregated butter type from start January	No change

Table 6.7: Extreme scenarios constructed for cacao butter portfolio.

6.2.4. Phase 3 - Interpretation of results

In phase 3, range-response graphs were created based on the PV scenarios using Microsoft Excel and Python. First, the extreme scenarios were plotted, the result of which can be found in Appendix G. Subsequently, the range-response graphs representing adaptability requirements were constructed by tracing the outer borders of each scenario. This resulted in the following set of adaptability requirements:

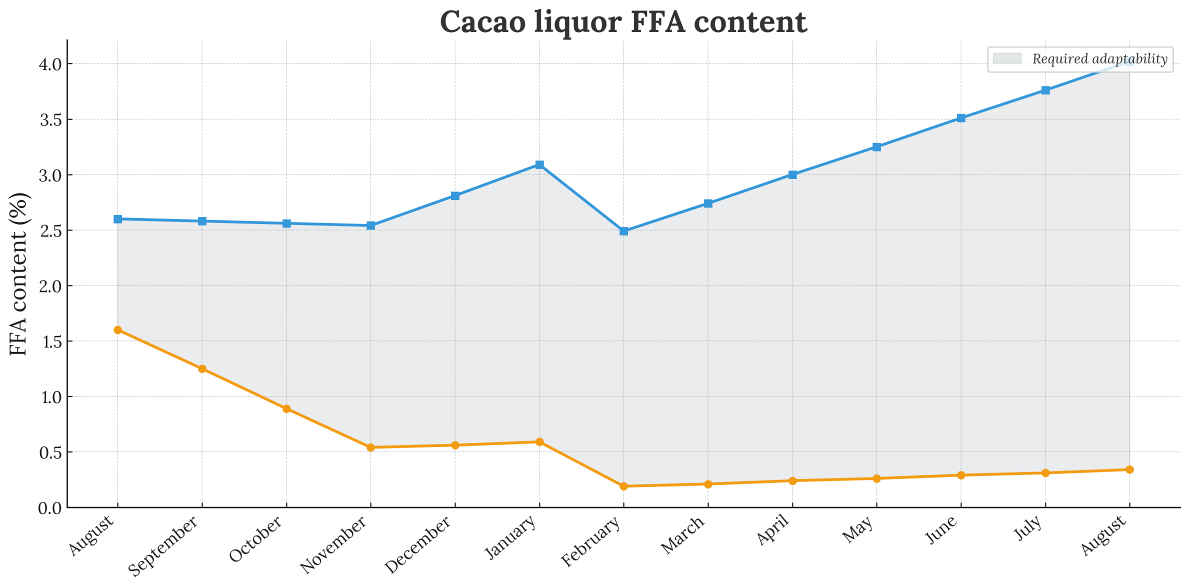

Figure 6.5: Adaptability requirements (Cacao liquor FFA content)

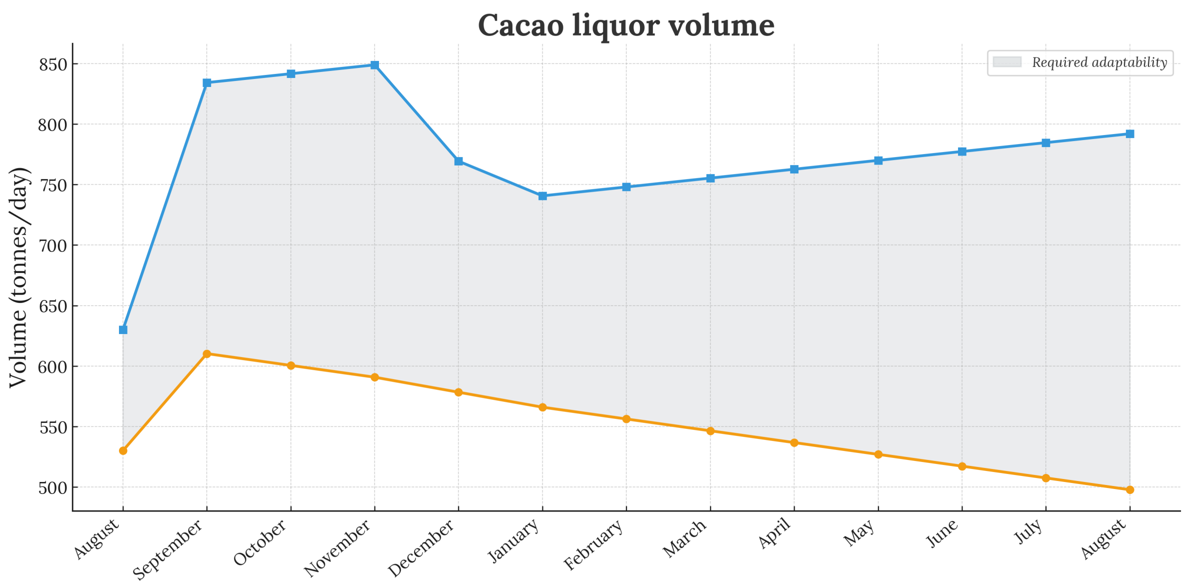

Figure 6.6: Adaptability requirements (Cacao liquor volume)

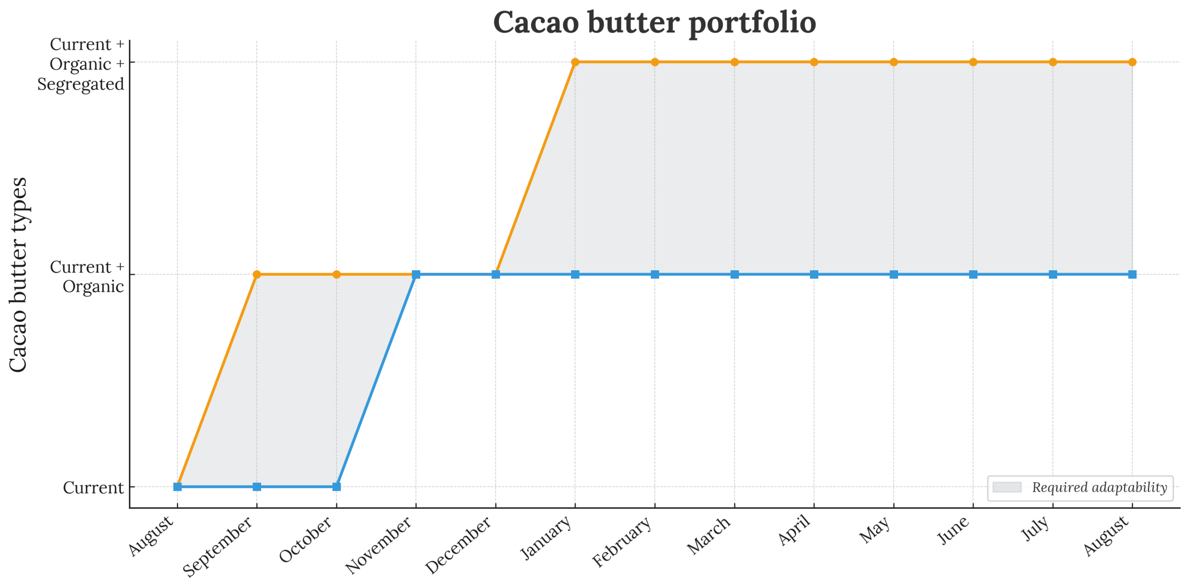

Figure 6.7: Adaptability requirements (Cacao butter portfolio)

The results of the analysis were discussed with the continuous improvement lead of Factory X. The goal of this discussion was twofold. On the one hand, the range-response graphs were analyzed to obtained insights into the required adaptability of the system. The perceived realism and usability of these results were examined. The results of Phase 2 (scenario generation) were also discussed, especially concerning the differences between respondents and their respective effect on the adaptability requirements. On the other hand, the session was utilized to obtain feedback on the methodology. A structure similar to the expert interviews was used in the discussion to verify and validate the methodological framework, the results of which are presented in Chapter 7.

6.3. Conclusion

The adaptability requirements as formulated in the case study represent the required adaptability in three types. The projections can be evaluated against the capability of the system to highlight areas that may require attention. For the volume, it is apparent that the system is possibly required to accommodate a large increase in the next four months. A evaluation may be necessary to assess whether the system is able to accommodate such a shift. In relation to the butter portfolio, it is clear that from January onwards a new segregated butter type may be required. It should be investigated if the manufacturing system is able to accommodate yet another segregated type. If this is not possible, adjustments to the system may be needed in time for the demand to be fulfilled. In practice, given the limited number of interviews conducted in this case study, these results should not be interpreted as an accurate representation of reality. Even so, the CDs and their effects can provide a glimpse of what is to come and how this affects the requirements of the system.

By comparing the interviews in the case study, it becomes evident that there are substantial differences in the CDs and PVs identified by each respondent. Likewise, the estimated effects of these drivers often vary. On one hand, this suggests that the set of interviews conducted in this case study likely does not provide a complete picture. Additional interviews could reveal new CDs or lead to alternative interpretations of existing ones. On the other hand, this highlights the value of the framework in capturing diverse perspectives and enabling comparison of differing perceptions. Each interview yielded additional insights into the manufacturing system, one by one contributing towards a holistic overview of all relevant factors. As such, the case study may have contributed to create an overview of relevant factors affecting the production system in Factory X.

7

Framework evaluation

In this section the results of the preliminary evaluation of the methodological framework are discussed. First, the feedback obtained from the expert interviews is presented. Second, the insights that resulted from the application of the framework in the case study are addressed.

7.1. Expert interviews

The evaluation results as addressed in this section originate from four semi-structured interviews. The procedure in which these interviews were conducted is addressed in Chapter 2. Interviews were conducted with three associate directors from Accenture, an international consultancy firm. The directors were part of a team dedicated to the manufacturing industry, each with over 15 years of experience working in the sector. In addition, the continuous improvement lead at the case company, who was involved throughout each phase of the case study, was interviewed to evaluate the implementation of the method. Figure 7.1 provides an overview of the experts that participated in the evaluation interviews. The feedback resulting from these interviews is structured in three areas. First, the perceived weaknesses of the method are examined, followed by its perceived strengths. Finally, proposed improvements to the framework are presented.

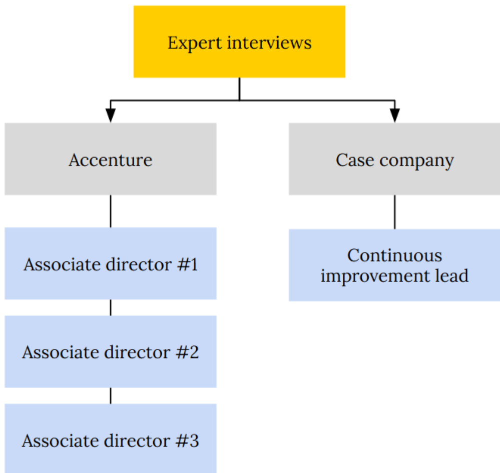

Figure 7.1: Expert interviews

7.1.1. Perceived weaknesses

The biggest weakness of the methodological framework as perceived by the interviewed experts was its strong dependence on the quality of input. Since the generated requirements are directly derived from the information provided by company participants, any unreliable data or predictions compromise the reliability of the entire output. As one interviewee put it: *"Garbage in, garbage out."* Another respondent further noted that, since the interviews are semi-structured and rely heavily on insights emerging from open discussion, the interviewer's skill becomes a critical determinant of the quality of information feeding into the analysis. An inexperienced interviewer may overlook important PVs, thereby substantially affecting the method's outcomes. This risk was considered particularly significant in Phases 0 and 1 but was believed to be less significant in Phases 2 and 3. An interviewee pointed out that, in practical application, it may be difficult to identify and involve individuals within the company who possess the necessary knowledge. This presents an additional challenge in obtaining high-quality input for the analysis. The initial scoping phase constitutes another perceived risk. Defining the scope of the manufacturing system is a critical step in the methodology, yet making an appropriate scoping decision requires comprehensive understanding of the production process. To ensure Phase 0 is carried out correctly, the analyst should be informed properly on how the process operates.

Another limitation of the framework as identified during the expert interviews is its lack of ability to account for the interdependence of PVs. In practice, PVs might interact in the production process, necessitating scenario's that predict the future for both PVs at once. Adaptability requirements for both PVs can be examined separately, but interdependence between the CDs constituting the extreme scenario's is not accounted for.

7.1.2. Perceived strengths

In general, the experts perceived the gap targeted by the methodology as highly relevant. They emphasized that, in their experience, the industry currently lacks such a practical method while its value is evident. It was noted that, while manufacturers might have similar practices in place, a systematic procedure was typically lacking. The combination of such a step-by-step guide based upon a solid theoretical foundation was perceived to be refreshing. It was indicated that a strength of the framework was its practical approach. The interviewees indicated that such a practical approach specifically suited the manufacturing industry, as this is a very practice-oriented sector.

The respondents considered the framework's greatest strength to be its systematic and repeatable nature. For one participant, repeatability was important because it enables reiteration over time, allowing stakeholders to learn from the results and compare them with realized scenarios, thereby continuously improving the analysis. Another participant emphasized that repeatability facilitates comparisons across company departments. By conducting the phases on varying employees, differences between departments become visible, enabling management to address disparities and get everybody on the same page. Multiple respondents praised the ability to bring together fragmented sources of information throughout a manufacturing company. They noted that, although most companies hold sufficient expertise, what is often missing is the ability to integrate and mobilize this knowledge effectively.

The visual representation of requirements was thought to be really useful, especially for easy communication of requirements. Even so, all experts agreed that the framework's main value did not lie in the adaptability requirements themselves. Rather, it is the systematic exercise of formulating these requirements that holds the true potential to generate insights for decision-makers.

7.1.3. Proposed improvements

A number of possible improvements to the framework were proposed to further increase its practical value.

- The inclusion of a feedback loop, enabling comparisons between projected scenarios and realized outcomes, was regarded as a potentially valuable addition. Such a mechanism would allow stakeholders to learn from past inaccuracies and progressively refine their predictions. Moreover, analyzing scenarios at the level of individual CDs could reveal how accurately specific effects were estimated. To further support this process, an interviewee suggested that the formulation of requirements could be made interactive, enabling users to trace changes in projections directly back to their underlying drivers.

- Another proposed improvement was the inclusion of a categorization of CDs, similar to the PV categorization. This could be used in combination with an updated questions set to structure the identification process in Phase 2. This would help interviewees systematically consider relevant trends and events that may affect the PV in the future, thereby reducing the risk of overlooking important factors. Along similar lines, one expert recommended providing illustrative examples of CDs to spark the inspiration of the respondents.
- Finally, it was suggested that the framework could be extended to incorporate even more temporal scales beyond variability and mean shifts, for instance by distinguishing between short-, medium-, and long-term horizons.

7.2. Case study insights

The application of the methodological framework on the case, as presented in Section 6.2 resulted in the following insights for the author of this thesis:

- When conducting the interviews, it is crucial to clearly explain the framework's purpose and boundaries at the outset. Although respondents were knowledgeable and eager to help, they often struggled to see where their input was needed and tended to delve into technical details beyond the scope of the methodological framework. Starting each session with a clear explanation helps focus the discussion and frames the interview as a collaborative exercise.
- Useful information exists within the company but is dispersed across people and digital sources. Every new interview in the case study lead to a range of new insights and potential CDs that were not identified earlier. In practice, interviews with many employees are needed to capture the full picture of adaptability. It is not essential to predefine all interviewees, as company experts often refer to colleagues better suited to specific questions.
- The initial selection and, in particular, the formulation of PVs should be approached with a high degree of flexibility. Insights obtained at later interviews often necessitate adjustments to the originally defined PVs.
- The company experts which participated in the method were interested and curious about the result. They thought, while acknowledging that this pilot would only result in rough estimations, that this was a meaningful exercise that could potentially lead to new insights.

7.3. Conclusion

The preliminary evaluation of the methodological framework in the case study and expert interviews resulted in several interesting insights and feedback. The framework's main weakness was perceived to be its reliance on input from company employees, posing a risk to the reliability of the outcomes. The value of the framework was perceived to be twofold. First, the visual representation of adaptability requirements facilitates clear communication and provides insight into potential future developments. Second, the systematic nature of the procedure was considered very valuable for consolidating information across the organization, creating a holistic overview of the factors influencing adaptability. In addition, it enables comparisons between the perspectives of different departments.

Although a number of potential improvements were proposed, the method was generally positively received. Moreover, the potential value unlocked by applying the framework was regarded as evident.

8

Discussion

First, the framework developed in this research is positioned in relation to existing literature. Subsequently, its practical implications are discussed. Third, the limitations of both the framework and the research process are addressed. Finally, recommendations for further research are presented.

8.1. Theoretical implications

This research advances a new theoretical perspective by integrating flexibility and reconfigurability as existing strategies for coping with dynamic manufacturing environments. While similar integrations have previously appeared in the literature under the concept of *"changeability"* (Napoleone et al., 2021; Schuh et al., 2009; Wiendahl et al., 2007), this study departs from that notion by adopting the term "adaptability". Unlike changeability, which is sometimes extended to encompass broader and more strategic notions such as transformability and agility (Wiendahl et al., 2007), adaptability is here explicitly defined as the direct combination of flexibility and reconfigurability. Furthermore, a new definition is proposed for manufacturing adaptability as the capability of a manufacturing system to adjust its production capacity and functionality in response to changing manufacturing requirements.

In the existing literature, the need for adaptability is generally attributed either to environmental uncertainty (B1) or to anticipated changes (B2). In the theoretical perspective proposed in this thesis, the need for adaptability is conceived as stemming from both the expected volatility and the uncertainty of predictions, thereby synthesizing these two viewpoints into a unified framework. Furthermore, rather than distinguishing short-, mid-, and long-term changes as in A.-L. ; Andersen et al. (2023) and Napoleone et al. (2021), a differentiation is made between variability and shifts of the mean. This distinction is not tied to a fixed temporal horizon but instead depends on the nature of the manufacturing operations under consideration.

Proposed methodologies in the existing literature generally express adaptability requirements in "flexibility types" (B1), or "reconfigurability characteristics" (B2). This thesis introduces a new classification of adaptability types, the taxonomy of which incorporates elements from established classifications of flexibility proposed by Olhager and West (2002), Narain et al. (2000), and Mishra et al. (2014). Whereas these prior classifications primarily focus on adaptability with respect to production outputs, the present framework also accounts for adaptability concerning the inputs processed by the manufacturing system. The few existing approaches that attempt to specify required levels of adaptability typically do so using qualitative descriptors, such as "high" or "low", which indicate only general magnitudes of each flexibility type or reconfigurability characteristic. This research proposes the use of range-response graphs to visually express the required level of adaptability for each type in detail. In Table 8.1, the concepts and terminology introduced in this research are compared to the existing perspectives outlined in Chapter 3.

	B1	B2	Proposed framework
Nature of adaptability	Flexibility	Reconfigurability + flexibility	Adaptability
Origin of need	Environmental Uncertainty + Manufacturing strategy	Change drivers	Environmental uncertainty + Change drivers
Formulation of requirements	Flexibility types; Flexibility dimensions; Range-response graphs	Reconfigurability characteristics; short/mid/long-term changes	Adaptability types; Variability + Shift of mean; Range-response graphs

Table 8.1: Comparison of adaptability concepts across B1, B2, and the framework proposed in this research.

8.2. Practical implications

As outlined in Chapter 3, the review of related literature revealed a lack of structured methodologies to support manufacturers in identifying adaptability requirements. While several methods have been proposed, most provide limited practical guidance. The few approaches offering practical applicability were found to lack the necessary specificity to effectively support decision-making in manufacturing systems. Despite strong industrial interest in adaptable manufacturing (R. Andersen et al., 2024), the absence of such frameworks for requirement generation hinders implementation of adaptability in manufacturing (Pansare et al., 2023). The proposed framework addresses this methodological gap by providing a practical and systematic method for generating adaptability requirements in manufacturing systems.

The practical value of the methodological framework for decision-makers in manufacturing systems is twofold, providing value through both application of the generated requirements and the generation procedure itself.
The *process* of generating requirements enables manufacturers to identify interdepartmental differences in perception and establish a shared understanding across the organization. As the PV scenarios are based on separately generated CD scenarios, the reasoning and choices are made explicit rather than remaining in the mind of the respondent. This facilitates identification of differences in CD effect interpretation when comparing across respondents. The systematic nature of the framework enhances its suitability for comparative analysis as phases are performed the same way each time. The systematic exercise of generating PV scenarios furthermore invites reflection on the manufacturing operations, possibly yielding new insights for participants.
Second, the methodological framework finds an application on two levels of decision making, which are outlined in Section 5.5. Figure 8.1 summarizes the different ways in which the methodological framework can deliver practical value.

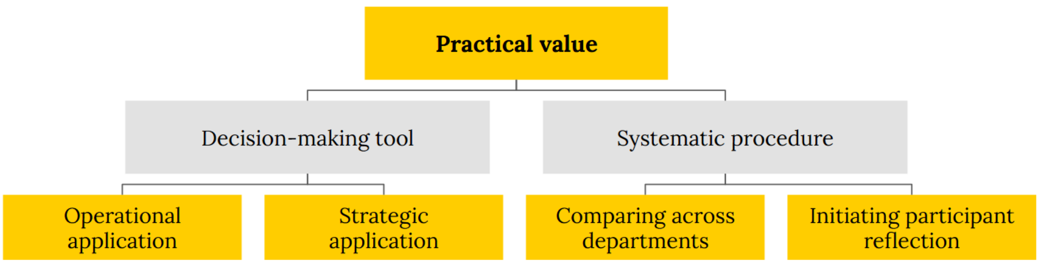

Figure 8.1: Practical value of the methodological framework

To generate the adaptability requirements, heterogeneous data from different departments is consolidated. Industrial companies often hold extensive information, yet this knowledge is typically dispersed across different departments, leaving no one with a complete overview. Since the scenarios are constructed through the identification of CDs, inputs from various departments can be combined into a single PV scenario. In this way, expertise from different domains is consolidated into a range-response graph that provides a comprehensive overview and can be used across the entire company (see Figure 8.2). Furthermore, the methodology does not depend on high-quality data streams but instead interprets knowledge about CDs obtained through interviews. This allows it to draw on all available expertise, including information that does not come in the form of neatly expressed quantitative predictions.

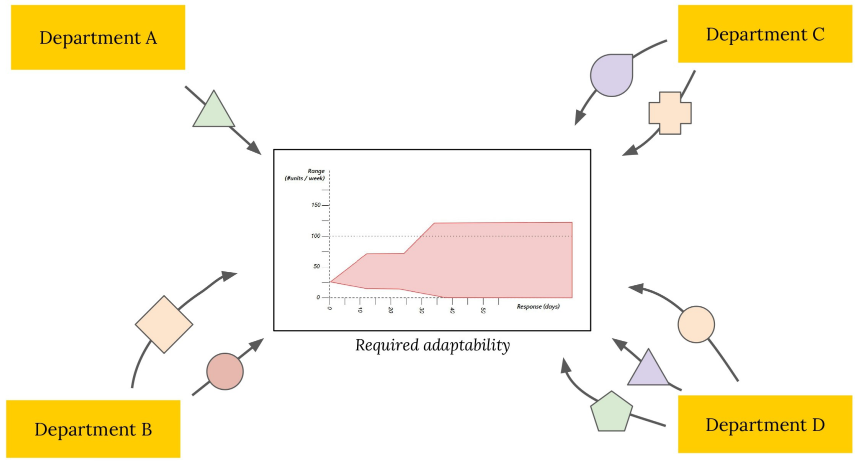

Figure 8.2: Consolidation of different data types from different departments into one single range-response graph

Manufacturing adaptability is a complex and multidimensional concept. As such, requirements in terms of adaptability are difficult to formulate and communicate. This thesis proposes a distinct classification of adaptability types with dimensions that can be visually expressed in range-response graphs. Such a visual representation facilitates clear communication among stakeholders and is easily interpretable, directly conveying insights at first glance.

8.3. Limitations

8.3.1. Limitations of the methodological framework

The most important limitations of the methodological framework are discussed here.

- **Simplification of CD effects:** The methodological framework is limited in its ability to capture complex CD effects. While an event is relatively easily described, a trend is defined by the accumulation of its effect over time. Complex trend effects may require simplification in order to be effectively used in the construction of PV scenarios. Consequently, complex trend effects may be assumed to be linear, as is shown in Figure 8.3. While this improves the interpretability of the results, too much simplification might lead to reduced accuracy and therefore must be applied with caution.

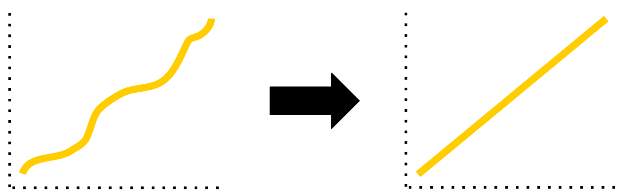

Figure 8.3: Linearization of a CD effect

- **Dependence on input:** The current framework is completely dependent on input as provided by the company experts. Since the generated requirements are directly derived from the information provided by company participants, any unreliable data or predictions compromise the reliability of the entire output. The interviews are semi-structured and rely heavily on insights emerging from open discussion. Consequently, the interviewer's skill becomes a critical determinant of the quality of information feeding into the analysis. An inexperienced interviewer may overlook important PVs, thereby substantially affecting the method's outcomes. In addition, information gathered from company employees will always contain a subjective element. Consequently, repeating the analysis on a different set of employees might yield different results. Especially during scenario generation, subjectivity might be introduced in the interpretation of the level of extremity that is to be applied when generating scenarios.
- **No representation of PV interdependencies:** An important limitation of the current framework is its inability to capture interdependencies between PV scenarios. While feasibility is assessed when combining CD scenarios into a single PV scenario, no such consistency check is performed across PV scenarios. As a result, the framework treats all PV scenarios as equally possible and independent, even though some may only be feasible under specific conditions. For instance, one scenario might indicate that production volume must be adaptable between 0 and 100 units per day, yet the maximum volume of 100 units may only be achievable under condition A. In that same condition, however, the product size may be limited below 50 cm. Consequently, the system would never actually need to produce 100 units of a 50 cm product per day. Such conditional dependencies are not represented in the adaptability requirements, but might be of interest to manufacturers depending on the nature of the manufacturing process. In the current framework, adaptability requirements that might be affected by such interdependence should be interpreted with common sense to prevent overestimation of the required adaptability.
- **Lack of variability-related requirements:** Requirements related to variability are only partially captured in the range–response graphs. The incorporation of variability as a band ensures that the range of fluctuations is accounted for, yet the required response time is not visually represented. In the current method, the required response to account for short-term fluctuations is to be derived from the description in terms of amplitude and frequency.

8.3.2. Research limitations

The methodological framework was in this study only evaluated to a limited extent. Only three evaluation interviews were conducted in this research. While the results of these interviews were predominantly positive, a larger number of respondents is required to further support the reliability of these findings. Moreover, the case study in which the functioning of the methodological framework was evaluated on the case system was very limited in scope. Due to a lack of time and constrained availability of company experts, only a limited number of interview were conducted.

Another important consideration when assessing the validity of the case study is that the methodological framework was developed with this specific manufacturing system in mind. Consequently, a degree of bias may be present, as the framework could be more tailored to this system than to other, unrelated manufacturing environments. Although the framework was designed with the intention of being generalizable across different types of manufacturing systems, additional industrial applications are needed to reliably confirm this generalizability.

8.4. Future research

The findings of this study highlight the need for further research in four areas. First, work is needed to further validate the methodological framework as proposed in this research. Especially the generalizability of the method across different types of manufacturing environments should be tested. Second, future research should look to improve the current method by addressing its limitations as discussed in Section 8.3.1. Furthermore, the proposed improvements as presented in Chapter 7 could form the basis for future improvements. Third, a supplementary framework to construct range-response graphs of system capability should be developed. The strategic application of the framework as described in Section 6.2 hinges on the system capability of a system being visually represented. The mapping of these capabilities are outside of the scope of this current research. However, in order to vastly improve the practical value of this methodology, a supplementary method to assess the capability of a manufacturing system in relation to adaptability should be designed. Fourth, future research could look to develop the methodological framework for future contexts. The method as put forward in this research aims to support manufacturers in the current industrial context. As such, the method was deliberately kept as simple as possible to maintain practical applicability. Since high-quality data and advanced technologies are not universally available in the manufacturing industry, the method was designed without big data analysis techniques that depend on stringent data requirements. Nevertheless, the framework has the potential to be extended toward more future-oriented applications, enabling greater automation in its execution.

Three levels of potential development are distinguished, each of which increases the degree of automation while drawing on increasingly innovative industrial paradigms. It should be noted, however, that higher levels also entail greater complexity and demand higher-quality data to ensure meaningful application. While this may reduce immediate practical value, it offers additional benefits as a theoretical exploration of what the future might, or at least could, look like.

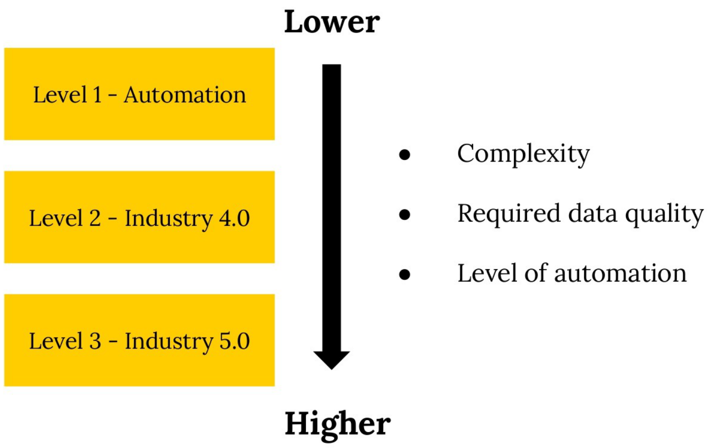

Figure 8.4: Framework development levels for future research

Level 1 - Automation

In the first level of development, research could look to develop simple tools to further automate the frameworks execution. On this level, the information is still gathered using semi-structured interviews and open discussion with company experts, but simple processing steps are automated using Excel or Python tools. A tool automatically converting the scenarios as resulting from Phase 2 (scenario generation) to range-response graphs could significantly accelerate the process of interpretation. Moreover, if Phases 2 and 3 can be performed using Excel or Python, changes in CD scenarios could be made to automatically propagate throughout all phases, ultimately directly adjusting the range-response graph. This enables straightforward experimentation with input values, greatly enhancing the framework's capacity to generate insights for manufacturers. In a strategic context, it allows the effects of different company decisions on required adaptability to be explored. In an operational context, the analysis can be repeated regularly to assess the short-term developments, each time requiring only minor parameter adjustments.

Level 2 - Industry 4.0

On the second level, future research could examine how the methodology could be implemented in an Industry 4.0 context. Industry 4.0 refers to the fourth industrial revolution, which is a transformation of manufacturing and industrial processes through the integration of digital technologies and data exchange (Vaidya et al., 2018). Leveraging technologies like artificial intelligence (AI), internet of things (IoT), and digital twins, the framework execution could be automated, and its accuracy enhanced. IoT can be used to accurately gather data from the production system in real-time. The predictive capability of AI models can then be applied to this data to directly generate CD or even PV scenario's. In addition, the data obtained from IoT sensors enables the creation of a digital twin of the manufacturing system. This digital counterpart precisely captures the capability of the production process, and is even able to project this capability into the future. Because the data is gathered continuously, the analysis can be updated dynamically, each time incorporating the latest projections and resource information. In this way, projections of required adaptability and system capability can be continuously compared, triggering warnings whenever corrective action is needed to maintain alignment between requirements and capabilities. Figure 8.5 shows how the framework could be implemented in an Industry 4.0 context.

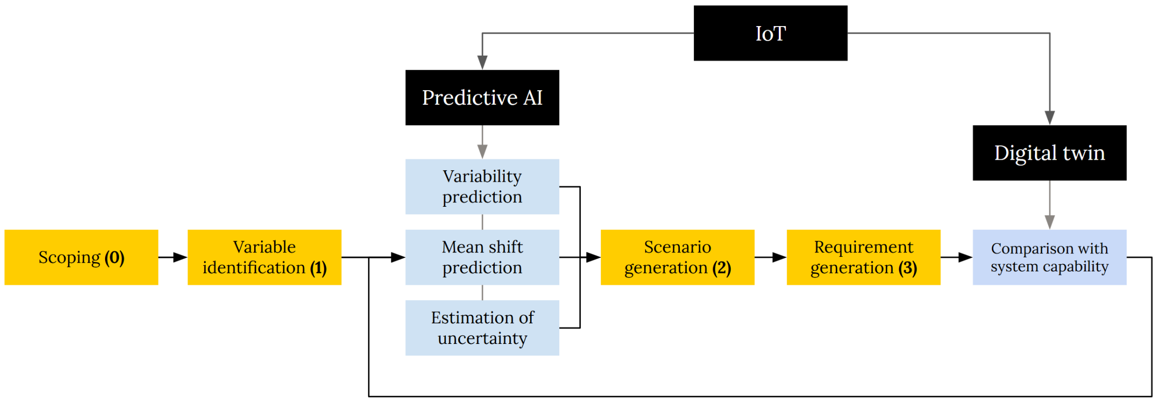

Figure 8.5: Possible extension of the methodological framework leveraging Industry 4.0 technologies

Level 3 - Industry 5.0

On the third level, future research could explore options to extend the methodological framework to an Industry 5.0 context. Industry 5.0 builds upon new technologies, but places the characteristics of human-centricity, sustainability, and resiliency at its core (Leng et al., 2022). To adopt to these values, it should be investigated how employee wellbeing and other societal factors can be included in the framework loop, placing new requirements upon the system. Emissions and other byproducts of manufacturing could be included in the PV identification, leading to requirements that formulate how these must stay between certain boundaries. Similarly, a dimension in the adaptability of the system that could be considered is the effect of system adaptations on employee wellbeing. New requirements could be formulated based on this, possibly ensuring more stable working hours or less repetitive task for factory employees.

9
Conclusion

In this thesis, a methodological framework for the identification of adaptability requirements was designed. During an initial gap analysis on the available scientific evidence, a methodological framework to support manufacturers in the identification of adaptability requirements was found to be lacking. In order to develop a new framework, the existing literature was critically analyzed in Chapter 3. Based on this analysis, a new theoretical framework was proposed in Chapter 4, integrating elements from existing perspectives in the published research. Grounded on this theoretical framework, the methodological framework as presented in Chapter 5 was designed. The method was subsequently applied on an industrial case study, which is highlighted in Chapter 6. The methodological framework was further evaluated using expert interviews, the result of which are described in Chapter 7. Finally, the practical contribution, scientific contribution and limitations of this research were discussed, resulting in a number recommendations for further research. All these activities served to answer the main research question:

"How can a methodological framework to identify adaptability requirements for manufacturing systems be designed by integrating concepts from the existing scientific literature?"

This main research question was answered with the aid of four research subquestions:

1) *What are the similarities and differences in concepts and terminology between the existing literature on identification of adaptability requirements from the perspective of flexibility and reconfigurability?*
2) *How can these perspectives from the existing literature be integrated into a new theoretical framework?*
3) *How can a methodological framework be constructed to identify adaptability requirements based on the proposed theoretical perspective?*
4) *How can the proposed methodological framework be illustrated and evaluated?*

The findings for each subquestion will now be discussed separately.

SQ1 - Existing concepts and terminology
The critical literature review resulted in a number of identified differences in concepts and terminology between B1 (flexibility) and B2 (reconfigurability). First, the two branches of literature conceptualize adaptability in distinct ways. B1 views adaptability as stemming solely from flexibility, while largely disregarding reconfigurability as a possible means to achieve it. B2, by contrast, emphasizes both flexibility and reconfigurability, often treating their combination under the broader notion of changeability. The perceived origins of adaptability also diverge between the two branches. In B2, adaptability is primarily attributed to volatility in CDs, whereas in B1 it is seen as arising from the interaction between environmental uncertainty and manufacturing strategy. When it comes to assessing the level of adaptability, B1 expresses it through different types of flexibility. B2 often expresses the required reconfigurability by incorporating reconfigurability characteristics. In particular, B2 distinguishes between short-, mid-, and long-term changes, classifying them as matters of flexibility or reconfigurability

depending on their nature.

The methodological contributions of each branch likewise differ. B1 provides only limited guidance for translating environmental uncertainty into specific adaptability requirements, offering only a weak connection between certain types of uncertainty and corresponding flexibility types. B2, in contrast, introduces several tools, such as questionnaires to identify the required degree of changeability. However, these tools tend to produce only broad and general approximations, rather than precise assessments, of the level of adaptability needed.

	B1	**B2**
Nature of adaptability	Flexibility	Reconfigurability + flexibility
Origin of need for adaptability	Environmental Uncertainty & Manufacturing strategy	Change drivers
Formulation of adaptability requirements	Flexibility types	Reconfigurability characteristics & short/mid/long-term changes
Methodological contribution	Links Environmental Uncertainty ⇒ Flexibility types	Questionnaires (and other methods)

Table 9.1: Comparison of concepts and terminology.

SQ2 - Theoretical framework

A new theoretical perspective was created by combining elements from B1, B2 and related scientific evidence. In this framework, flexibility and reconfigurability are regarded as means to achieve adaptability, making the distinction meaningless when assessing total adaptability requirements. Manufacturing systems are regarded as input-output transformations, in which adaptability is required to cope with changing production PVs that describe the input and output stream to the system. The theoretical framework combines the notion of environmental uncertainty and CDs, assuming the need for adaptability to originate from both expected volatility and uncertainty of predictions. Similar to B2, a distinction between short- and long-term changes is made, classifying volatility in either variability or shifts of mean. CDs are classified as being either a trend or event, depending on their immediacy of effect. A classification of PVs is made to help distinguish a set of adaptability type. Each adaptability requirement is visually represented using a range-response graph, indicating the required change of the system over time.

SQ3 - Methodological framework

A scenario-based methodological approach consisting of four phases was proposed based on the theoretical framework. In the initial phase 0, the scope of the analysis is determined, simplifying the system as an input-output transformation and defining the prediction horizon. In phase 1, a list of relevant PVs are gathered using semi-structured interviews. A question set and a matrix procedure are provided as tools during this selection process. In the second phase, two scenarios are generated for each PV, representing the uncertainty of predictions. These scenarios are constructed based on separate CD scenarios, which are derived in semi-structured interviews. A morphological analysis is proposed to combine these CD scenarios while accounting for real-life feasibility. In the final phase, adaptability requirements are generated based on the PV scenarios that were generated in phase 2. These requirements are visually represented on range-response graphs for each PV that was selected in phase 1, resulting in a complete set of requirements representing the adaptability that is required to deal with future changes in PPR.

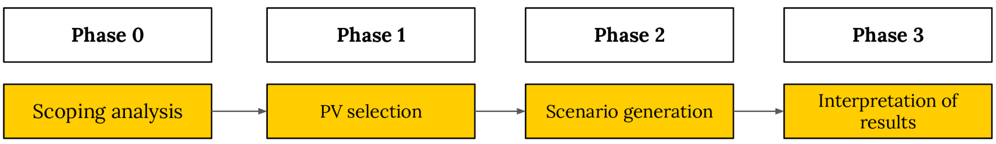

Figure 9.1: Overview of the methodological framework

The range-response graphs can subsequently be used in strategic decision making by overlaying the requirement areas with the projected capability of the system. In a more operational setting, the requirements can facilitate the reconfiguration planning.

SQ4 - Evaluation
The methodological framework was evaluated using a case study and expert interviews. While additional validation is required in future research, initial results showed positive feedback on the methodology. The industrial necessity for such a framework was perceived to be very real, especially in a practical form. One perceived benefit of the method was its ability to provide a visual representation of requirements, thereby facilitating clear communication. Respondents also noted that the systematic nature of the method held potential to generate valuable insights for manufacturing companies, even in cases where requirements were not yet fully formulated. Another strength identified was the method's capacity to consolidate fragmented expertise distributed across the organization.

At the same time, a key weakness was the subjectivity of the input and the corresponding high degree of dependence on the employees providing it. The case study itself was conducted with limited time and company experts, which limited the development of fully detailed graphs. Nevertheless, the company commissioner acknowledged that the process still yielded some interesting insights.

Conclusion
In conclusion, this thesis contributes to the scientific literature by providing a methodological framework to identify adaptability requirements, thereby addressing the gap as identified in the literary gap analysis. In addition, the thesis puts forward a fresh theoretical framework that introduces new terminology and conceptual framing to this field of research.

The practical value of this methodological framework is perceived to be substantial, although further validation is required to reliably confirm thesis findings. The proposed method offers a way to consolidate expertise fragmented throughout manufacturing companies into a clear and complete set of adaptability requirements that can readily be used throughout the organization. The change driver based approach ensures transparency in the results, facilitating easy insight into the nature of the required adaptability and perceived differences within the company. Although the method contains a number of limitations that need to be addressed in future research, it has the potential to bring significant value to decision makers in the manufacturing industry, both on strategic and a more operational level.

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Appendix

Appendix A - Question set A

- Time period T: The prediction horizon as determined in phase 0
- Time period K: The time period in which the production rate is being measured. Appropriate value is chosen based on the manufacturing system and goal of analysis.

Question set

Input variables

For each input product X defined as a stream of input in the manufacturing process, ask the following questions:

1) Are any characteristics of input product X expected to change in time period T?
2) Is the volume of product X available for processing per time period K expected to change within time period T?
3) Is the total volume of input products being processed per time period K expected to change within time period T?
4) Is the amount of different input products being processed at the same time expected to change within time period T?
5) Is the ratio of input products being processed expected to change within time period T?
6) Is an introduction of a new type of input product potentially expected during time period T?
    a. If yes, question 1 and 2 are repeated for each product type

In addition, for every question determine the perceived uncertainty in regards to the future projections of this category.

Output variables

For each product X defined as a stream of output from the manufacturing process ask the following questions:

7) Are any characteristics of output product X expected to change within time period T?
8) Is the volume of product X to be produced per time period K expected to change within time period T?
9) Is the total volume of products to be produced per time period K expected to change within time period T?
10) Is the total volume of input products being processed per timer period K expected to change within time period T?
11) Is the amount of different products being produced at the same time expected to change within time period T?
12) Is the ratio of products being produced expected to change within time period T?
13) Is a product expected to be introduced to the production portfolio in time period T?
    a. If yes, question 7 and 8 are repeated for each product type

In addition, for every question determine the perceived uncertainty in regards to the future projections of this category.

Other

14) Are there any relevant PVs that you can think of that are expected to change during time period T, thereby having an effect on the production system?
15) Are there any relevant PVs that you can think of that you are very unpredictable or uncertain for time window T, thereby possibly affecting the production system?

Appendix B - Question set B

- Time period T: The prediction horizon as determined in phase 0
- Time period A: The aggregation window as determined in phase 0

Question set

For each PV selected in phase 1, ask the following questions:

Mean value

- What is the present average value of the PV per time period A?
- Are there any events you expect to impact this average value within time period T?
  - If yes, can you give a rough estimation of the effect of this event?
- Are there any trends you expect to impact this average value within time period T?
  - If yes, can you give a rough estimation of the effect of this trend?

Variability

- How does the value of the PV currently fluctuate within time period A?
- Are there any events you expect to impact the nature of this fluctuation within time period T?
  - If yes, can you give a rough estimation of the impact of this event?
- Are there any trends you expect to impact the nature of this fluctuation within time period T?
  - If yes, can you give a rough estimation of the effect of this event?

Appendix C - Impact-Volatility and Impact-Uncertainty matrices

Appendix C.1 - Impact-Volatility matrix

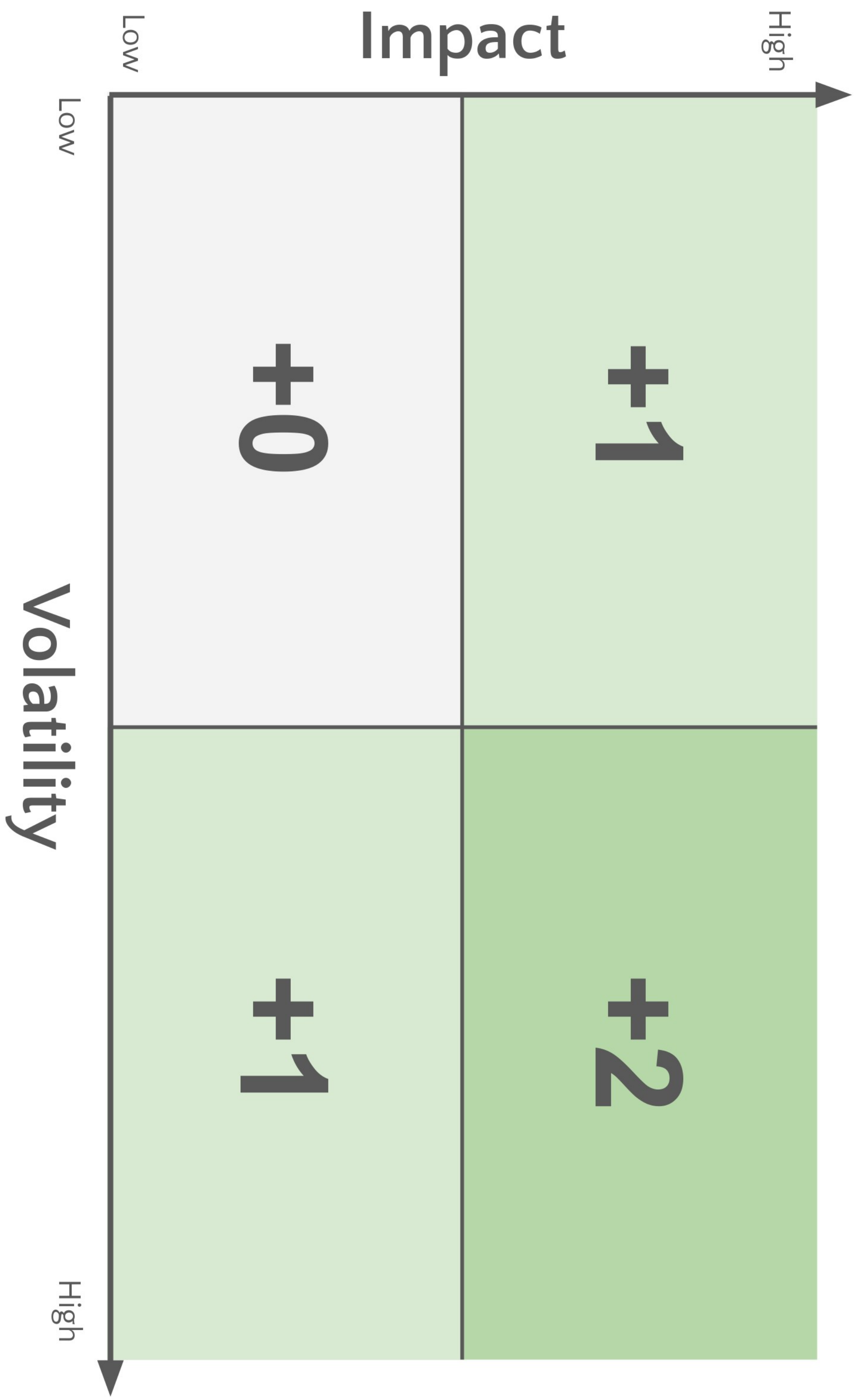

Figure 2: Impact-Volatility Matrix

Appendix C.2 - Impact-Uncertainty matrix

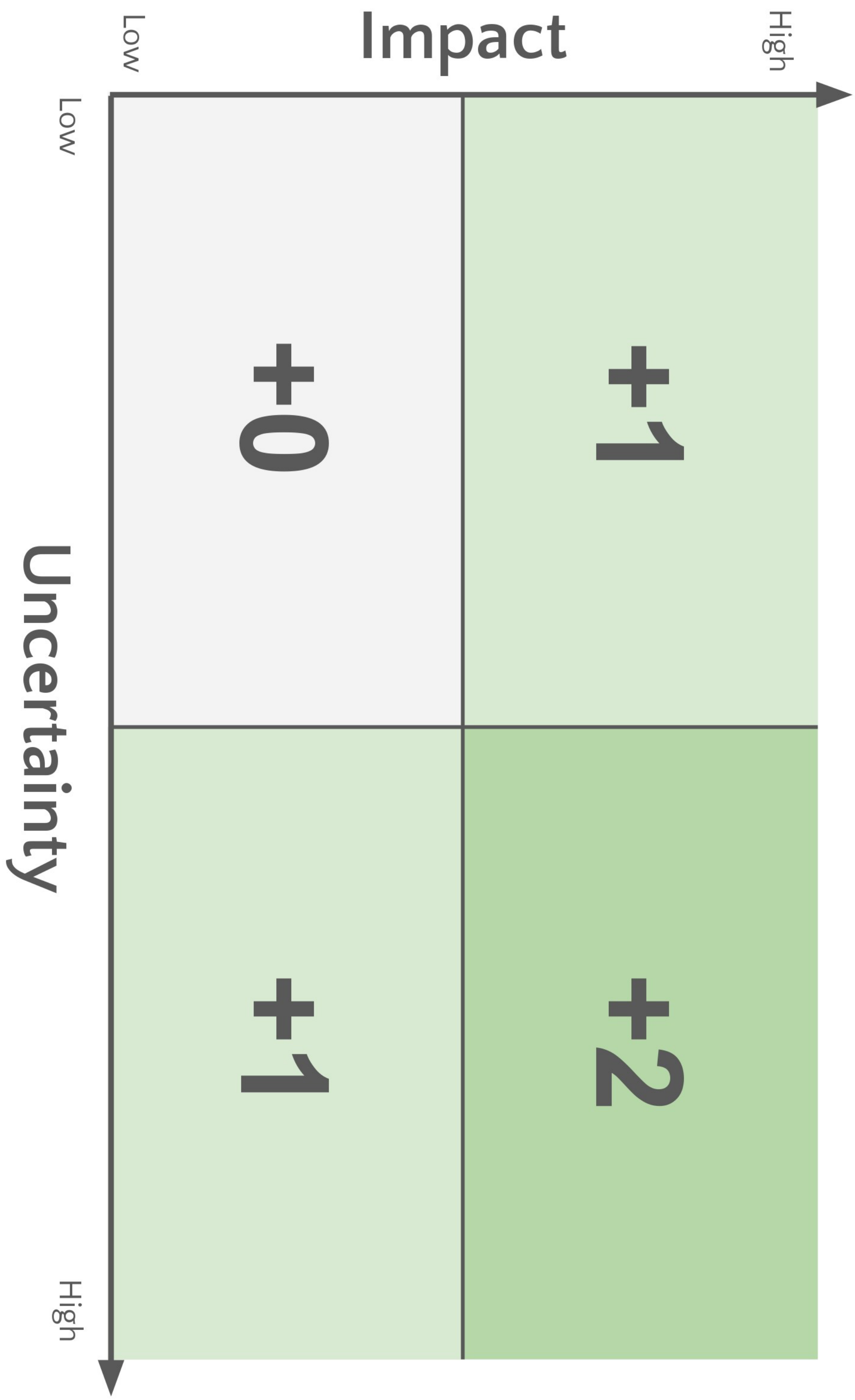

Figure 3: Impact-Uncertainty Matrix

Appendix D - Morphological chart template

PV:		
Change driver	**Scenario #1**	**Scenario #2**

Appendix E - Values and variability of PVs

The results of the interviews are color-coded along the following scheme:

- Black – *Continuous improvement lead*
- Blue – *Master planner cacao beans & butter*
- Red – *Cacao butter planner*

PV	Current value	Current variability
Cacao liquor FFA content	3% FFA percentage 2.1% 2.1%	Amplitude: 0.25% Amplitude: 0.5% Amplitude: 0.7% Frequency: Daily
Cacao liquor volume	600 tonnes per day 587 tonnes per day 500–600 tonnes per day	Amplitude: – Amplitude: – Amplitude: 50 Frequency: Daily
Cacao butter portfolio	Complete type set Complete type set Standaard / Mainstream RFA / Low alk / High alk	–

Table 2: Interview results for current value and variability

Appendix F - Change drivers and corresponding scenarios

The results of the interviews are color-coded along the following scheme:

- Black – *Continuous improvement lead*
- Blue – *Master planner cacao beans & butter*
- Red – *Cacao butter planner*

Cacao liquor FFA content		
CD	**Scenario #1**	**Scenario #2**
Seasonal change	+1% over 6 months	-2% over 6 months
Strategic blending choices	Variability amplitude – 0.25%	No change
Bean supplier change	+1% over 12 months	-1% over 12 months
Better cacao liquor sampling	Variability amplitude -0.125%	Variability amplitude +0.25%
Mid-crop arrival	-1% over September to December	-0.5% over September to December
New main crop arrival	-0.3% over February	-0.7% over February
Main crop arrival	-1.5% from December	-0.7% from Januari
Mid crop arrival	-1% from August	-0.5% from September
Crop season increase	+0.13% per month through entire year	+0.17% per month through entire year

Table 3: Interview results for Cacao liquor FFA content

Cacao liquor volume		
CD	**Scenario #1**	**Scenario #2**
Cacao butter price	-60 tonnes over 12 months	No change
Seasonal change	+30 tonnes in September	No change
Contract acquisition	+30 tonnes over 12 months	-30 tonnes % over 12 months
Rouen takeover	+100 tonnes from start September	+100 tonnes from start September
Bad harvest (cacao butter price)	-15% over next year	+10% over next year
EUDR (european legislation)	-5% from 1st January	-2% from 1st January
New contaminant regulation	-5% from 1st December	No change
Seasonal change	+15% during September – November	No change
EUDR	?	?
Rouen takeover	200 per week increase from start September	250 per week increase from start September
Jonker production shift	300 per week increase from start September	400 per week increase from start September

Table 4: Interview results for Cacao liquor volume

Cacao butter portfolio		
CD	**Scenario #1**	**Scenario #2**
Project Pula	3 product reduction from start November	No change
Rouen takeover	Organic butter added from start September	Organic butter type from start November
Segregated streams unconsolidated	Additional segregated stream in January	No change

Table 5: Interview results for Cacao butter portfolio

Appendix G - Extreme PV scenarios plotted

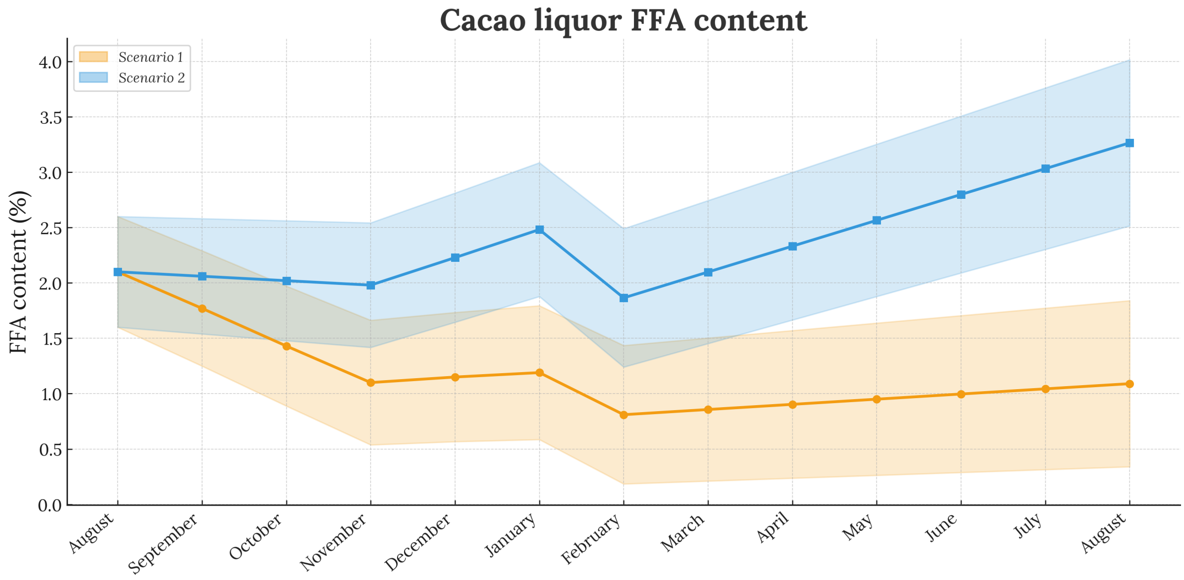

Figure 4: Extreme scenarios for cacao liquor FFA content

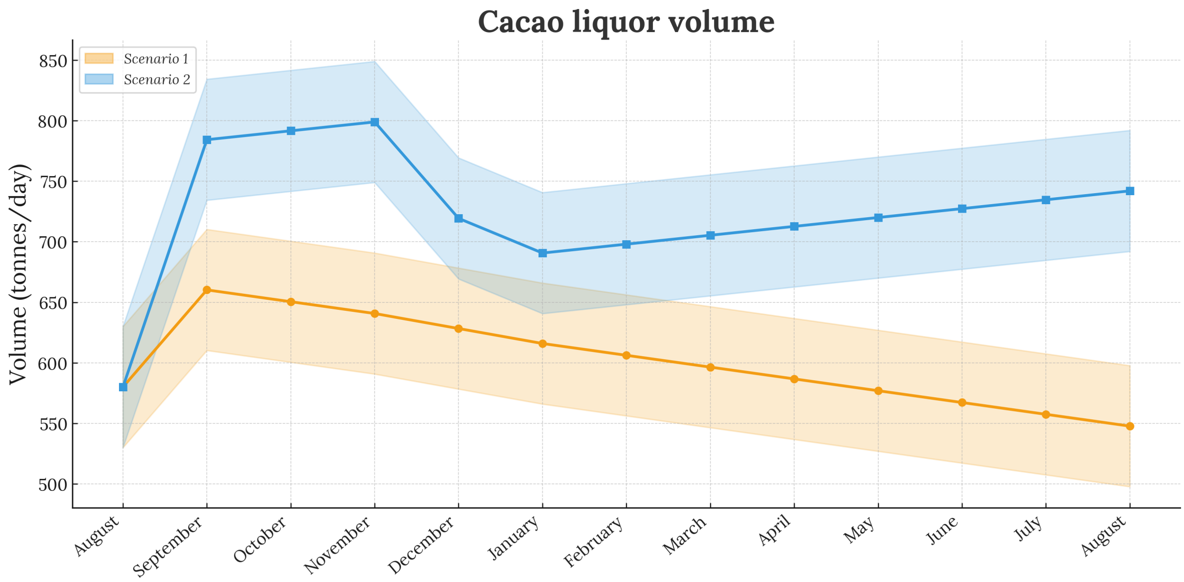

Figure 5: Extreme scenarios for cacao liquor volume

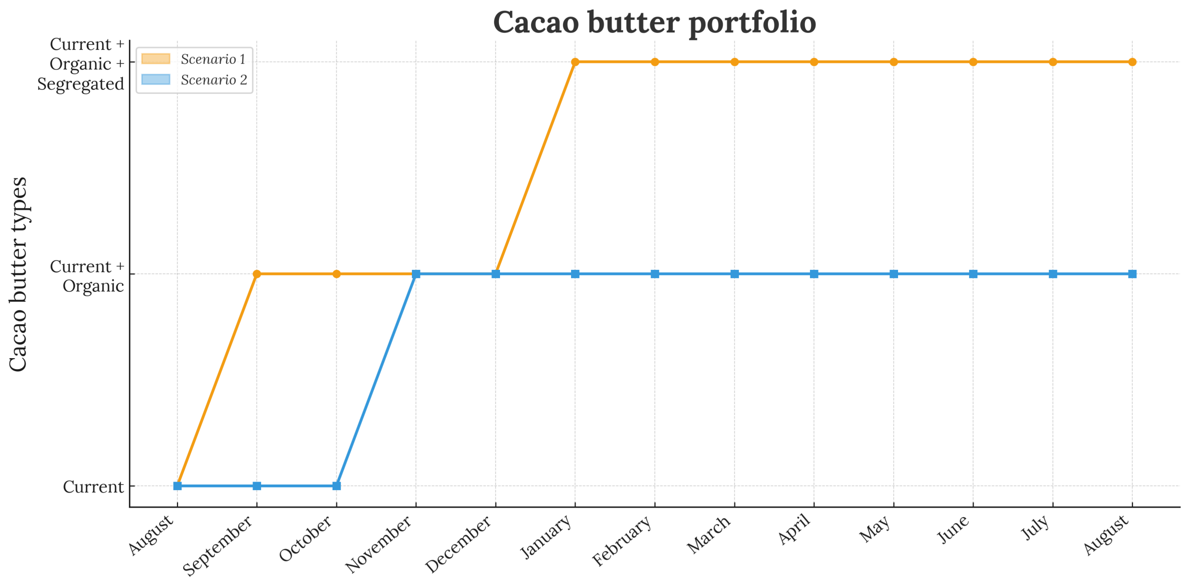

Figure 6: Extreme scenarios for cacao butter portfolio