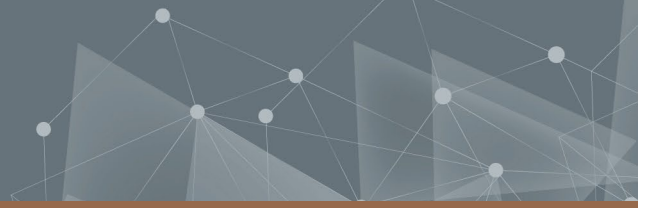




CHALMERS
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Strategic Direction to Manage Increased Production Volumes

Exploring Challenges and a Possible Strategic Direction for
PowerCell's Production System

Master's thesis in Quality and Operations Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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SUMMARY

A prominent challenge in today's society is to decarbonize industries that rely heavily on fossil fuels, such as the transport sector. One way of doing this is by utilizing hydrogen, for example with hydrogen fuel cells that generate electricity with no other emissions than heat and water. PowerCell is a cleantech company with a long history of research and development within hydrogen fuel cells that has experienced a large organizational growth during the past years. Recently, PowerCell started to commercialize their fuel cell solutions, and they are today offering highly customized fuel cell solutions to their customers. With the anticipated growth of the fuel cell market, organizational preparedness for higher production volumes is required. To achieve this, there is a need to evaluate PowerCell's current production strategy and decide on a strategic direction related to the production system. Therefore, this thesis aimed at identifying challenges related to PowerCell's current production system and based on these provide guidance to PowerCell in developing a strategic direction for their production system. The study began with a pre-study consisting of a literature review, observations, and interviews with employees at PowerCell. Based on the results from the pre-study, a framework was developed to provide a basis for creating a comprehensive production strategy. Furthermore, in the main study, the framework was used to evaluate PowerCell's current production strategy which led to an identification of 65 strategic decisions made related to the production system. Each decision was evaluated, and challenges and initial solutions were proposed. Then, the identified challenges were clustered into six prominent challenging areas: insufficient cross-functional communication, a lack of clear production strategy obstructs development of the production system, low degree of manufacturability of products, the high degree of customization obstructs managing increased production volumes, inadequate quality management efforts, and non-value-adding work in the production system. Each of these prominent challenging areas were addressed with a proposed strategic direction, enabling creating a comprehensive production strategy.

Keywords: production strategy, production process, mass customization, do-or-buy decisions, supplier relationships, quality management, Lean Production, product and process innovation, DFMA, production planning and control

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Sara Petersson & Sofia Norrby, Gothenburg, May 2024

Glossary

CODP: Customer order decoupling point.

Fuel cell stack: Multiple hydrogen fuel cells combined in series to generate electricity from chemical reactions in the fuel cells.

Fuel cell system: Consists of a fuel cell stack and components that ensure that the desired output for the application is obtained.

The PS100 system: One of PowerCell's fuel cell systems, which is built by one person from beginning to end. The power output is 100 kilowatt.

The PS200 system: One of PowerCell's fuel cell systems, consisting of three modules. The power output is 200 kilowatt.

Engineering department: PowerCell's product development department, who delivers new products and product revisions.

Applications department: The Applications department conducts customer projects, either constructing and building wholly customized products from scratch or modifying existing products.

Operations department: The department responsible for running operations at PowerCell, by managing for example production, purchasing, and quality.

JIT: Just-in-time.

FAT: Factory Acceptance Test. This is the last test performed on PowerCell's fuel cell systems, testing the whole product to ensure the highest quality.

LIM wagon: Lab Interface Module wagon. Fuel cell systems are mounted on these wagons upon entering the lab area, to enable FAT testing of them.

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1 Introduction

This Master's thesis examines the production system and related strategic decisions at PowerCell, a company developing and producing hydrogen fuel cells. This introductory section provides a background to the study in terms of the industry being studied and a description of the case company. This is followed by a problem description, leading to the aim of the report and research questions. After that, the scope and delimitations to the study are presented. The introductory section is partly based on results from a pre-study consisting of interviews with employees at the case company and partly based on observations in the production area.

1.1 The Clean Hydrogen Market

To manage decarbonizing industries that rely heavily on fossil fuels today, hydrogen will constitute a crucial part (Fonseca et al., 2023). However, a precondition for using hydrogen to reduce carbon emissions is that the hydrogen is generated in a renewable or low-carbon way, which is referred to as clean hydrogen (Hydrogen science coalition, 2023). Heid et al. (2022) argue that hydrogen has potential to account for more than 20% of global emissions reduction annually in 2050, thus, it can play a big role in achieving net-zero emissions. The clean hydrogen market is expected to grow over the upcoming years, with an increased announced industrial consumption from 0.11 million tons hydrogen per year in 2023 to 7.13 million tons in 2030 (Fonseca et al., 2023). One type of hydrogen consumption is through hydrogen fuel cells, which can be used for electricity production in a broad range of applications in multiple sectors (Hydrogen and Fuel Cell Technologies Office, n.d.).

The clean hydrogen market is characterized by regulations and economic incentives (Fonseca et al., 2023). EU has, among other things, established decarbonization policies aiming to foster a clean hydrogen market, set obligations for using hydrogen in the mobility sector, and developed funding programs with the aim of supporting hydrogen usage and related technologies. Similarly, the US has introduced federal spendings toward reducing carbon emissions (McKinsey & Company, 2022). Thus, the demand for hydrogen solutions, for example hydrogen fuel cells, is currently highly characterized by different types of regulations and economic incentives.

Several segments comprise the clean hydrogen market, some of which are: conventional industry, steel, and mobility (Fonseca et al., 2023). In the mobility sector, which has been growing year by year, hydrogen fuel cells can be used to generate electricity from hydrogen stored in tanks on the vessel (Fonseca et al., 2023). Due to strict regulations regarding replacement of fossil fuels in the marine sector and the aviation sector, these are sectors with a high demand for hydrogen fuel cells.¹ It should,

¹ P. Brouzell, personal communication, January 22 & March 19, 2024

however, be noted that using hydrogen to fuel aircrafts is still in an early development phase (Fonseca et al., 2023).

To meet the increasing demand for clean hydrogen, there are several challenges to overcome, where two of the most prominent ones are the hydrogen infrastructure and scaling up production of clean hydrogen (Heid et al., 2022). If these challenges are overcome, the demand for hydrogen fuel cells is expected to grow. However, for this demand growth to be realized, there is a need for simultaneous development of regulations and economic incentives along with the previously mentioned infrastructure and clean hydrogen supply. If all these aspects are collectively considered, it should lead to an increased demand for hydrogen fuel cells.

1.2 PowerCell

One actor on the clean hydrogen market is PowerCell Group, henceforth referred to as PowerCell, which is a cleantech company that develops and produces hydrogen fuel cell solutions for mobile and stationary customer segments (PowerCell Sweden AB, 2023). PowerCell was established in 2008 as an industrial spin-out from Volvo Group and is since December 2023 listed on Nasdaq Stockholm. The headquarter is located in Gothenburg, Sweden, with approximately 150 employees, of whom 70 have joined within the past three years (PowerCell Sweden AB, 2020; PowerCell Sweden AB, 2022; PowerCell Sweden AB, 2023). Besides the organizational expansion, the company has experienced significant financial growth during the past years, with increased revenues of 27% between 2022 and 2023 (PowerCell Sweden AB, 2023). This reflects the global shift towards an increasing usage of hydrogen for fossil-free energy generation.

With a history of over 25 years of research and development, PowerCell has developed competence to meet the growing demand for low emission solutions in their target customer segments: marine, aviation, off-road, and power generation (PowerCell Sweden AB, 2022; PowerCell Sweden AB, 2023). In the automotive segment, Robert Bosch GmbH, henceforth referred to as Bosch, has since 2019, licensed PowerCell's hydrogen fuel cell technology. PowerCell's product portfolio comprises hydrogen fuel cell stacks and systems. The hydrogen fuel cells operate on hydrogen, generating electricity and heat with no emissions other than water (PowerCell Sweden AB, 2022). The fuel cell stacks, composed of multiple layers of hydrogen fuel cells, form the core of PowerCell's technology, while the fuel cell systems offer a plug-and-play solution that incorporates the fuel cell stacks as a key component among others. PowerCell's main offering currently consists of two fuel cell systems, differentiated by the power generated by the system, the PS100 system and the PS200 system. Additionally, across all product segments, PowerCell places a strong focus on providing highly customized applications to meet individual customer needs.²

² L. Kylhammar, personal communication, January 30 & March 19, 2024.

Historically, technology exploration as well as research and development projects have constituted a large part of PowerCell's revenues, with universities and research institutes serving as primary end customers, with most orders regarding single units (PowerCell Sweden AB, 2022).¹ However, with the globally growing clean hydrogen market, there is a notable increase in commercial customers seeking the hydrogen fuel cell solutions offered by PowerCell. Particularly promising is the growing focus on the marine and aviation sectors, both of which are highly regulated in terms of CO₂ emissions (PowerCell Sweden AB, 2022). However, demand is fluctuating, as it is a new product in a relatively new market.³ Additional aspects affecting the demand are the challenges regarding infrastructure and clean hydrogen supply characterizing the clean hydrogen market, and the regulatory environment. Thus, the customer base is not yet stabilized, and most customers are not yet recurring. With the anticipated heightened demand for commercial applications and serial deliveries, organizational preparedness for higher production volumes is required (PowerCell Sweden AB, 2022).

The previously mentioned history of PowerCell being a development-oriented organization still highly affects how the company operates. This can, for example, be seen by the absence of a comprehensive production strategy. Decisions are often made in response to an existing customer order, and this can lead to strategic decisions being made in an ad-hoc manner. The lack of production strategy has not affected PowerCell significantly as production volumes have previously been low. However, increasing production volumes entails a need to incorporate production considerations into the organization, by reviewing the production system and the accompanying strategic decisions.

1.2.1 PowerCell's Production System

Bellgran and Säfssten (2010) define a production system as a collection of components, such as labor or machines, which are interrelated in an organized way to transform input to output. The large focus on customized solutions divides the production process into two parts: production of standard products, in this study defined as products produced in the main production area, managed by the Operations department, and production of customized products, which are produced in a separate area and managed by the Applications department.³ Customized products can either be produced entirely in this separate area or be derived from standard products. It is, however, important to note that products produced in the main production area, so-called standard products, can differ notably between customer orders. Thus, both the production of standard products and customized products have a high degree of variety.

The main production area at PowerCell is located in the main facility, next to the office, the warehouse and goods arrival. When goods arrive, they are inspected by warehouse employees, three in total, in various ways depending on the type of goods, before being transferred to the warehouse's shelves.⁴ When the parts are needed in the production,

³ C. Magass, personal communication, January 22 & March 19, 2024.

⁴ V. Oscarson, personal communication, January 24 & March 13, 2024.

initiated by a manufacturing order, warehouse employees receive a message in their handheld device and collect the correct parts in a kit. The kit is placed on a wagon adjacent to the production area. Then, the operator picks up the parts and starts the production process. There are ten operators in total, both production technicians and production assemblers, working with production.⁵

Fuel cell stacks are produced in a secluded area, as this process is delicate in several aspects.⁶ The manufacturing process of fuel cell systems consists of mainly assembly work for the two standard fuel cell systems, the PS100 system and the PS200 system. The production time in terms of total throughput time is several weeks for both the PS100 system and the PS200 system, however, for the PS100 system, it is slightly longer than for the PS200 system. The production time is partly a consequence of currently having production employees only working office hours during weekdays, thus, on day shift. Another difference between the systems is that the same operator must manufacture the PS100 system all the way from start to finish, while the PS200 system is modular and can hence be worked on by several people simultaneously.³

A large part of the production system is the testing process for fuel cell stacks and systems, which is done both at the production site and in a separate lab area.⁶ The testing constitutes a substantial part of the total production time and is conducted during several phases of the production process, as well as when the product is finished, with a factory acceptance test (FAT). When deviations are identified during testing or upon arrival of goods, these are reported to the quality team, who are responsible for informing the product development department, denoted as the Engineering department. The deviating parts or material are placed in a quarantine area next to the production site and is handled in an appropriate way depending on the situation.⁷ If the deviation concerns defective material, the material is returned to the supplier, and if it is a testing issue, rework is typically done.

As part of its growth journey, PowerCell has established production objectives of increased volumes (PowerCell Sweden AB, 2023). As part of achieving this, they have formed a strategic partnership with Bosch for the manufacturing of one type of fuel cell stack. This is done to achieve lower production costs and faster production time, as Bosch produces hydrogen fuel cells on a larger scale. The collaboration allows PowerCell to focus on the development of new fuel cell stacks, as well as development, assembly, and delivery of fuel cell systems (PowerCell Sweden AB, 2023).

The pre-study showed that there are several challenges related to the production system, which might be amplified if production volumes are increased. These challenges must be addressed to be able to adopt a comprehensive production strategy.

⁵ P. Wallin, personal communication, January 30 & March 18, 2024.

⁶ M. Holmberg, personal communication, January 22 & March 13, 2024.

⁷ I. Andersson, personal communication, January 16 March 13, 2024.

1.3 Aim

The aim of this study is to identify challenges related to PowerCell's current production system and based on these, provide guidance to PowerCell in developing a strategic direction for their production system. The suggestions should support the organizational objective of increasing production volumes and align with the organization's rapid product development.

1.4 Problem Description

As the clean hydrogen market expands, it is, as discussed, anticipated that the hydrogen fuel cell sector will grow too, attracting more actors into the market. Currently, PowerCell is one of few hydrogen fuel cell developers and producers, thus being a pioneer facing evolving uncertainties. By examining PowerCell's unique challenges and providing strategic guidance on their production strategy, other development-oriented companies facing similar challenges could benefit.

PowerCell has previously been development-oriented and only recently started to focus on the efficient and effective functioning of operational processes by establishing an Operations department.⁵ This, along with the previously relatively low production volumes, has resulted in a production system that is not yet fully developed, and there are several challenges related to the production system that need to be addressed to manage increased production volumes. Six areas were, based on the conducted pre-study, identified as critical: the need for a flexible production process, capacity expansion, aligning product development and production, planning production, externally sourcing parts of production, and the testing activities. These areas are further discussed below.

The first critical area concerns that the production system at PowerCell is characterized by its need for high flexibility.⁵ Flexibility is a performance objective that refers to the ability to rapidly and efficiently adapt production to necessary changes (Bellgran & Säfsten, 2010). Slack and Lewis (2020) argue that an operation is flexible when it can exhibit a wide range of activities, and move between these quickly, smoothly and cheaply. With a highly flexible production system, one can respond more easily to changing market requirements, such as new customer needs and fluctuating volume demands. A highly flexible production system is of importance to PowerCell for two main reasons: because there are frequent product updates from the research and development department, henceforth referred to as the Engineering department, and because of the high degree of customization offered to customers.² These two reasons are consequences of the organization being highly development-oriented.

Firstly, updates from the Engineering department range from annual updates, called annual releases, that are planned, yearly updates to the products, to smaller responses to quality issues or new customer demands. Considering the relatively long production

time, product updates can be released in the middle of producing an order.⁸ This can lead to either the scrapping of products, or misunderstandings between affected departments. An example of where misunderstandings can arise is between the Engineering department and the Sales department, where the latter must coordinate with the customers regarding the different product versions, sometimes without having all the information.

Secondly, the flexibility needed due to the high level of customization affects the production of standard products because, as previously noted, the standard production process must accommodate many different product variants.⁶ Producing a high variety of products requires high flexibility, which in turn typically implies high costs (Slack & Lewis, 2020). Furthermore, Slack and Lewis (2020) emphasize a trade-off between flexibility and cost, a critical consideration when PowerCell plans to increase their production volumes. While PowerCell currently maintains flexibility at low production volumes, scaling up could amplify the significance of this trade-off, increasing costs, which is why this area must be taken into consideration.

The strong emphasis on product development and customization has resulted in a high variation in production, indicating that the organization is in the early phases of development and potentially utilizing what Utterback and Abernathy (1975) describe as a performance-maximizing product strategy. This phase is characterized by unique products and varying customer requirements. At the same time, the process development seems to be uncoordinated, due to the high degree of manual and non-standardized work (Utterback & Abernathy, 1975).

The second critical area concerns how capacity expansion will be handled. If PowerCell increases their production volumes, at some point a decision must be made regarding how to expand capacity. Such decisions can, according to Slack and Lewis (2020), include considerations as where to locate the new facility and how to allocate tasks to different sites. For example, as the majority of PowerCell's customers are in Europe and USA, and due to the regulatorily favorable conditions in USA, a potential new site for PowerCell could be placed in USA.¹ Furthermore, a potential decision could be whether to have what Slack and Lewis (2020) refer to as dedicated sites, by having one site producing fuel cell stacks and one producing fuel cell systems, or if all sites should be able to produce all types of products.

The third critical area regards the alignment between product development and production. As customer requirements are highly prioritized when developing products manufacturability is sometimes compromised, leading to products that are not fully adapted to production.³ Additionally, this requires a high skillset from operators in production, due to the yet not standardized production. Products are, thus, sometimes developed more according to customer requirements than production capabilities, which, according to Slack and Lewis (2020) causes a risk for misalignment in the

⁸ N. Euler-Renstedt, personal communication, January 23, 2024.

organization. The authors emphasize the importance of reconciling the market, or customer, requirements with the operational capabilities, and to develop these in parallel. Furthermore, Wheelwright and Clark (1992) argue that it is important to consider manufacturing issues early in the design process to achieve a better interface between design choices and the production system. The anticipated increase in PowerCell's production volumes will require a stronger focus on developing production capabilities in alignment with the customer requirements, and designing products that are more adapted to the production.

The fourth critical area concerns production planning and control. PowerCell has until recently only produced according to customer orders but has during 2023 introduced aspects of production to stock, by producing certain products even if there is no order, to ensure a more even production rate.⁵ This was decided partially to reduce lead times and partially to ensure that the operators learn how to produce the products in a standardized manner, with consistent quality. Bellgran and Säfsten (2010) describe these two commonly used types of production planning and control, which are Make To Order (MTO) and Make To Stock (MTS). Both have several consequences for the production system, for example, MTO facilitates small production volumes and high production variation, resulting in a medium-long time to customer. Contrastingly, MTS entails a very short time to customer and is suitable for large production volumes and low product variation. Thus, transitioning from low production volumes to high production volumes implies moving from MTO to MTS, a transition that PowerCell has begun to do. However, while MTS might be the best choice when production volumes have increased, there will, during the period of growth, be a need to find a balance between MTO and MTS that aligns with increased production volumes. At PowerCell, the transition towards MTS has, as their current production system is characterized by frequent updates from the Engineering department, induced a risk of obsolete products and costs of scrapping.⁴

The fifth critical area regards externally sourcing parts of their production. The partnership with Bosch for production of fuel cell stacks was established with an aim for a faster production time and lower production costs (PowerCell Sweden AB, 2023). According to Bellgran and Säfsten (2010), a common reason for externally sourcing production is cost reduction. Typically, activities that distract an organization from focusing on their core competence are externally sourced, which is not fully correspondent to PowerCell's situation, as the fuel cell stacks are considered part of their core competencies. Bellgran and Säfsten (2010) argue that a company that externally sources production but does the product development itself is exposed to the risk of issues occurring in the interface between these two activities – that is, product development might not get sufficient feedback from production, leading to an inferior product. Additionally, it is of high importance that the supplier's production is of sufficiently high quality. As the fuel cell stacks are considered by many employees to be the core of PowerCell's technology, the outsourcing decision has led to a risk of insufficient feedback to product development and insufficient quality. These are two aspects that should be considered alongside the benefits of reduced cost and production

time. If production volumes are increased, there is a need to decide how to move forward with this partnership in the future; if all fuel cell stacks should eventually be externally sourced from Bosch or if they should be produced in-house.

The sixth critical area concerns the testing activities in the production process, which constitute one bottleneck in the production.³ This is due to several reasons: the testing activities are time-consuming, tests are being conducted during various phases of the production process, and fuel cell systems must be mounted on lab interface module wagons (LIM wagons) before entering the lab area, which also takes time. Additionally, production, the Engineering department, and the Applications department share resources in the lab area, meaning that testing activities must be coordinated. The shared lab area indicates a focus on resource efficiency, maximizing the utilization of resources, rather than flow efficiency, the focus on consistent flows and reduction of non-value adding activities (Wernicke et al., 2017). The focus on resource efficiency is, according to Modig and Åhlström (2011), common in organizations due to a perception that maximizing resource efficiency reduces costs. However, the high resource efficiency can result in increased inventory and queues (Slack et al., 2013). When PowerCell plans for increased production volumes, a strategic decision must be made regarding the balance between resource efficiency and flow efficiency related to the structure of the testing activities.

To summarize, certain strategic decisions have been made regarding PowerCell's production system, however, these decisions lack comprehensiveness and there is no clear production strategy. Moving forwards, there is a need to establish a clear production strategy and align it with the anticipated growth in demand. Furthermore, it is apparent that the newness of the product and the market along with the constantly evolving organization result in a complex situation that must be addressed to achieve the set goals of increasing production volumes.

1.5 Research Questions

The conducted pre-study unveiled six challenging areas related to the production system, each of which will need to be further explored to enable the development of a strategic direction for PowerCell's production system. PowerCell currently lacks a comprehensive production strategy, however, certain strategic decisions have been made, and these need to be identified. There is also a need to examine the strategic decisions further, as these might induce challenges in the production system and could have consequences if production volumes are increased. Furthermore, these challenges should be assessed to identify initial solutions and the most prominent challenging areas. Considering all these aspects, certain strategic decisions can be proposed regarding the production system to address the identified prominent challenging areas and support increasing production volumes. To fulfill the aim of this study, four research questions have been formulated.

RQ1: Which strategic decisions have been made regarding PowerCell's current production system?

RQ2: Which challenges associated with the strategic decisions can be identified, and what initial solutions can be proposed to address these challenges?

RQ3: Which challenging areas related to PowerCell's current production system are the most prominent?

RQ4: Which strategic decisions regarding the production system should PowerCell make to overcome the identified prominent challenging areas and support increasing production volumes?

1.6 Scope & Delimitations

This study focuses on PowerCell's production system and interfaces between the production system and other parts of the organization, for example, information and material handovers between the Operations department and other departments. Furthermore, this study examines the production process for products manufactured in the production system rather than products manufactured in other locations, such as Applications projects. A delimitation to this study is that it is assumed that production volumes will increase to a certain extent, however, no exact growth rate is assumed. Another delimitation is that the aftermarket is not considered in this study, hence, the activities in the warehouse are limited to those related to production of new products rather than services related to existing products.

2 Frame of Reference

The following section presents a frame of reference for the report, introducing the most relevant terms and concepts for the study. The topics covered in this section are performance objectives, a framework for production strategy, and a detailed description of the six strategic decision areas of the framework.

2.1 Performance Objectives

Slack et al. (2013) describe that there are five basic objectives, referred to as performance objectives, that any operation benefits from acknowledging: quality, speed, dependability, flexibility, and cost. Bellgran and Säfssten (2010) describe the same objectives but refer to them as competitive factors and merge speed and dependability into one single factor called deliverability. Quality refers to how consistently the output of the operation conforms to customers' expectations and specifications. A high quality means fewer errors and increased customer satisfaction (Slack et al., 2013). Speed is defined as the time between a customer places an order and that the customer receives the product. High speed means that customers get the products earlier. Dependability is the objective of delivering the right things to customers at the right time, thus, high dependability means that customers can trust that they will receive the correct things at the expected time. Flexibility means that the operation can change in response to customer demand, for example in terms of introducing new products, offering a wide range of products, scaling up or down output quantities, or changing the time of delivery. Lastly, the performance objective of cost refers to how cost-efficiently the operations run. Slack et al. (2013) argue that cost is always important for operations, even if the company does not compete directly on price on the market.

Typically, there are trade-offs between different performance objectives, thus, organizations must prioritize between the different objectives (Slack et al., 2013). One common trade-off that organizations are faced with is the one between cost and flexibility, in terms of the variety of products offered to customers. Slack et al. (2013) argue that there is a so-called efficient frontier characterizing each operation that organizations position themselves along, where each level of cost efficiency corresponds to a certain, maximum, level of variety. If the organization seeks to improve their cost-efficiency without compromising the variety offered to customers, it must improve operations in some way to extend the efficient frontier.

2.2 Framework for Production Strategy

In the following section literature on production strategy is presented. The theory on the subject is synthesized into a Proposed Integrated Framework used throughout the project to fulfill the study's aim.

2.2.1 Skinner's Model of Trade-offs in Production

According to Bellgran and Säfsten (2010), Wickham Skinner was a pioneer in bringing production to a corporate strategic level, referring to it as manufacturing strategy. The essence of his recognized article from 1969 is that manufacturing functions often represent a substantial investment for organizations and should therefore be supported by management to reach targets. Skinner (1969) argues that a manufacturing strategy clarifies that production can contribute to company competitiveness. Furthermore, the author describes that very few executives are aware of the trade-offs when designing and operating a production system, wherefor the importance of reflecting top management decisions in the production perspective is stressed.

Skinner (1969) suggests five different decision areas within which a company must make strategic decisions regarding manufacturing strategy: facilities and equipment, production planning and control, labor, product design and development, and organization and leadership. In each of these areas, decisions about certain standpoints will be taken, thus, a trade-off between alternatives arises.

For example, decisions regarding facilities and equipment comprise decisions about plant size, and whether the company should have one big plant or several small plants. Further examples of decisions in each decision area with corresponding trade-offs are listed in Table 2.1 below.

Table 2.1: *Some important trade-off decisions in manufacturing (Skinner, 1969).*

Decision area	Decision	Trade-offs
Facilities and equipment	Plant size	One large or several small
	Span of process	Make or buy
	Plant location	Near customers or near materials
Production planning and control	Inventory size	High or low
	Quality control	High reliability and quality or low costs
	Use of standards	Formal, informal, or none
Labour	Job specialization	Highly- or not highly specialized
	Wage system	Many or few job grades
	Supervision	Close or loose

Product design and development	Size of production line Design stability Technological risk	Many customer specials or few or none Many changes or frozen design Unproved processes or follow-the-leader policy
Organization and leadership	Organization type Executive use of time Degree of risk assumed	Functional or product focus Involvement in production planning or cost control or other Decisions based on much or little information

2.2.2 Bellgran & Säfsten's Manufacturing Strategy Model

Bellgran and Säfsten (2010) propose a manufacturing strategy that is partly based on Skinner's (1969) model of trade-offs in production, however, they add certain elements. The authors argue that Skinner (1969) emphasizes what they refer to as structural decision categories. Structural categories are, according to Bellgran and Säfsten (2010), characterized by their long impact, large capital requirements, and resistance to change. In their proposed model, the authors also incorporate infra-structural decision categories, which are referred to as more tactical decision areas, where decisions are made at a higher frequency, and capital requirements are typically lower than with structural decisions. Bellgran and Säfsten's (2010) model of manufacturing strategy content is presented below in Figure 2.1.

Manufacturing Strategy Content		
Competitive Factors	Decision Categories	
	<i>Structural</i>	<i>Infrastructural</i>
Cost, quality, deliverability, and flexibility	Production process, capacity, facilities, and vertical integration	Quality, organization, and production planning and control

Figure 2.1: Manufacturing strategy content (Bellgran and Säfsten, 2010).

The content of Bellgran and Säfsten's (2010) manufacturing strategy model is based on two dimensions: competitive factors and decision categories. The competitive factors are how the organization aims to compete in a certain market, and these are: cost, quality, deliverability, and flexibility. These correspond to the five performance

objectives described in section 2.1 of this report, however, Bellgran and Säfsten (2010) combine speed and dependability into the competitive factor of deliverability.

The other dimension, the decision categories, are the company capabilities used to achieve the objectives, and these are: production process, capacity, facility, vertical integration, quality, organization, and production planning and control (Bellgran & Säfsten, 2010). Decisions regarding the production process are split into process type, layout, and technical level, and this decision category relates to how resources are transformed into products. A suitable process type and process layout can be chosen based on the relationship between the volume and variety of the process, visualized by a product-process matrix, as presented in section 2.3.1 of this report. The technical level regards how automated the process ought to be (Bellgran & Säfsten, 2010). The decision category capacity regards which capacity the organization has at a certain point of time to conduct a certain activity, and the capacity can be adjusted according to product demand in one of three ways: personnel, technology, and buying or selling capacity. An organization can choose whether to have a so-called leading strategy or a lagging strategy, choosing whether to adjust capacity proactively, before demand changes, or reactively, after demand changes.

The decision category facility refers to the building where the production process occurs, for example where it should be in relation to the market and suppliers, or how many factories are needed (Bellgran & Säfsten, 2010). The next decision category, vertical integration, relates to the degree to which the organization acquires different parts of the supply chain, for example component producers or distributors, to achieve better control over the entire process. The decision category quality refers to how quality issues are handled, for example, if a proactive or reactive approach is chosen, and who is responsible for what. Organization and human resources is a decision category related to organizational structure and sharing of responsibility and work tasks. The last decision category, production planning and control, comprises decisions regarding the customer order decoupling point (CODP), which decides where the planning point should be, material planning, and order sequences.

2.2.3 Slack & Lewis' Operations Strategy Matrix

According to Slack and Lewis (2020), operations strategy relates to the reconciliation of market requirements and operations resources. The content of the operations strategy is presented in a matrix according to Figure 2.2, and comprises two dimensions: required performance, based on an understanding of the market, and strategic decisions, based on an understanding of operations resources and processes. The required performance is represented by the five performance objectives, as described in section 2.1 of this report. There are four strategic decision areas, namely: capacity, supply network, process technology, and development and organization.

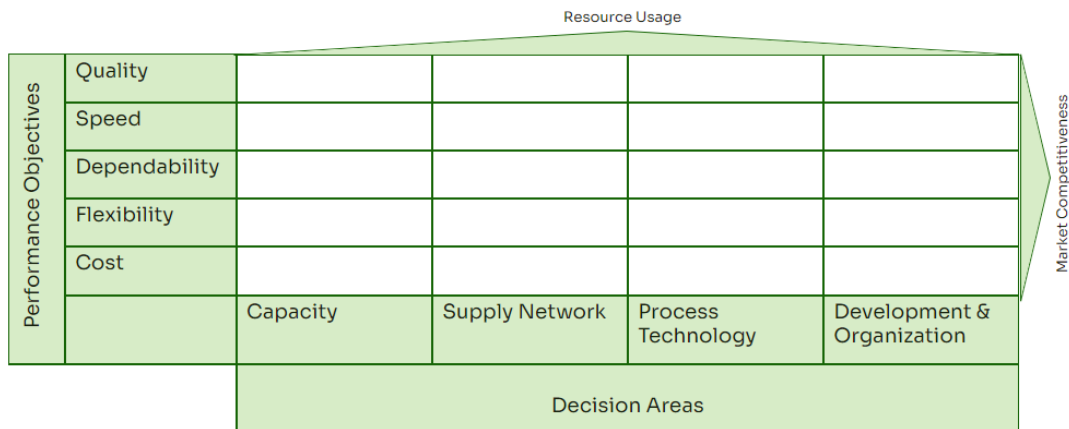


Figure 2.2: *Operations strategy matrix (Slack & Lewis, 2020).*

Capacity is a decision area that regards how the capacity and facilities should be utilized, for example, how capacity should be adjusted according to demand, how many sites the organization should have, and where the sites should be located (Slack & Lewis, 2020). The supply network decisions regard how the operation is positioned in relation to its customers and suppliers, for example, the degree of vertical integration and the relationships the organization should have to its suppliers. The process technology decisions are concerned with how technology, such as systems or machines to be used for the transformation of resources into products, is chosen. The last decision area, development and organization, comprises decisions regarding how the operation should be run more long-term, for example how processes can be enhanced and how product development is organized.

2.2.4 Proposed Integrated Framework

To map and create a production strategy suitable for PowerCell’s specific situation, the three different frameworks described in sections 2.2.1, 2.2.2, and 2.2.3, have been combined into one integrated framework presented in Figure 2.3. The purpose of the proposed framework is to provide a basis for identifying which strategic decisions have been made regarding PowerCell’s production system and for mapping challenges in PowerCell’s current production system. Furthermore, the framework can be used to emphasize areas where strategic decisions should be made, to formulate a strategic direction regarding the production system in a structured way. The frameworks decision areas will further serve as a foundation for areas of relevance in the literature review and when conducting interviews. The performance objectives will be used to cluster decisions based on their intended result.

		Resource Development					
Performance Objectives	Quality						Market Competitiveness
	Speed						
	Dependability						
	Flexibility						
	Cost						
		Production process	Capacity	Supply Network	Quality Management	Development & Organization	Production Planning & Control
		Decision Areas					

Figure 2.3: *Proposed Integrated Framework of synthesized literature.*

Like the operations strategy matrix by Slack and Lewis (2020), the integrated framework is visualized through a matrix comprising the two dimensions required performance and decision areas forming 30 individual cells. The required performance consists of the five performance objectives quality, speed, dependability, flexibility, and cost, which, according to Slack et al. (2013), are required to be competitive on the market. The decision areas are based on resources and processes considered crucial for PowerCell production strategy and comprise production process, capacity, supply network, quality management, development and organization, and production planning and control.

First, production process decisions regard process type, layout, and technical level as described by Bellgran and Säfsten (2010). These are decisions of importance to PowerCell when planning for scaling up production volumes, as they would need to consider the changes in the relationship between the volume and variety and based on that find a suitable process type and process layout.

Second, capacity decisions regard facilities and capacity, for example number of sites an organization should have, where these should be located, and how production capacity should be adjusted to demand (Bellgran & Säfsten, 2010; Skinner, 1969; Slack & Lewis, 2020). In accordance with PowerCell’s plans for expansion, decisions about how to allocate and plan capacity strategically will be crucial.

Third, supply network decisions concern how an operation positions themselves in relation to suppliers and customers, as described by Slack and Lewis (2020). Similarly, this is described as vertical integration by Bellgran and Säfsten (2010) but is considered more comprehensive and suitable to PowerCell’s situation when treated as supply network decisions. If PowerCell increases output volumes, decisions that concern supplier relationships and the degree of vertical integration will need to be considered in accordance with the performance objectives. This can, for example, refer to the partnership with Bosch and the appropriate degree of outsourcing.

Fourth, quality management in terms of being a decision area is not equivalent to quality as a performance objective. As argued by Bellgran and Säfsten (2010), this

decision area refers to how quality issues are handled. Making strategic decisions about the process of handling quality issues will be of high importance for PowerCell when scaling up production volumes, to ensure consistency in production.

Fifth, the decision area development and organization concerns how operations should be run in the long-term perspective, and how product development is organized (Slack & Lewis, 2020). Decisions in this area must be stressed by PowerCell, as scaling up production volumes will imply organizational changes and strategic decisions to be made about the currently highly development-oriented organization.

Sixth, and last, the production planning and control decision area described by Bellgran and Säfsten (2010) will be of high importance to PowerCell when scaling up production volumes, as it comprises strategic decisions about for example material planning and order sequences. For example, the decisions regarding the CODP need to be reviewed to ensure that the correct balance between MTO and MTS is selected.

2.3 Strategic Decision Areas

The following section provides and discusses theory on the strategic decision areas used in the Proposed Integrated Framework. The strategic decision areas are production process, capacity, supply networks, quality, development and organization, and production planning and control.

2.3.1 Strategic Production Process Decisions

A production process is defined as a process transforming resources into products (Bellgran & Säfsten, 2010). According to Bellgran and Säfsten (2010), strategic decisions related to production processes comprise three types of decisions: process type, layout, and technical level.

Production Process Type

The process type associated with a production process is, according to Bellgran and Säfsten (2010), the way that activities are organized to perform the transformation of resources. The process type is typically closely related to the output volume and variety of the production process, where different relationships between volume and variety imply selection of different process types. Slack et al. (2013) argue that when designing a process, the volume and variety requirements on the output should be the main guidance for decisions. There is a spectrum ranging from low volume and high variety to high volume and low variety, where processes are positioned, as visualized in Figure 2.4 below (Slack et al., 2013). This leads to five main types of manufacturing processes: project processes, jobbing processes, batch processes, mass processes, and continuous processes. Project processes have a low volume and high variety and manage products that are typically highly customized and that require a long time to complete, with resources exclusively devoted to them. In the project processes, the product flow is almost non-existent (Jonsson & Mattsson, 2009). Jobbing processes also have low volume and high variety; however, process resources are shared between products in

this type of process (Slack et al., 2013). Jobbing processes produce a higher volume than project processes, but each product might still require specific attention and have different needs. The jobbing process is appropriate for production of different types of products (Jonsson & Mattsson, 2009). Further, this type of process can require a certain amount of skill and knowledge (Slack et al., 2013). The third type of process, the batch process, produces batches of products that are similar. This process type typically has a lower variety than jobbing processes, as products within batches are similar, however, products can differ between batches. The characteristics of the batches determine the process's volume and variety levels. Mass processes produce high volume and low variety output and are repetitive with low uncertainty. The last process type, the continuous process, is characterized by an even higher volume and lower variety. This type of process is commonly conducted in an endless flow.

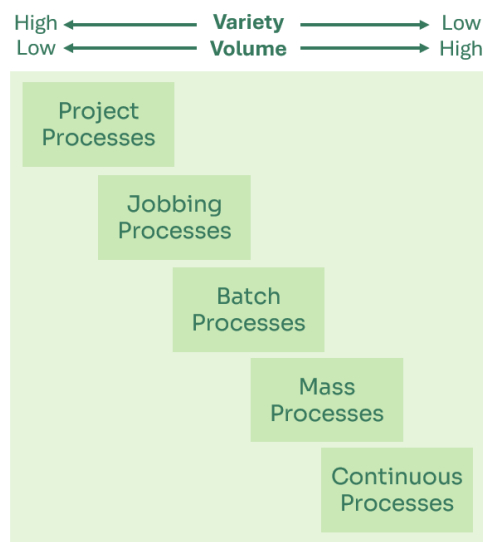


Figure 2.4: Volume-variety characteristics for different process types (Slack et al., 2013).

A common way of visualizing the process's volume-variety characteristics is by the so-called product-process matrix, shown in Figure 2.5 (Slack et al., 2013). The authors argue that layout and technology decisions also are related to the volume-variety characteristics of the process. The spectrum of volume-variety characteristics constitutes a so-called natural diagonal across the matrix, where processes should be positioned. Deviation from the natural diagonal will typically entail higher operating costs; moving to the right side of the natural diagonal means that the process has a higher flexibility than required and that opportunities for standardization are missed, and being on the left side of the natural diagonal implies an over-standardization, with too low flexibility and thus high costs of changing between activities.

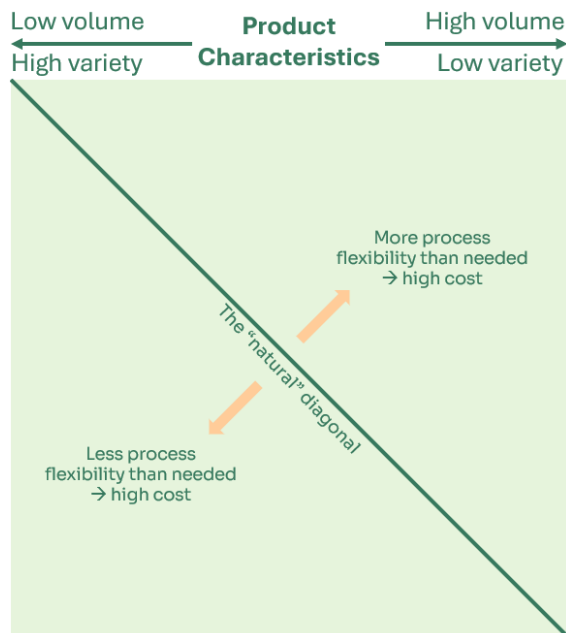


Figure 2.5: *The product-process matrix (Slack et al., 2013).*

Achieving a high flexibility typically comes at the expense of having a low volume. However, there are also ways to reach a high flexibility and offer a high degree of customization while still producing high volumes in a relatively cost-efficient way, and this is called mass customization (Slack et al., 2013). The aim of mass customization is, thus, to overcome the trade-off between variety and cost (Slack and Lewis, 2020). The concept of mass customization is built on the assumption that markets are increasingly fragmented, while new technologies can facilitate enhanced flexibility. An example of mass customization is where product families are developed with basic features that can be modified according to individual customer needs. Other examples are standardization of components, modular designs, or products built on platforms. This topic is further explored in section 2.3.5 of this report.

Production Process Layout

Layout decisions regard the physical location of the transforming resources and how tasks are allocated to them (Slack et al., 2013). The process layout determines how products will flow through the production system. There are four basic types of layouts that can be altered and combined according to the requirements of the production system: fixed-position layout, functional layout, cell layout, and product layout. Firstly, a fixed-position layout implies that the transforming resources are arranged so that the product is stationary, thus, resources and equipment are moved in a way that is necessary to build the product (Slack et al., 2013). This layout is appropriate when the product is too large or delicate to move. However, as volume increases and variety decreases, the fixed-position layout entails issues with product flows. Secondly, a functional layout means that similar resources or equipment are clustered, so that products flow between activities in the production system as needed. Thus, different products take different routes, which can be appropriate when there is still a certain

degree of variety. This layout typically increases resource efficiency but also increases product flow complexity. Thirdly, a cell layout is a layout where products upon entering the operation are guided to one part of the operation, referred to as a cell. In the cell, required resources and equipment are available and arranged in either a functional or product layout. One cell can be succeeded by another cell, where other processes take place. A cell layout is, according to Slack et al. (2013), a solution to the complex flows of the functional layout and can be appropriate when there is a degree of variety, but certain categories of products can be distinguished. Fourthly, and lastly, a product layout implies that every product moves according to a specific path of activities, and the resources and equipment are arranged according to this path. In the product layout, product flows are clear and predictable, making it suitable for products with a high degree of standardization.

When choosing a layout, Slack et al. (2013) argue that the importance of product flow is essential. The lower the volume and the higher the variety, the lower the importance of product flow. This is because products flow very infrequently through the operation. However, as volume increases and variety decreases, the product flow becomes more important. The five different process types based on different volume-variety characteristics, explained previously, are typically related to the four layouts in the following way: project processes have fixed-position layouts, jobbing processes have fixed-position or functional layouts, batch processes have functional or cell layouts, mass processes have cell or product layouts, and continuous processes have product layouts. The layout choice should also consider the cost element, where fixed and variable costs differ among the four layouts (Slack et al., 2013). The fixed-position layout entails low fixed costs, but high variable costs associated with each product. The functional- and cell layouts have higher fixed costs but lower variable costs, and the product layout commonly has the highest fixed costs, but the lowest variable costs associated with each product.

Technical Level of the Production Process

The last decision regards the technical level of the production process. This implies choosing a suitable level of technology to be used in the production system (Bellgran & Säfsten, 2010). Slack and Lewis (2020) describe the need to consider the volume-variety characteristics to find a suitable technical level for the production process. Three characteristics of the process technology differ according to the volume-variety characteristics: the scale, the degree of automation, and the degree of coupling. Scale refers to the technology's capacity to process work in terms of the size of the units of technology. This can, for example, mean the decision to have one large machine or several smaller machines. Each choice has certain consequences for the production system; large units of process technology typically lead to lower operating costs but imply risks in terms of increased vulnerability and lower flexibility of the operation and reduced opportunity to exploit new technology, while smaller units of process technology might entail higher operating costs but a more robust production system (Slack and Lewis, 2020). The degree of automation refers to the amount of work each unit of technology does and how much human intervention there is. A high degree of

automation typically means lower direct costs and higher speed in the process. However, Slack and Lewis (2020) point out that in many cases, automation does not reduce the total costs, due to regular maintenance and the increased labor cost that comes with the change in competence required. Furthermore, the authors argue that automation can reduce the flexibility and dependability of the process, and the implementation is often time-consuming. Coupling refers to how integrated different process technologies are. A high degree of coupling can lead to lower work-in-progress and costs due to a higher degree of synchronization, however, it reduces the robustness of the process in the event of failure at any part of the process. A reduced robustness might, on the other hand, act like a catalyst of change as it exposes weaknesses in the production system, which is a perspective emphasized in Lean Production (Slack et al., 2013).

Choosing a technical level can, as previously mentioned, be done by reviewing the volume-variety characteristics and the product-process matrix. The scale, degree of automation, and coupling are related in the sense that a large-scale technology enables high coupling and a higher degree of automation, and the other way around. For a process prioritizing cost efficiency over variety, a large scale, high coupling, and high degree of automation is usually suitable, while a process with high requirements for flexibility and variety typically can benefit from a smaller scale, low coupling, and low degree of automation. A production process should, as previously noted, be positioned on the natural diagonal of the product-process matrix, and the process technology should be chosen in accordance with the volume-variety characteristics of the specific position in terms of scale, coupling, and degree of automation.

Slack and Lewis (2020) further argue that information processing technology can overcome the trade-off between volume and variety. This can lead to opportunities for increasing volume while maintaining a relatively high variety, thus utilizing a mass customization approach.

2.3.2 Strategic Capacity Decisions

An organization's capacity strategy within operations defines scale of the capacity, site distribution, allocated activities, and site locations (Slack & Lewis, 2020). The capacity strategy may require adjustments as the competitive landscape changes. The process of changing capacity usually involves deciding when capacity levels should be increased or decreased, how large each step of change should be, and how fast capacity levels should change. Slack and Lewis (2020) highlight five crucial areas to consider regarding capacity decisions.

Total Capacity Level

The first capacity decision is how much capacity an operation should have, which is influenced both by market requirements and operations resources. Forecasting future demand carries uncertainty that can hinder investment decisions. Excess capacity can offer flexibility to meet short-term demand increases, especially crucial during product launches or in competitive markets where satisfying immediate demand is vital, but is

costly (Slack & Lewis, 2020). Undersupplying a market might increase customers' willingness to pay, depending on how well the product or service is positioned in the market and how much competition there is. However, Slack and Lewis (2020) argue that undersupplying the market could reduce demand, benefiting competitors. Organizations could manage this by adjusting prices and promotions, which highlights the importance of aligning capacity decisions with market strategy. Expanding capacity is a common strategy among firms aiming to broaden their business reach and boost profits, particularly in anticipation of market expansion (Kamoto, 2015). Evaluating the worth of such expansions and making investment choices becomes crucial for firms to optimize their investment value. Slack and Lewis (2020) claim that expanding physical capacity in advance of effective capacity can generate greater returns in the long run, meaning that it can be favorable to invest in larger facilities directly despite the higher initial costs.

Number of Production Sites

The second decision concerns how many separate sites an operation should have. Slack and Lewis (2020) mean that an organization in general should establish multiple smaller sites if customer demand is widely distributed or if customers demand high absolute levels. Multiple smaller sites located closer to the customer are also preferable if an operation provides few larger units, to lower the transportation costs of goods (Slack & Lewis, 2020). A small number of larger units may also be less costly to supply with input resources. On the other hand, it can be difficult to exploit economies of scale with many small sites, wherefore fewer larger sites could be beneficial.

Long-Term Capacity Change Strategy

The third capacity decision treated by Slack and Lewis (2020) regards long-term capacity change strategy. Slack and Lewis (2020) describe three main strategies for timing capacity changes: capacity leads demand, capacity lags demand, and smoothing with inventories. The capacity leads demand strategy increases production capacity before forecasted demand increases, potentially yielding higher revenues but at increased costs. The capacity lags demand strategy adjusts capacity introduction to closely match or slightly lag actual demand, potentially leading to missed selling opportunities but useful when capital access is limited. Smoothing with inventories aligns capacity introduction with current capacity levels supplemented by inventory buffers, providing consistent supply to meet demand but implies additional costs and inventory risks. Regardless of timing strategy, Slack and Lewis (2020) stress that the lowest capacity, or bottleneck, in a supply chain will limit the capacity of a whole chain of operations and planning for capacity change must therefore be balanced.

Task Allocation to Each Site

The fourth capacity decision regards task allocations to an operation's sites. The main issue with this decision is whether to have focused operations or not, hence, whether sites should be specialized on certain specific tasks or not (Slack & Lewis, 2020). Focused operations entail the benefit of specializing in a narrow range of tasks with clear performance objectives, however, they might be vulnerable to market shifts and

lack economies of scale. Bellgran and Säfsten (2010) call this process or product focus. A process-focused site is a general, not dedicated operation, flexible and capable of handling various products. Contrastingly, a product-focused site has focused operations and specializes in producing one or a few products in high volumes, often emphasizing cost efficiency.

Location of Each Site

The fifth capacity decision involves determining the location of each site, thus, where an organization places its operational capacity (Slack & Lewis, 2020). Effective location decisions require a comprehensive understanding of how costs, revenues, and investments vary across different geographical areas. For instance, locating a manufacturing plant in an area with a shortage of skilled labor can impact product quality and costs due to challenges in attracting the right talents. Additionally, Slack and Lewis (2020) mean that customer service expectations heavily influence location decisions, as closeness to customers ensures prompt and consistent supply, meeting their needs efficiently. Market factors, such as the suitability and perception of the site's location, also influence this decision-making process. Furthermore, operational considerations like land and energy costs, required investments, availability of specialized resources, and community dynamics are pivotal in determining the optimal location. Similar to the location considerations highlighted by Slack and Lewis (2020), Bellgran and Säfsten (2010) discuss that when planning the establishment of a facility or factory, several crucial decisions come into play. These include determining the ideal location of the facility, considering factors such as proximity to markets, raw material suppliers, and logistics centers.

2.3.3 Strategic Supply Network Decisions

A supply network is a system comprising interconnected organizations whose various processes and activities collectively produce value (Slack & Lewis, 2020). Each organization will have linkages to both suppliers and customers, and competitors, and the importance of the supply network, according to Slack and Lewis (2020), is that operations managers must understand the capabilities of the resources that form the network, and how effectively these are linked together. Adopting a supply network perspective can also include broader aspects than buyer-seller relationships or competition, such as the collaboration or complementation between different elements of the network. Slack and Lewis' (2020) main reasoning is that any organization should ask themselves two things: how their suppliers' operations can help their operation become more effective and how they can help their customers' operations become more effective. The strategic supply network decisions hence revolve around deciding the organization's desired position in the supply network.

Type of Supply Network

One objective when managing the supply network is to achieve a strategic fit between the organization and its suppliers, which can be done by first understanding the level of uncertainty and the supply chain capabilities (Chopra & Meindl, 2013). For organizations facing uncertain demand from their customers, for example due to a new

product, forecasting is difficult. Thus, it can be challenging to match the supply to the demand. If this is the case, Chopra and Meindl (2013) argue that a responsive, rather than an efficient, supply network is to be preferred. This implies a supply network that can respond quickly to wide ranges of quantities, offer short lead times, and offer many product variants, and suppliers should be chosen based on their speed, flexibility, dependability, and quality. This type of supply network typically entails higher costs, while the opposite, an efficient supply network, focuses mainly on predictability and lowering costs. In an efficient supply network, suppliers should be chosen based on cost and quality. To achieve a strategic fit, according to Chopra and Meindl (2013), the supply network responsiveness should be matched with the level of demand and supply uncertainty.

Do-or-Buy Decisions

One type of strategic decision regarding the supply network is about choosing which processes to perform in-house and which to outsource (Chopra & Meindl, 2013). This type of decision is referred to as a do-or-buy decision (Slack and Lewis, 2020). Do-or-buy decisions involve both strategic importance and operational considerations, however, the authors argue that it is relatively common that the focus is on short-term cost savings, rather than efficiency maximization. The do-or-buy decision affects the organization's performance in various ways, which can be categorized into the five performance objectives.

In terms of quality, errors are typically easier to trace and correct when producing something in-house, however, a supplier might be specialized or have a more standardized production process due to higher volumes (Slack & Lewis, 2020). For speed, producing something in-house might facilitate synchronization of flows, however, internal customer-supplier relationships might not always be prioritized in the same way as external customer-supplier relationships. When buying from a supplier, lead times might be contractually defined but there is also a risk of transport delays. Dependability might increase when producing in-house due to easier communication, however, there is still the issue of internal customers receiving a lower prioritization. On the other hand, when buying from a supplier, late delivery penalties can be included in the contract, possibly reducing the risk of delays. In terms of flexibility, in-house production will be limited by the scale and scope of the organization, while suppliers might have broader capabilities. It can be easier to scale up and down volumes when buying than to adjust capacity according to demand fluctuations. Lastly, when producing in-house, the organization can eliminate the profit margin otherwise paid to the supplier, however, low production volumes make it difficult to reach economies of scale. Buying from a supplier might be less costly as suppliers can reach economies of scale, however, administrative and coordinative costs will be induced.

Do-or-buy decisions are, according to Dabhilkar (2011), rooted in transaction cost economics and the resource-based view. Transaction cost economics recommends using outsourcing when it is possible to reduce overall production costs (Dabhilkar, 2011). The resource-based view describes firms as collections of resources that, when utilized

effectively, lead to competitive advantage. Core business capabilities should be kept internal, while non-core functions can be outsourced. Kroes and Gosh (2009) also describe how do-or-buy decisions enhance a firm's competitive advantage, adding two perspectives: agency theory and the knowledge-based view. Agency theory emphasizes the delegation of authority and the need for alignment between different organizations, explaining outsourcing as the delegation of responsibility to a more efficient provider (Kroes & Gosh, 2009). The knowledge-based view focuses on leveraging specific knowledge sets for competitive advantage, whether from internal or external sources. Overall, these theories suggest that organizations should exploit activities, such as production processes, that offer additional competitive advantages. Conversely, activities that do not offer such advantages should be externally sourced (Kroes & Gosh, 2009).

Supplier Selection

Luthra et al. (2020) emphasize the criticality of supplier selection for manufacturing industries due to the substantial costs associated with raw materials and services. Typically, organizations allocate around 60% of product costs towards acquiring raw materials. The quality of these raw materials significantly impacts the production of high-quality end products at optimal costs, underscoring the importance of the customer-supplier relationship. This relationship encompasses various aspects such as material quality, reworking services, handling of customer complaints, and delivery performance (Luthra et al., 2020). One important step in fostering the customer-supplier relationship is selecting the right supplier (Luthra et al., 2020). Reliable suppliers can help lower inventory costs, enhance quality, and contribute to overall supply chain efficiency (Luthra et al., 2020). Therefore, effective supplier selection is critical for long-term business success and competitiveness in the marketplace. Luthra et al. (2020) further outline selection criteria for suppliers, which can include assessing previous performance, quality system adherence, capacity, technical support, cost optimization, and business track record. Methods for evaluating potential suppliers include financial analysis, performance history review, on-site visits, quality system confirmation, and customer feedback analysis.

Another decision to be made when selecting suppliers is the number of suppliers for each component, and there are two main approaches: single sourcing and multiple sourcing (Jonsson & Mattsson, 2017). Single sourcing is when a single supplier is used for a certain component, while multiple sourcing implies using several suppliers for a certain component. Using a single sourcing approach can be suitable when sourcing low volumes, as administrative costs from using multiple suppliers might be too high, or when there are only a few options available in the market. Additionally, if aiming for partnerships with suppliers, single sourcing is more suitable, as it facilitates communication and information sharing between the company and the supplier. The main reasons for choosing multiple sourcing are the possibility of decreasing prices by putting suppliers against each other and the reduced risk of delivery disruptions from a single supplier. Further, it can increase flexibility to scale volumes according to demand compared to a single sourcing approach. A multiple sourcing approach has, according

to Jonsson and Mattsson (2017) traditionally been the most common, however, the authors argue that the price paid is only a fraction of the total cost associated with the purchasing activity, and that the lack of partnership with suppliers can reduce opportunities of ongoing improvement work.

Managing Relationships in the Supply Network

In managing the supply network, it is important to review suppliers and to determine the suitable level of relationship to have with each supplier (Uygun et al., 2023). Firstly, securing reliable suppliers that meet quality requirements is crucial for long-term cost savings, especially for complex parts. Secondly, collaboration with suppliers fosters trust and minimizes the risk of receiving parts that do not meet the quality requirements. Furthermore, as complexities in outsourced parts can induce a risk of intellectual property leakage, better collaboration with suppliers and understanding of technology can mitigate this risk, reduce cultural distance and improve knowledge exchange (Uygun et al., 2023). Supplier relationships can be conceptualized along a continuum ranging from transactional to partnership relationships (Slack & Lewis, 2020). Transactional relationships in outsourcing production involve short-term, transaction-focused interactions governed by formal contracts. Communication is limited, and the focus is on immediate exchanges of goods or services. In contrast, partnership relationships entail deeper, long-term collaborations between the buyer and supplier. These involve open communication, joint problem-solving, and a focus on mutual success beyond formal contracts (Slack & Lewis 2020). The emphasis is on building trust, sharing knowledge, multiple points of contact, joint learning, and problem-solving initiatives, and achieving common goals for sustained competitive advantage.

If managed in a suitable way, partners in the supply network can help an organization improve (Liker, 2005). For example, if customer relationships are effectively managed, the value of the customers for the organization can be maximized (Kumar & Reinartz, 2011). Furthermore, as emphasized in Lean Production, if an organization strives for continuous improvement together with its partners, quality can be improved (Liker, 2005). This might imply educating partners. Driving continuous improvement with partners can, for example, be done using the quality management tools as described in section 2.3.4 to expose problems and encourage improvements. Additionally, innovation can be pursued together with suppliers to maintain a technological advantage on the market.

2.3.4 Strategic Quality Management Decisions

Quality is not just a performance objective; it is also a critical aspect of strategic decision-making in production processes (Bellgran & Säfssten, 2010). Garvin (1987) defines quality based on eight dimensions, namely: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. It is, according to Bellgran and Säfssten (2010) essential to establish routines that ensure these eight dimensions are met to maintain consistency. Another definition of quality is proposed by the Swedish Standards Institute (2016), as the ability of products and services to satisfy customers and the impact they have, intended or unintended, on other

stakeholders. Examples of stakeholders are the government, society, and employees (Gremyr et al., 2020).

Defining the Desired Level of Quality

It is important to provide quality according to specifications, as stressed by Gremyr et al. (2020). However, Sandy (2020) emphasizes the importance of avoiding excessive investments in early product development phases, because as the product's value might still be uncertain, prioritizing top-tier quality continuously could be counterproductive. Overemphasizing quality and scale too soon could result in significant waste, such as delaying time-to-market and impeding the collection of crucial customer feedback needed to steer the product's development (Sandy, 2020). This risk is especially high if the product fails or shifts direction substantially after its initial launch. It is thus important to find the level of product specification providing good enough quality.

Quality standards can be viewed as one way to establish a certain desired level of quality (Kelemen, 2003). It is common that conformance to certain quality standards is required by, for example, customers or governments, or by regulations in the industry. The ISO 9000 series, regarding consistent quality, and the ISO 14000 series, regarding environmental aspects, are two of the most important standards, according to Kelemen (2003). While quality standards are a way of achieving customer satisfaction as they serve as a signal of quality, their implementation entails considerable documentation and, in certain cases, substantial costs.

Proactive & Reactive Quality Approach

Bellgran and Säfsten (2010) mean that quality often serves as an order-qualifier by meeting customer requirements and establishing a baseline for acceptability for many companies. When it comes to quality in production, two key questions emerge regarding quality. Firstly, organizations should decide between a reactive and a proactive quality approach. A reactive approach focuses on identifying faults during or after production and preventing faulty products from reaching the customer, while a proactive approach aims to prevent issues from arising in the first place (Bellgran & Säfsten, 2010). The second key question is about roles and responsibilities. Bellgran and Säfsten (2010) argue that it is often challenging to separate responsibility from execution, as the person in charge of a task is also responsible for ensuring the right quality. Due to the high importance of assuring quality, companies typically invest significant effort in securing their processes to uphold quality standards.

Black (2008) highlights methods from Lean Production theory to be used in production systems to assure quality in the manufacturing process. Poka-yoke is one concept rooted in Lean Production theory, which serves as a mistake proofing device or procedure designed to prevent or highlight defects (Black, 2008). Thus, poka-yoke is a quality approach aiming to proactively ensure quality is secured throughout the manufacturing process. It could be in the form of either a warning or control

mechanism. Warnings provide alerts designed to prevent additional errors or defects from occurring, while control mechanisms stop the next step of a work in progress item from happening if defects or errors are found. In manufacturing, Black (2008) describes three main types of poka-yoke to assure quality: contact, fixed-value, and motion-step methods. Contact methods use sensing devices to ensure proper product positioning, either physically or through photoelectric beams. Fixed-value methods track the completion of tasks or parts assembly, signaling when requirements are met correctly, and the item is ready for the next step. Motion-step methods monitor sequences or timing, alerting if steps are not performed correctly.

The Three Principles of Quality Management

Dean and Bowen (1994) propose three fundamental principles of quality management: customer focus, continuous improvements, and teamwork. Firstly, an organization-wide effort is needed to provide products that customers need. Secondly, processes must constantly be revised and improved to maintain customer satisfaction. Thirdly, teamwork is needed, both internally and with customers and suppliers, to achieve the two previous principles of customer focus and continuous improvement.

The first principle, customer focus, is described by Gremyr et al. (2020) as divided into several parts, two of which are understanding customer needs and expectations and becoming more customer oriented. To understand customer needs, it is important to understand both explicit and implicit needs, hence, needs that customers explicitly express when asked and needs that customers do not explicitly say, either because they consider them obvious or because they are not aware of them (Gremyr et al., 2020). Gremyr et al. (2020) argue that it is essential that all parts of an organization are customer oriented to ensure the highest quality. Additionally, Modig and Åhlström (2015) emphasize the role of internal customers, where each production step has an internal supplier and internal customer, and it is of high importance for the internal supplier to understand three things: what the internal customer needs to produce the product for the external customer, when they need it to be able to deliver the product at the specified time, and how much they need to produce the product. The internal supplier in this specific process then acts as an internal customer in the preceding production step, and so on. This is a common method of working in Lean Production, where material is pulled through the production system.

The second principle, continuous improvement, is described by Gremyr et al. (2020) as the systematic translation of customer needs into improvements. As a basis for continuous improvement, processes are a relevant starting point (Gremyr et al., 2020). Processes can have different levels of standardization, but exist in all organizations, and the purpose of a process is to create value for a stakeholder. The stakeholder can be an external customer, but also an internal customer. Gremyr et al. (2020) emphasize the importance of having a process view, as it enables cross-functionality in creating value for the downstream customer of any process.

Furthermore, Lean Production principles emphasize continuous improvement (Gremyr et al., 2020). In Lean Production, continuous improvement is encouraged throughout the organization, eliminating waste in processes and maximizing value creation. This implies a focus on flow efficiency as opposed to resource efficiency. Flow efficiency puts emphasis on the flow of units and is a measurement of the value-adding activities in relation to the throughput time (Modig & Åhlström, 2015). Flow efficiency can thus, from a customer perspective, lead to a faster delivery with a higher quality (Gremyr et al., 2020). Contrastingly, the traditional view is the resource efficiency, which is when resource utilization, in terms of employees and equipment, is maximized (Modig & Åhlström, 2015). The flow efficiency focus characterizing Lean Production results in free capacity in the production system, which might be costly if focusing strictly on flow efficiency, thus, Gremyr et al. (2020) propose that there should be a balance between flow efficiency and resource efficiency, the goal is to have both as high as possible. However, achieving this is challenging, especially if facing high demand uncertainty (Modig & Åhlström, 2015). The point that is stressed by Modig and Åhlström (2015) is that even though the ideal position is challenging, if not impossible, to reach, an organization should strive to get there by continuous improvements. One part of this is to achieve better flow efficiency, which can be done by reducing waste, in terms of non-value adding time (Gremyr et al., 2020). In Lean Production, there are seven categories of this type of waste, called Muda: transport, inventory, motion, waiting, overproduction, over-processing, and defects.

Another aspect of continuous improvement is the usage and selection of quality management tools (McDermott et al., 2022). Ishikawa (1976) presents seven basic quality management tools, whereof some are: Pareto charts, process flow charts, and control chart. Firstly, Pareto charts are based on the Pareto principle, which states that 80% of the effects typically arise from 20% of the causes (Tarantino, 2022). Pareto charts can be used to determine top priorities in an organization by identifying areas where improvement will yield the strongest results with the least effort (Kelemen, 2003). Secondly, process flow charts provide a graphical display of the different steps constituting a process (Tarantino, 2022). A process flow chart can help an organization emphasize areas where improvements are needed by mapping value-added and non-value-added steps of the process. Furthermore, process flow charts provide a basis for communication and mutual understanding in the organization (Kelemen, 2003). Thirdly, control charts are used to check whether a process is in control or out of control. Measurements, in the form of sample values of a certain quality characteristic in the process, are plotted on a chart with upper and lower control limits and warning limits. The plot will indicate the variation in the system, and whether the process is in control or not.

Another tool used for continuous improvement is 5S, used in Lean Production (Elbert, 2013). 5S comprises five steps to eliminate waste in, for example, the production system, and the aim is to reduce the number of errors. The five steps are: sort, straighten, shine, standardize, and sustain. Firstly, sort refers to the elimination of all unnecessary

tools and supplies in the workplace. Secondly, straighten is about organizing by establishing a certain place for everything, arranging items in a logical manner. Thirdly, shine is to ensure that equipment and resources are clean and well-maintained. Fourthly, standardize refers to the creation of a process and a production system that facilitate continuously maintaining the first three S's. Lastly, sustain is about ensuring continuous improvement throughout the organization, and that the previous S's are maintained.

The third principle for quality management is teamwork. Gremyr et al. (2020) argue that cross-functional teamwork is necessary as a basis for achieving the first two principles. One way of doing this is, as in Lean Production, to encourage quality improvements from all parts of the organization. It can also be to encourage innovation together with suppliers, as, according to Gremyr et al. (2020), teamwork with suppliers can result in higher product quality. Furthermore, the authors discuss the role of uncertainty when deciding how to organize teamwork. When the uncertainty is high, for example regarding customer requirements, it is crucial to have a high degree of collaboration between the organization and the customers.

2.3.5 Strategic Development & Organization Decisions

Slack and Lewis (2020) describe decisions regarding development and organization as broad and long-term to govern how the operation is run. Commonly in models of product development, the final step involves creating the operations processes needed to make the designed product or service. Slack and Lewis (2020) emphasize that product development and process development are closely connected. Typically, process decisions come after certain product characteristics have been determined, reflecting the aim to design products that meet market requirements.

Product & Process Innovation

The design of products and the processes that produce them are, as previously noted, closely intertwined (Slack & Lewis, 2020). While they are often treated as separate activities, Slack and Lewis (2020) argue that product development must consider the constraints and capabilities of the production processes involved. Similarly, advancements in process technology impact future product development. Hence, understanding the degree of change in products or services is crucial, ranging from minor modifications to radical innovations (Slack & Lewis, 2020). Managing the overlap between product and process development is challenging but essential for effective and efficient development processes. Furthermore, Utterback and Abernathy (1975) argue that there is a strong mutual relationship between an organization's strategy and its environment, as well as between its strategy and the specific types of product and process innovations pursued. Additionally, the significance of aligning strategy with the deployment of productive resources is stressed, particularly in relation to the level of advancement achieved in production processes.

Utterback and Abernathy (1975) outline how a product and process development evolve over time and impacts an organization's innovation and competitiveness. As a

production process advances towards increased production volumes, it follows a pattern: becoming more capital intensive, enhancing labor productivity through specialization, streamlining material flows, standardizing product design, and increasing process scale. Utterback and Abernathy (1975) describe how the production process passes through several developmental stages: uncoordinated, segmental, and systemic.

Firstly, in the uncoordinated stage, the market expands, and the product and process frequently change, leading to a variety of products among competitors. Innovation is here driven by market requirements. Usually, the process mainly involves manual work that is non-standardized or depends on adaptable equipment (Utterback & Abernathy, 1975). This phase is flexible, with loosely connected process parts. Although this flexible system can easily adjust to environmental changes, it tends to be inefficient and has some unused capacity. During this phase, the focus tends to be on maximizing the performance of the products. Secondly, in the segmental stage, industries and product groups mature, and Utterback and Abernathy (1975) argue that production processes here become mechanized and specialized. Innovation is here driven by technological opportunities. Parts of the production system sequentially become more complex through automation and process control in this stage, leading to production processes with segmented quality. This extensive development requires at least a few product designs mature enough to have relatively large sales volumes (Utterback & Abernathy, 1975). During the segmental stage, the focus is typically on maximizing the sales. Finally, in the systemic stage, highly integrated processes make selective improvements challenging and costly. Innovation is here driven by production-related factors. Process redesigns usually slow down as the production process matures but could change, although at high costs, in response to new technologies and market changes. During this stage, the aim is typically to minimize costs. The stages for product and process development are visualized in Figure 2.6.

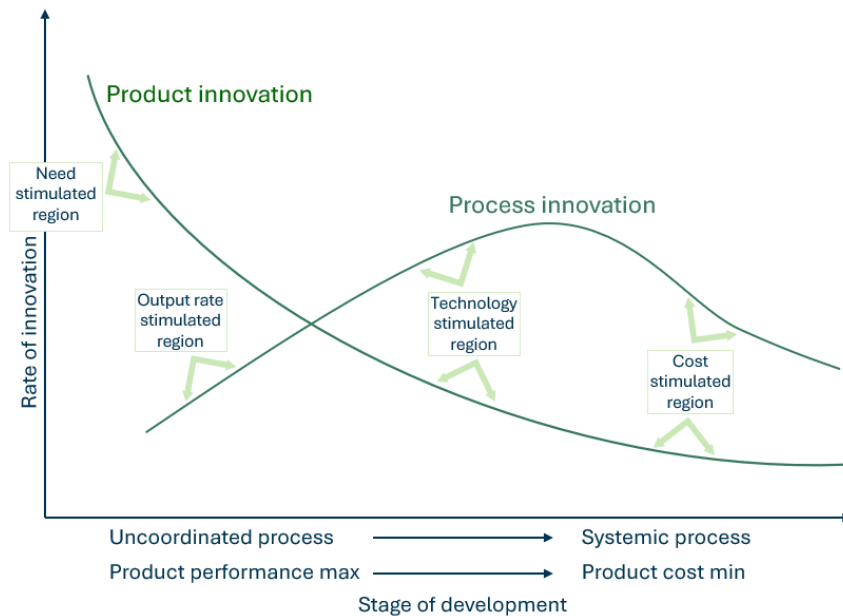


Figure 2.6: *Innovation and stage of development (Utterback & Abernathy, 1975).*

Furthermore, Utterback and Abernathy (1975) synthesize the product and process innovation stages into a proposed classification, see table 2.2 below. characterizing an organization’s stage of innovation including both products and processes. This synthetization clarifies the need to develop processes and products in parallel.

Table 2.2: Proposed classification of innovation stage (Utterback & Abernathy, 1975).

Innovation stage	Characteristics
1	Uncoordinated process Performance-maximizing product strategy Most innovations are stimulated by market requirements
2	Segmental process Sales-maximizing product strategy Most innovations are stimulated by technological opportunities
3	Systemic process Cost-minimizing product strategy Most innovations are stimulated by production related factors

Cross-Functional Interaction

One strategic decision area within organization and development concerns the patterns of interaction between upstream groups and downstream groups, for example, between product development and production (Wheelwright & Clark, 1992). Firstly, Wheelwright and Clark (1992) describe four dimensions of communication between groups: richness of media, frequency, direction, and timing. The richness of media concerns how communication is done, for example, via sparse media such as documents or rich media, for example, face-to-face communication. Frequency regards how often the communication happens, and direction concerns whether the communication is one-way or two-way. Lastly, timing is about how early or late in a process communication happens. Utilizing these four dimensions of communication in different ways results in four different modes of interaction between the upstream group and the downstream group (Wheelwright & Clark, 1992). Firstly, the mode with the least interaction between the groups is where communication is done via sparse media, infrequently, one-way, and late. This typically means that the upstream group, once done with its tasks, hands over the task to the downstream group in a batch-like manner. Secondly, the next mode of interaction is done in the same way, however, the downstream group starts working before they receive the information from the upstream group. Thirdly, the next mode of interaction includes frequent two-way communication with rich media, starting earlier during the process. Fourthly, the last mode of interaction starts with communication even earlier.

Sequential & Concurrent Engineering

Related to the modes of interaction, there are, according to Syan and Menon (2012), two main types of product development: sequential engineering and concurrent engineering. Sequential engineering is a more traditional approach, where each step of the design process is carried upon completion of the preceding step. The authors argue that the sequential engineering approach has several disadvantages, for example, it results in insufficient product specification and many modifications. Furthermore, there is a risk of manufacturability issues arising late in the process. Hence, sequential engineering can induce a lot of costs due to late changes. The concurrent engineering approach implies a more integrated design process with overlapping activities, and information is here exchanged in a frequent and rich manner. Concurrent engineering can, according to Syan and Menon (2012), lead to both cost reductions and lead time reductions.

Design for Manufacturability

According to Wheelwright and Clark (1992), manufacturing issues traditionally arise after basic designs are set, as the primary aim is typically achieving functionality rather than producibility. Additionally, Syan and Menon (2012) argue that between 60% and 95% of the total costs induced by a product during its life cycle are determined already in the design phase. One methodology for addressing these issues is Design for Manufacturability and Assembly (DFMA), that aims to bring manufacturability into an earlier stage of the design process (Gupta & Kumar, 2019). DFMA is a methodology aimed at simplifying the product structure and thereby reducing production costs

(Boothroyd et al., 2002). According to Wheelwright and Clark (1992), DFMA can for example be conducted via design rules, which are described as boundaries guiding the product design, such as tolerances, number of adjustments, material types, and number of parts. The design rules are a way of stating what is needed from the product design to be able to produce the required product performance, volume, cost, and quality. Furthermore, examples of DFMA are minimizing the total number of parts in a product, simplifying parts, or modifying parts to facilitate assembly. However, to ensure that DFMA yields the desired results, Wheelwright and Clark (1992) argue that it is important to consider the interaction between parts, products, and the production system.

Besides DFMA, another way of organizing product development is via mass customization and modular designs, as mentioned briefly in section 2.3.1 (Slack and Lewis, 2020). These ways of designing products can help an organization overcome the perceived trade-off between flexibility and cost. One production strategy for mass customization is Delayed Product Differentiation (DPD), using product platforms (Bortolini et al., 2023). The strategy involves designing product platforms, defined by Bortolini et al. (2023) as common structures built by sub-systems, from which different product variants can be produced. This approach is based on the idea that the initial production process can be similar for many different products, as the product differentiation is delayed until later parts of production.

Job Design

One area of strategic decisions regarding organization and development is what Slack et al. (2013) refer to as job design. Job design involves decisions regarding individual employees' work, for example allocation of work tasks. This mainly concerns the division of labor, the degree to which specialists or generalists should be used. On one side of the spectrum, highly divided labor, using specialists, means that work is divided into many small parts where each person or team is responsible for one part (Slack et al., 2013). A high degree of specialization is typically related to the increase of simplification of tasks, repetition, and automation (Salvendy, 2001). One benefit of having a high division of labor is that employees can learn faster, and another is that automation becomes easier when having split the work into many, smaller parts (Slack et al., 2013). Additionally, smaller and easier tasks reduce the non-productive work in the sense that employees do not have to search for parts or tasks to the same extent as if working on a larger and complex task. However, a high degree of specialization implies monotonous work tasks for employees which might decrease motivation (Salvendy, 2001). Furthermore, Slack et al. (2013) argue that this type of job design decreases the flexibility of the production system, as operators' tasks must be redesigned if introducing a new product. It can also reduce robustness of the production system; if one stage experiences issues, the whole system is disrupted. The other part of the spectrum, a high degree of generalization, entails increasing variety, autonomy, skill usage, and growth for employees (Salvendy, 2001). This typically implies a higher motivation and involvement from employees, thus enabling a higher social

sustainability; however, it might lead to more errors and staffing difficulty, according to Salvendy (2001).

A way of achieving balance between a highly specialized workforce and a highly generalized workforce, Slack et al. (2013) propose four additions to a high division of labor: job rotation, job enlargement, job enrichment, and empowerment. Job rotation means that employees rotate between the different sets of tasks to increase variety of work and skill flexibility. Job enlargement implies that each employee performs more tasks that are broadly within the same area but decreases monotony. Job enrichment means that tasks involving more decision-making and control are added to the work description. Lastly, empowerment is defined as increasing employees' authority to improve their job tasks.

To facilitate high-quality products, work instructions are commonly used in manufacturing (Pimminger et al., 2020). A work instruction should, according to Pimminger et al. (2020), be easily understood and require minimal cognitive effort from the employee. Additionally, it is of high importance that effort is put into creating the work instructions and keeping them up to date. There are several types of work instructions, for example, simple, paper-based or interactive, augmented-reality-based; however, there are varying views on which is better. Pimminger et al. (2020) argue that the instruction type only affects the first assemblies done by a person, thus, the more times an employee performs an assembly task, the less the work instruction matters for the total assembly time. Contrastingly, Eversberg and Lambrecht (2023) argue that digital work instructions with spatial information can reduce both costs, errors, and the cognitive effort required by the employee. In their study, digital work instructions were preferred by all ten participants, and resulted in faster task completion time and lower perceived cognitive effort.

2.3.6 Strategic Production Planning & Control Decisions

Strategic decisions related to production planning and control regard how production is planned and how material is handled (Bellgran & Säfsten, 2010). Jonsson and Mattsson (2009) define production planning and control as activities related to material flows from suppliers to end users, such as planning, development, management, and control. Decisions about production planning and control are, according to Bellgran and Säfsten (2010), fundamental to ensuring the efficiency and effectiveness of manufacturing operations. These decisions revolve around selecting principles for material handling and production aligned with market requirements as well as to coordinate manufacturing activities to be a competitive company (Bellgran & Säfsten, 2010; Jonsson & Mattsson, 2017). Bellgran and Säfsten (2010) and Mattsson and Jonsson (2017) treat planning and control decisions at three different levels; master planning and strategic control, requirements planning and tactical control, and detailed planning and operative control. At each level, different aspects are considered to collectively support an organization's production objectives.

Levels of Production Planning & Control

Firstly, master planning operates on a timeframe of more than a year and is the first stage where plans for selling and production operations are established (Bellgran & Säfsten, 2010). This involves coordinating planned deliveries, ensuring the right capacity, and choosing the right CODP. Similarly, strategic control has a long-term focus with a time horizon of over a year and is mainly focused around helping a company with choosing its position in the business environment (Jonsson & Mattsson, 2017). Strategic control decisions could regard what product mix to have, which customer segments and markets to focus on, what production resources to provide internally and what parts of production to purchase externally.

Secondly, the output of the master planning and strategic control are inputs to the next levels, requirements planning and tactical control (Bellgran & Säfsten, 2010; Jonsson & Mattsson, 2017). According to Bellgran and Säfsten (2010), requirements planning typically spans from two to six months and focuses on ensuring availability of material and components when needed, activities typically executed by a procurement function. Planning decisions at this level include choosing a time-controlled or tact-based planning method depending on how frequently production operates. Time-controlled planning means planning each order separately at pre-set times. Tact-based planning is used when setup times are short and work content is consistent across resources, making production cycles more efficient and productions flows more synchronized. Tactical control should according to Jonsson and Mattsson (2017) adapt and develop the structure of the company goals that results from strategic control, covering periods of about half a year. This level could for example include control decisions about choosing manufacturing layout, having a centralized or decentralized planning organization, and establishing rules for determining order quantities and safety stocks.

Thirdly, detailed planning and operative control are based on the output from the previous levels and occur monthly or daily, being the levels closest to production (Bellgran & Säfsten, 2010; Jonsson & Mattsson, 2017). The detailed planning involves tasks such as order release and material inspections, and stock size management decisions including factors such as cost, risk, and alternatives like reducing set-up times or adopting just-in-time deliveries to optimize inventory management practices (Bellgran & Säfsten, 2010). Operative control concerns daily activities, aiming at utilizing the selected operations strategy in practice which is developed from strategic and tactical control decisions (Jonsson & Mattsson, 2017). Activities about operative control include setting delivery dates to customer orders, monitor deliveries, and assigning production priorities in the factory.

Jonsson and Mattsson (2017) emphasize that decisions regarding production planning and control impact all control levels and are influenced by them, necessitating comprehensive consideration. Essentially, as Bellgran and Säfsten (2010) assert, the

three levels of production planning operate symbiotically to efficiently utilize resources and fulfill market demands, thereby enhancing manufacturing competitiveness.

Choice of Customer Order Decoupling Point

An important decision in a manufacturing organization, as mentioned to be central in master planning, is how much of the production should be initiated by customer orders, hence, where the CODP should be (Jonsson & Mattsson, 2009). The CODP is defined by Jonsson and Mattsson (2017) as the point in the product structure whereafter the production is determined by customer orders. Before the CODP, the manufacturing activities are determined by forecasts. This splits the manufacturing flow into two parts: a forecast-based flow and a customer-driven flow (Bellgran & Säfsten, 2010). Four main types of production planning and control are Engineer to Order (ETO), MTO, Assembly to Order (ATO), and MTS, visualized in Figure 2.7 (Rudberg & Wikner, 2004). ETO is where products are constructed according to customer order specifications, and material acquisition is made upon receiving a customer order (Jonsson & Mattsson, 2017). Thus, the CODP is positioned very early in the product structure. MTO is where products are constructed and ready for manufacturing, and a lot of the material acquisition is done without connection to a customer order, but where the actual manufacturing is done upon receiving a customer order. ATO is where components are acquired and manufactured based on forecasts, and that the final product is assembled according to a customer order. MTS is where the CODP is placed after the final product in the product structure, meaning that the whole product is manufactured before the customer order is received. The products are kept as stock.

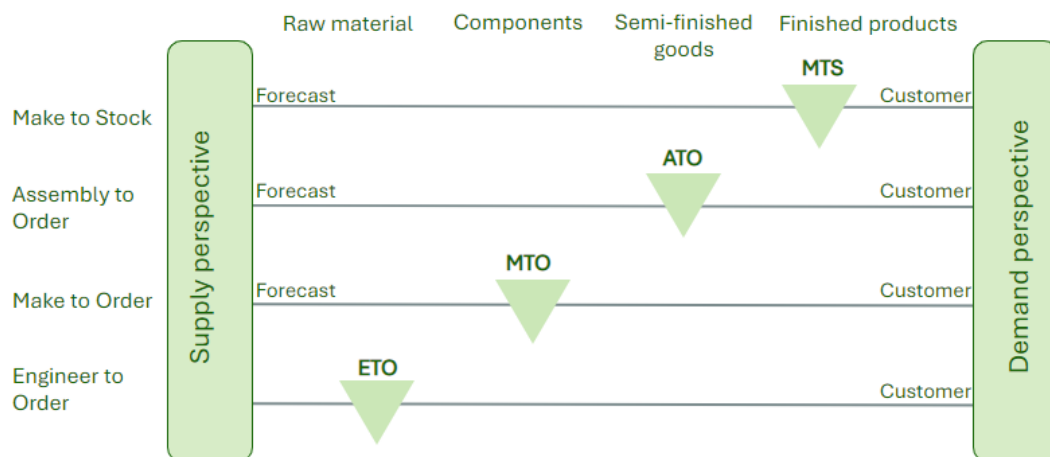


Figure 2.7: *The four types of production planning and control and their associated CODP (Bellgran & Säfsten, 2010).*

The choice of CODP depends on the requirements of the production system (Jonsson & Mattsson, 2017). In terms of the volume-variety characteristics of the production process, having the CODP early in the product structure, as seen in ETO and to a certain extent in MTO, is associated with a low volume and high variety and high degree of customer order integration. Contrastingly, a CODP that is placed later in the product

structure, as is the case for MTS and to a certain extent in ATO, is suitable for a production process with high volume and low variety and low degree of customer order integration. Furthermore, the later the CODP, the shorter the time to customer and the less integration with the customers.

It is also possible to utilize a hybrid approach to production planning and control by finding a balance between MTO and MTS. This can be beneficial to try to reduce the disadvantages inherent with each of the two; MTO typically entails a long lead time and MTS might result in excess inventory (Perona et al., 2009). Beemsterboer et al. (2016) argue that the hybrid approach can lead to both cost savings and other benefits, as shown in their study. The hybrid approach can be applied to different products or intermediate items, identifying certain parts that are more suited for MTO or MTS (Perona et al., 2009). The DPD production strategy discussed in section 2.3.5 of this report is one sort of MTO-MTS hybrid, where the common structures, the product platforms, are produced according to MTS. Then, as customer orders arrive, the product platforms can be modified into end products with an MTO approach.

Handling Uncertainties

Another area to address that affects production planning and control is how to handle uncertain forecasting. Mula et al. (2006) classify uncertainties affecting production processes into two groups: environmental and system uncertainty. Environmental uncertainty regards factors beyond the production process, like demand and supply fluctuations, while system uncertainty involves uncertainties within the production process itself, such as operation yield, lead time, quality, system failures, and product structure changes.

As previously mentioned in section 2.3.2 about strategic capacity decisions, Slack and Lewis (2020) mean that forecasting future demand for an organization's products is essential for planning investments. However, the inherent uncertainty can make it difficult for organizations to invest to meet anticipated demand levels, as there is the risk of over- or undersupplying the market. Overinvestment could lead to financial losses if demand falls short, while underinvestment may result in missed opportunities and loss of market share. Yet, Slack and Lewis (2020) argue that maintaining excess capacity can offer flexibility to respond to sudden increases in demand, particularly during product launches. Additionally, Chopra and Meindl (2013) argue that when forecasting is difficult due to uncertainties, it can be preferable to plan for a responsive supply network, to be able to quickly react to environmental uncertainties.

Given the complexity induced by uncertainties in production planning, Mula et al. (2006) propose new approaches to manage environmental and system uncertainties in production planning and control. Enhancing organizational agility could enable quick adaptation to changes in environmental uncertainties and, thus, ability to adjust production planning and control (Mula et al., 2006). Moreover, the so-called fuzzy set theory is considered an applicable methodology for handling both environmental and system uncertainty, allowing for nuanced decision-making by assigning degrees of

membership to sets (Lowen, 2011; Mula et al., 2006). This theory accommodates vague or imprecise information, proving useful in planning and control systems, and decision making (Lowen, 2011). Mula et al. (2006) suggest that fuzzy set theory can advance the development of new models that address various sources and types of uncertainty.

Push & Pull Production Systems

One decision regarding production planning and control is how to provide orders in the production system (Bellgran & Säfsten, 2010). There are two primary types of planning methods: push production and pull production. In a push production system, products or components are pushed through the system according to a pre-selected production plan. This type of production system entails buffer storage between different stages of the production process, which increases robustness of the system in cases of disturbance. Push production systems typically imply a focus on resource efficiency rather than flow efficiency.

Furthermore, in a pull production system, planning is based on actual need, in the form of customer orders, rather than on forecasts (Bellgran & Säfsten, 2010). In a pull production system, parts, supplies, and information are pulled by internal and external customers precisely when needed. A pull production system implies a focus on flow efficiency rather than resource efficiency, as certain resources might not always be fully utilized with this approach. However, a pull production system reduces waste through eliminating excess inventory.

To communicate in a pull production system, kanban can be used (Black, 2008). Kanban, or kanban cards, signal backward in production when there is a need for materials (Tarantino, 2022). Every item or set of items that flows through the production system carries its own kanban (Black, 2008). Tarantino (2022) means that kanban requires strong discipline and a commitment to continuous improvement to work effectively. Pulling work based on customer orders is unlikely to be successful unless all types of waste are handled, including long set up times. Extensive setup times are tolerable when building large lots of materials but are considered too expensive when using kanban to build single orders (Tarantino, 2022).

Just-in-Time (JIT) is a pull production system from Lean Production theory, that aligns inventory with production schedules, aiming at meeting actual demand to minimize on-hand stock (Black, 2008). JIT deliveries extend to all processes, from product design to external and internal supply, culminating in the delivery of the final product to the external customer (Liker, 2011). One advantage with JIT is that it boosts productivity by streamlining manufacturing processes (Black, 2008). However, JIT also possesses challenges, such as higher cost per piece due to frequent, smaller orders, vulnerable to supply chain disruptions, the risk of stockouts if demand is inaccurately predicted. Implementing JIT production successfully requires steady production with high-quality workmanship and reliable suppliers (Black, 2008). JIT includes evenly distributing the

production of different items throughout the day and week, linking processes, producing items one at a time whenever feasible, and aligning the pace of work in every process with marketplace sales (Black, 2008).

Material Handovers Between Parts of the Production System

Wagner and Enzler (2006) describe the need for managing material flows between different system borders, for example, between different company-internal processes in the production system. This entails a need for cooperation and communication between stakeholders from the different parts of the production system.

One type of material flow between company-internal processes is between the warehouse and the manufacturing area. With a production characterized by high variety and a customer demand for customized products, the production system must handle many components. Jonsson and Mattsson (2017) describe three principles of handing over material from the warehouse to the production area: kitting, batching, and line stocking. Christmansson et al. (2002) describe two ways of material kitting: picker-to-material and material-to-picker principles. A material kit comprises parts or assemblies needed for a single assembly or installation job and is usually supplied by a single vendor and delivered to the point of use precisely when required (Black, 2008). Traditionally, material kitting is done by the picker-to-material principle where a material picker in the storage area moves between storage packages and picks materials to the material kits. This type of picking process is in general time-consuming as pickers move throughout the storage area. However, the material-to-picker system has emerged to reduce the need for transportation in the packaging area; storage packages are moved closer to the material pickers, who then pick materials into the kits (Christmansson et al., 2002).

In addition to kitting, Jonsson and Mattson (2017) describe, as mentioned, batching and line stocking principles to transfer material from warehouse to production. When batching is used, larger packages of selected materials to be used in production during a specific time period are delivered at certain times to the manufacturing- or assembly station, allowing the operator to pick materials directly from a batch instead of receiving it as a complete kit. Furthermore, line stocking involves transferring small packages of a larger quantity of material types to the production or assembly unit. The packages are replaced as they are consumed (Mattson & Jonsson, 2017). Line stocking exposes material required in production by being positioned at the production or assembly station and therefore requires much physical space.

De Vries et al. (2016) furthermore describe several advanced picking technologies for increasing picking quality and productivity, two of which are pick by voice and pick to light. Pick by voice is a picking method where audio is utilized as guidance for the picking process. The picker here wears a headset and is guided by voice commands to the location of the next component to be picked. Pick by voice is described by the

authors as suitable for picking operations where pickers independently work from start to finish on the orders. Pick to light is a picking method that supports pickers with light signals, often utilized when retrieving items from shelves (De Vries et al., 2016). A display lights up with required information at specific storage locations when the product belonging to that storage must be picked. Pickers confirm the pick by pressing a button and continue picking to light until all displays with lights have been turned off, indicating the picking for that order is completed (De Vries et al., 2016).

2.4 Synthesizing Theory into the Proposed Integrated Framework

To utilize the Proposed Integrated Framework, the content of the strategic decision areas is summarized in Table 2.3 below. The content is based on the theory presented in section 2.3. The information in each column of Table 2.3 can be used as a checklist when reviewing each specific decision area of the current production strategy. Additionally, the five performance objectives – quality, speed, dependability, flexibility, and cost – should be ranked according to the organizational priorities, which will help determine critical cells of the production strategy.

Table 2.3: Summary of content in the strategic decision areas.

Production Process	Capacity	Supply Network	Quality Management	Development & Organization	Production Planning & Control
Chosen process type	Level of capacity	Type of supply network	Defining desired level of quality	Determining the level of product and process innovation	How master planning and strategic control is conducted
Chosen process layout	Number of separate sites	Do-or-buy decisions	Proactive or reactive quality approach	Level of cross-functional interaction	How the customer order decoupling point is chosen
Chosen level of technology	Long-term capacity change strategy	Supplier selection	How customer focus is achieved	Usage of sequential and concurrent engineering	How uncertainty is handled
	Task allocation to each site	Managing relationships in the supply network	How continuous improvement is achieved	How manufacturability is embedded in product development	How a pull production system is utilized
	Location of each site		How teamwork is achieved		How material is handed over between different

				Allocation of tasks in production	parts of the production system
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If the Proposed Integrated Framework is used for reviewing and mapping the current production strategy, the checklist can be used for identification of strategic decisions. Additionally, these strategic decisions are clustered according to the performance objective that they aim to achieve. If a strategic decision is aimed at achieving multiple performance objectives, it will appear in several cells of the matrix.

If the Proposed Integrated Framework is used for proposing a new production strategy, the checklist can be used to indicate areas where strategic decisions should be made. The strategic decisions should be distributed in cells in the framework according to the performance objective they intend to achieve. If the strategic decision aims to achieve multiple performance objectives, it should be added to multiple cells. The performance objectives should be prioritized according to organizational objectives, and this can aid in emphasizing areas of the production strategy that are of particular importance.

3 Methodology

In this section, the methodology used to fulfill the purpose and answer the research questions is presented. The research strategy and design are addressed, as well as the data collection, data analysis, and ethical considerations.

3.1 Research Strategy & Research Design

This study adopted a qualitative approach, which is one type of research strategy proposed by Bell et al. (2019). The qualitative research strategy was chosen for the study because it emphasizes words and images as opposed to collecting and analyzing numerical data. Furthermore, this study followed a deductive approach, where theory was used as a basis for the data collection and analysis. A case study design was used for the research, examining a single organization, PowerCell, and its unique situation. According to Bell et al. (2019), case studies are well-suited for, and widely used in, business research. PowerCell was chosen as the case company because of the complex setting they operate in, with a relatively new market that is expected to grow. The results from studying PowerCell can be used to conclude how this type of organization can make strategic decisions about their production system.

3.2 Data Collection

The phases of the data collection process are visualized in Figure 3.1 below. A pre-study was used to gather initial information regarding PowerCell and the clean hydrogen market, via interviews, observations, and a literature review. This data was then used to formulate the research questions and to create a Proposed Integrated Framework. After this, interviews, observations, and a literature review were conducted in parallel during the main study. The interviews were conducted to aid in understanding PowerCell’s production system and specific challenges related to it, and the literature review was conducted with the aim of relating PowerCell’s situation to theory. The observations increased the knowledge about the production system and helped with identifying challenges related to it.

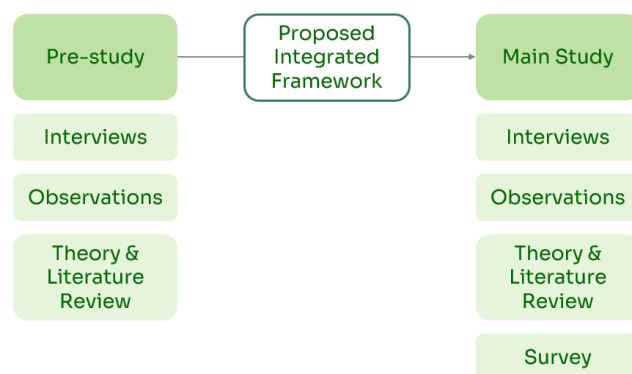


Figure 3.1: An overview of the phases of data collection.

3.2.1 Pre-study

As an initial step in this study, a pre-study was conducted to define the project's scope and to acquire introductory insights about the case company and market, via interviews, observations, and a literature review.

During the initial two weeks of the project, ten unstructured interviews were conducted with employees from various positions at PowerCell. This approach was taken to ensure a comprehensive understanding of the company's situation. The respondents are presented below, in Table 3.1. According to Bell et al. (2019), unstructured interviews are similar to conversations, which allowed for respondents to answer openly and for the interviewers to react with supplementary questions. Furthermore, all interviews were audio-recorded and transcribed, allowing the researchers to fully focus on the discussions without the need for taking notes. The recording and transcription allowed for a more thorough examination of what respondents said and how they said it, which is advantageous when conducting qualitative research (Bell et al., 2019). In addition to the interviews, observations were conducted during visits to the production site to gain a deeper understanding of the surrounding conditions and production layout at PowerCell. To complement the interviews and observations, literature about the clean hydrogen market and hydrogen fuel cell market was searched for and reviewed. This enabled the authors to better understand the unique and complex position the case company possesses.

The insights gained from the pre-study allowed the researchers to formulate the aim of the study and research questions to fulfill the aim.

Table 3.1: *Description of pre- and main study interviews.*

Reference number	Respondent	Respondent's position at PowerCell	Topics covered during interview	Date and duration of interview	Participation in pre-study	Participation in main study
1	Patrik Brouzell	SVP Sales	Markets, sales, customers	22/1-2024, 45 minutes and 19/3-2024, 30 minutes	X	X
2	Lisa Kylhammar	SVP Engineering	Research and development of the products	30/1-2024, 45 minutes and 19/3-2024, 30 minutes	X	X
3	Christian Magass	Production Capacity & Order Planning Manager	Production planning, capacity	22/1-2024, 45 minutes and 19/3-2024, 40 minutes	X	X

4	Viktor Oscarsson	Supply Chain Manager	Warehouse, supply chain	24/1-2024, 45 minutes and 13/3-2024, 45 minutes	X	X
5	Peter Wallin	SVP COO	Operations strategy	30/1-2024, 60 minutes and 18/3-2024, 30 minutes	X	X
6	Mattias Holmberg	Production Manager	Production system, ERP-system	22/1-2024, 60 minutes and 13/3-2024, 45 minutes	X	X
7	Ingela Andersson	Supplier Quality Assurance Manager	Quality management	Weekly meetings and 13/3-2024, 45 minutes	X	X
8	Nadja Euler-Renstedt	Customer Service & Sales Coordinator	Customer orders, sales department, purchasing team	23/1-2024, 30 minutes	X	
9	Karl Hartvig	Manager Product Integration	The testing process in the lab area	18/3-2024, 30 minutes		X
10	Victor Åkerlund	Chief Analytics & Sustainability Officer	Business strategy, long term goals	22/1-2024, 30 minutes and 14/3-2024, 30 minutes	X	X
11	Karl Samuelsson	SVP Customer Applications	Customer applications projects	14/3-2024, 30 minutes		X
12	Andreas Bodén	CTO	Customer segments, product design, product tests	20/2-2024, 30 minutes		X
	Alfred Vidén & André Örjas	Business Development Interns	Market trends, hydrogen, regulations,	24/1-2024, 30 minutes	X	

			hydrogen fuel cells			
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3.2.2 Interviews

Qualitative interviews were used to collect data primarily regarding RQ1 and RQ2. The interviews were conducted in a semi-structured way, which, according to Bell et al. (2019), is commonly used in qualitative research. Semi-structured interviews are conducted according to interview guides based on a set of both open and closed questions; however, there is room for deviations. Thus, further questions can be asked depending on received answers. The allowance for follow-up questions and exploration of topics that arise during the interview made semi-structured interviews suitable for this study, as it places emphasis on what the respondent finds particularly important. The interview guide was prepared in accordance with Bell et al.'s (2019) proposals, by preceding each interview with a brainstorming session with the researchers regarding relevant topics, for example based on findings from the pre-study. Then, questions were formulated related to the chosen topics. Emphasis was placed on avoiding too specific or leading questions. All interviews were finalized with a common question, asking respondents to elaborate on PowerCell's priorities in terms of the five performance objectives. To receive the answers in a concrete manner, a survey was sent out to the respondents after the interviews, where they could prioritize the performance objectives numerically.

The respondents were selected based on their expertise in topics related to the research questions. Thus, the study employed what Bell et al. (2019) refers to as a purposive sampling approach, which is when participants are chosen in a way that corresponds to their relevance for answering the research questions. Additionally, to a certain extent, a snowball sampling approach was used, which is a sampling method where respondents propose other people that would be relevant to interview (Bell et al., 2019). During the interviews conducted in the pre-study, respondents were asked if they had any suggestions regarding respondents for the next round of interviews. The respondents are presented above, in Table 3.1, together with the pre-study interviews.

The interviews were audio-recorded and transcribed, as is common practice in qualitative research (Bell et al., 2019). As described in section 3.2.1 of the report, transcribing interviews has several advantages, such as allowing for a more comprehensive analysis of what the respondents say. It can furthermore strengthen the research quality in the sense that it counteracts bias from the researchers in analyzing the data. It can also increase readers' perception of the validity of the data collection. It should, however, be noted that when recording interviews, the researchers should be aware of the possibility of respondents refraining from discussing certain topics.

After the interviews, some of the respondents were contacted via e-mail, for follow-up questions regarding clarifications of the interviews. The answers to these questions were provided in text form. Furthermore, the five performance objectives were

discussed qualitatively during the interviews of the main study; however, a survey was also conducted after the interviews to receive respondents' thoughts on the subject quantitatively. These answers' quality was secured by thoroughly explaining the definition of the five performance objectives, both during the interviews and in the survey.

3.2.3 Observations

Because of the importance of descriptive detail in qualitative research, observations are frequently employed to capture behaviors and settings relevant to the research (Bell et al., 2019). Moreover, observations can be combined with other methods, such as interviews, to provide a more comprehensive understanding of the subject. In this study, observations were conducted through visits to the warehouse, production site, and lab area as a complement to interviews and literature. The observations were documented via notes. These observations allowed for mapping details of the production system and for identifying challenges in the system to answer RQ1 and RQ2.

3.2.4 Literature Review

Undertaking a thorough literature review is a crucial phase of any research project (Bell et al., 2019). Scrutiny of existing literature is important to identify relevant materials to incorporate into the research and distinguish them from those that are not pertinent. By doing so, an informed decision about what to include and exclude from the study can be made (Bell et al., 2019). In this study, the literature review was divided into two parts. The first literature review was conducted to generate a general framework for the data analysis, while the second literature review focused on elaborating specific parts of the framework.

Bell et al. (2019) describe different types of literature reviews suitable for different types of projects. In this study, a narrative approach was adopted to provide a comprehensive overview of the literature on the subject. Furthermore, the literature review was made iteratively. Firstly, due to the conducted pre-study interviews, literature was searched for to create a framework suitable for the project. Keywords used here were production strategy, operations strategy, and performance objectives.

The literature review process began with the utilization of specified keywords to find relevant publications from databases including Scopus, Web of Science, ScienceDirect, accessible via Chalmers library, and Google Scholar. The relevance of the obtained literature was assessed through screening of titles and abstracts, followed by critical examination to determine its appropriateness for the review, guided by the principles advocated by Bell et al. (2019). Additionally, references cited within relevant articles were scrutinized to identify additional relevant research on the subject. Consequently, literature on production strategy was synthesized and the Proposed Integrated Framework used in the study was created. After this, the literature review process was repeated but this time keywords included production process, automation, mass customization, capacity, supply network, do-or-buy decisions, supplier relationships, quality management, customer focus, Lean Production, development and organization,

product and process innovation, DFMA, and production planning and control, customer order decoupling point, to focus on literature relevant for the decision areas in the framework and literature relevant to create questions for the main interviews.

3.3 Data Analysis

The data analysis was divided into two main parts, one for the pre-study and one for the main study. The data derived from the pre-study, via interviews, observations, and a literature review were examined through a thematic analysis. A thematic analysis is, according to Bell et al. (2019), an approach where themes are sought for in the collected data. Themes were found mainly by looking at repetitions of topics during the interviews. This approach was used to find relevant topics to examine further during the main study and to determine the aim and the research questions. The thematic analysis was organized via a workshop conducted with the affinity-interrelationship method, described by Alänge (2009) as a problem-solving tool to analyze qualitative data. During the workshop, findings from the data collection were discussed and grouped, and the result from this was the six critical areas presented in section 1.4 of this report. Furthermore, the existing frameworks for developing a production strategy found via the literature review were reviewed and synthesized based on their relevance for the case company. This analysis was mainly based on the six identified critical areas, to find the most relevant decision areas for the framework. The analysis subsequently led to the Proposed Integrated Framework.

The data analysis for the main study revolved around utilizing the Proposed Integrated Framework to fulfill the aim of the study and to answer the research questions. The data collected via the survey on performance objectives was summarized in a graph, visualizing the difference among respondents' answers. The collected data from interviews was first used to answer RQ1 by mapping out strategic decisions that have been made at the case company in the Proposed Integrated Framework. First, strategic decisions were differentiated based on the strategic decision area they belong to. Then, all strategic decisions were categorized according to the performance objective they aim to fulfill. RQ2 was then answered by reviewing the identified strategic decisions and identifying associated challenges and initial solutions to these challenges, based on the interviews and observations conducted. Additionally, the literature review was used to answer RQ2 by reviewing the strategic decisions from a theory-based perspective, analyzing potential consequences of these decisions, both for PowerCell's current situation and when production volumes are increased. Additionally, initial solutions to the identified challenges were proposed. A thematic analysis was conducted to review collected data and determine the most prominent challenging areas, thereby answering RQ3. Lastly, to answer RQ4, the literature from the content in the Proposed Integrated Framework was used to propose strategic directions for the production system, and highlighting specific areas of the framework that should be specifically revised by PowerCell.

When preliminary results were presented, two workshops were held with the supervisor at the case company to improve the data analysis. The workshops focused on identifying additional challenges and initial solutions for RQ2.

3.4 Research Ethics

This study was conducted considering ethical aspects when formulating the aim and research questions. The aim of proposing strategic decisions for PowerCell's production system includes aspects of sustainability. Ecological sustainability was considered, as PowerCell wishes to continue to contribute to the green transformation, and social sustainability was considered from the perspective of the employees working with production.

Furthermore, Bell et al. (2019) discuss four ethical considerations that are relevant when conducting business research: informed consent, privacy, preventing deception, and avoidance of harm. Informed consent means participants of a study must receive enough information to decide their participation. In this study, respondents received information about the study before being given the choice of participating or not participating, ensuring that all respondents voluntarily participated. Privacy is described by Bell et al. (2019) as the protection of participants' privacy, which was upheld in this study by giving participants the choice of not answering questions or withdrawing their answers if questions were perceived as sensitive. Respondents were further offered to read the report before publishing to ensure that the disclosed information was correctly reproduced, and that any information considered private was removed. Further, researchers should prevent deception by representing the research in accordance with what it is (Bell et al., 2019). In this study, the aim and the nature of the research were shared transparently with respondents and representatives from the case company, to prevent deception. Additionally, Bell et al. (2019) emphasize the importance of assessing the possibility of harm to research participants and minimizing this risk. In this study, potential risks of harm to respondents were assessed and minimized. A non-disclosure agreement was signed with the case company to prevent any confidential information from being exposed, and regular meetings with representatives from the case company were held to further ensure this.

3.5 Methodology Discussion

When conducting qualitative research, Bell et al. (2019) propose trustworthiness and authenticity as two criteria for assessing research quality, as opposed to the traditional criteria reliability and validity often used in quantitative research. The criterion trustworthiness comprises four dimensions: credibility, transferability, dependability, and confirmability. Credibility concerns assuring that data is collected correctly and that the collected data is accurately interpreted. In this study, representatives from the case company read the report regularly during the process to ensure that the collected data was interpreted in a way that reflects the real situation. Furthermore, a workshop was held with a team of respondents where preliminary results were disclosed, and the

managers gave input on the data's validity. When the study's results were presented at the case company, feedback was used to further improve the thesis. Transferability refers to how transferable the study is to other situations (Bell et al., 2019). However, this criterion, due to the typically contextual nature of qualitative research, is mainly about providing a detailed description of the situation that is being studied, so that others may assess to which degree the study is transferable to their own specific situation. In this study, a thorough description of the case company is provided to ensure transferability. Dependability concerns how dependable the results are and can be achieved through keeping thorough documentation of the process and having the study reviewed, for example by peers (Bell et al., 2019). In this study, all phases were documented, and interviews were transcribed to ensure dependability of the research methodology and the collected data. Further, three seminars were conducted with peers during the study to audit the methodology and results. Lastly, confirmability aims to ensure that the research is conducted in a way that does not let the researchers' personal values influence the findings of the study (Bell et al., 2019). During the study, regular meetings were held with the supervisor to ensure that the findings were not influenced by personal values.

This study was conducted to achieve the highest validity by frequently discussing and confirming the collected data with employees at the case company. Furthermore, the respondents were chosen based on their expertise, both in the production system and in other areas related to the production system. Additionally, two interviews were conducted with most respondents, to be able to achieve a comprehensive dataset for the study. Furthermore, a survey was conducted to quantify the data regarding the performance objectives. However, as the survey only had ten participants, the result could not be analyzed in a thorough way but could rather be used to indicate differing opinions among respondents. Furthermore, the identified challenges were solely based on interviews rather than quantified data from the production system, meaning that identified bottlenecks are not statistically confirmed. Additionally, the study's results were collected and analyzed using a framework created by the authors. Therefore, the quality of the Proposed Integrated Framework determined the quality of the study's results. Albeit the framework was created by the authors, it is a synthesis of three existing frameworks, thus, it should be sufficiently comprehensive and valid.

4 Results & Analysis

In this section, the results from the data collection are presented and analyzed. Firstly, the identified prioritization of performance objectives is presented. Then, the identified strategic decisions, associated challenges, and initial solutions are presented. After this, challenges are clustered into six prominent challenging areas, which are subsequently addressed by proposed strategic directions.

This chapter presents strategic decisions and their consequences for the production system, however, certain aspects affecting the production system are categorized as circumstances. For example, PowerCell recently started to commercialize their products and established an Operations department, which affects the characteristics of the production system. Furthermore, the fuel cell market is relatively new and characterized by many uncertainties, both in demand and regulations. Additionally, it is assumed that the production volumes of fuel cell stacks will increase more rapidly than the production volumes of fuel cell systems, as these are sold separately, but also are part of the fuel cell systems. Consequently, fuel cell stacks can be replaced with new ones when servicing customers' fuel cell systems becomes necessary.

4.1 Identified Prioritization of Performance Objectives

In this section, the identified prioritization of the five performance objectives quality, speed, dependability, flexibility, and costs is discussed. The results are based on the interviews, and some quotations from the interviews are also presented.

Firstly, respondents discuss that quality is currently not seen as one of the most important performance objectives. However, PowerCell continuously works with quality. For the customer segments aviation and marine, quality is crucial due to strict regulations. In the future, there is consensus among respondents that PowerCell should prioritize quality more, to be able to increase their production volumes.

“Quality, to demonstrate to customers and the world that fuel cells are reliable, robust, and functional.”

“So, what we really need, and what we have already started doing, is to focus much more on quality.”

“If you ask me, I believe we will need to talk about quality a lot more. And that means, both the actual quality of the product and also the quality of our entire operation.”

“If I have to choose, it is quality. Period. Because quality will generate predictability. It will generate speed. It is basically a prerequisite for everything else.”

Secondly, speed is currently highly prioritized at PowerCell, as stressed by all respondents. It is relatively common that customers want short lead times upon placing an order, thus, PowerCell completes the order accordingly. However, when the products are ready for shipment, customers are usually not ready to receive the

products. Therefore, respondents perceive that PowerCell sometimes prioritizes speed too much. Thus, on a general level, respondents discuss that PowerCell will not need to put additional focus on speed in the future, as they are already fast. However, in the production system, respondents argue that parts of the production process, such as fuel cell system assembly and testing activities, should be done faster. The main reason behind this argument is that it will help reduce production costs rather than reaching the end customer faster.

“Speed is important, but I feel like we are fast enough. Sometimes, too fast.”

“So, speed, there is a lot of talk about it, but it is... I mean, it is a lot like, ‘oh, we have to get the stuff to the customers’, and then it sits in their depot for two years because they were not ready themselves. Because it's not just a new market for us, but also for those receiving it.”

“Then, of course, there are financial goals; one would like to invoice quickly. That is usually the driving force behind setting a short lead time.”

“I think speed should have less priority. That's where you can have a dialogue and agree that even if there are long lead times, it should be okay for customers to accept lower speed deliveries.”

“So, we are probably very fast, but maybe we need to be a bit smarter. To make the customer understand, to guide the customer, and to be a bit more consultative. Explain to the customer, ‘this is what you need to do’.”

Thirdly, respondents discuss that dependability is not currently that highly prioritized. This is due to the customers’ projects typically having long time horizons, where schedules often change as the projects progress. However, in the marine segment, dependability is very important, as PowerCell has a specific time slot for installing their products in the customer's application. In the future, respondents argue that dependability should be higher prioritized for PowerCell, especially if products are standardized to a higher degree.

“Getting what you expect when you want it, in a way. And that's something that could theoretically change during the project as schedules and such change. But there, it is all about communication with the customer.”

“However, I definitely think we should be good at keeping promised dates.”

Fourthly, PowerCell currently prioritizes flexibility very much, as stressed by all employees. Flexibility is seen as crucial right now to meet customer requirements and adapt the products to customers’ specific applications, as the fuel cell market is relatively new. In the future, some respondents stress the need for PowerCell to have two different approaches to meet customer requirements; one part with more standardized products, and one part with more customized products, as some customers are expected to still require a certain degree of customization. Furthermore, other

respondents argue that keeping a high flexibility might compromise the other performance objectives, thus, flexibility should be less prioritized.

“Today, we have only survived because we are flexible. We have been able to attract customers because you can get exactly what you want. And you will never become a high-producing company if you have high flexibility.”

“Customers do not really know what they want, even if they think they do when they order something, it has usually not exactly what they want in the end. And there, I think by working closely with our customers, we can help them succeed better.”

“I think we need to split ourselves quite harshly here. In terms of flexibility. Yes, but then it has to be customers who are willing to pay for it.”

“As for flexibility, it has been quite high, being able to accommodate almost anything, but I think we should scale it back. Moving more towards standardization and limiting the number of choices customers have, if any. Because having too much flexibility can lead to a lot of changes, slowness, and perhaps less dependability.”

Fifthly, respondents discuss that cost currently has a high prioritization in the production system, to reduce the costs of goods sold. The cost focus is related to production time and material acquisition, but some respondents mean that production time does not affect the costs substantially. Hence, these respondents mean that to reduce costs, the focus should be on sourcing material more cost-efficiently. From the perspective of end customers, respondents claim that these are currently not that price sensitive, especially in the aviation and marine segments. Contrastingly, the stationary segment is very price sensitive. In the future, many respondents are in consensus that cost should have a higher priority than it currently does. Furthermore, the customer segments are expected to become more price sensitive as the market matures.

“If we look at what we have in operations, it is definitely cost. How can we reduce material prices, construction time, and those aspects.”

“Price sensitivity is not the concern at the moment.”

“Okay, but if I start with what I think is most important going forward, I think we should be obsessive about driving lower production costs.”

Below, in Figures 4.1 and 4.2, the results from the survey are presented, where respondents have ranked each performance objective on a scale between one and five. Figure 4.1 visualizes how respondents perceive PowerCell’s current prioritization between the performance objectives, while Figure 4.2 visualizes respondents’ opinions regarding how PowerCell should prioritize in the future, to achieve higher production volumes.

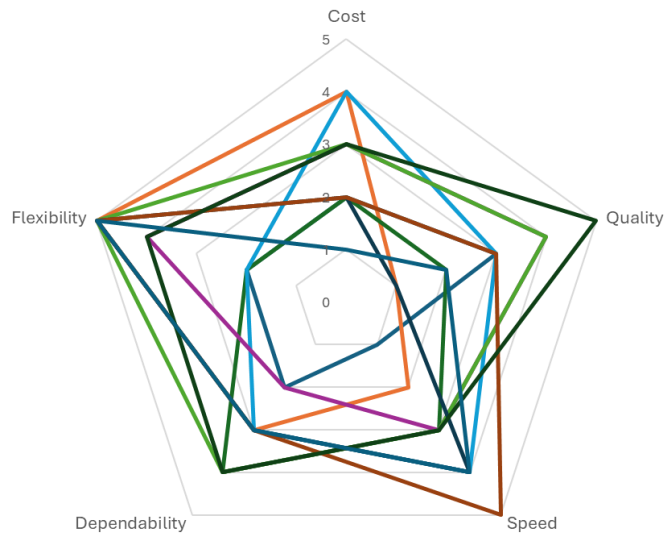


Figure 4.1: Respondents' opinions on PowerCell's current prioritization of performance objectives.

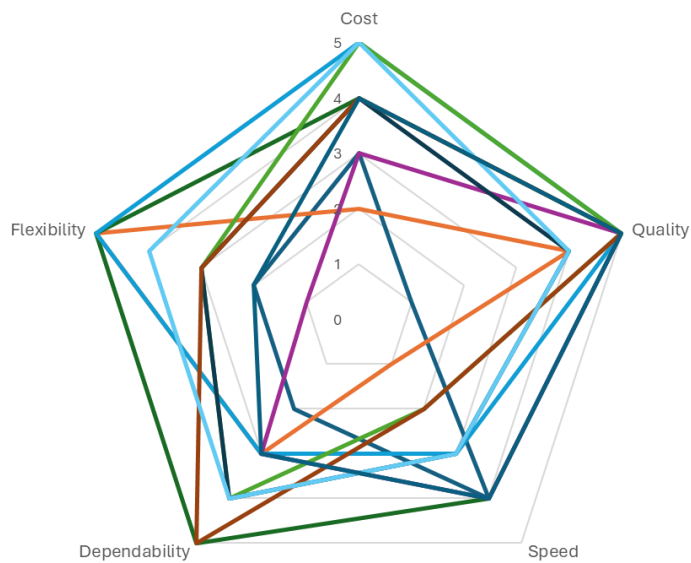


Figure 4.2: Respondents' opinions on how PowerCell should prioritize in the future, to achieve higher production volumes.

4.2 Strategic Decisions, Associated Challenges & Initial Solutions Related to PowerCell's Current Production System

In the following section, the answers to RQ1 and RQ2 are presented, hence, strategic decisions that have shaped PowerCell's current production system, challenges associated with each strategic decision, and initial solutions to the identified challenges.

The results are based on interviews, observations, and the theory on the Proposed Integrated Framework and its strategic decision areas, as presented in Chapter 2 of this report. 65 different strategic decisions were identified, listed below in correspondence with the associated strategic decision area.

4.2.1 Strategic Production Process Decisions, Associated Challenges & Initial Solutions

The following section describes the strategic decisions made at PowerCell within the strategic production process decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented. The content of this section is based on the theory presented in section 2.3.1 of this report, interviews, and observations.

1. The production process is of jobbing process character with aspects of a batch process type: The production process type was observed to be mainly of jobbing process character, as orders are of relatively low volumes but highly customized, thus demanding a high flexibility. When orders are larger, they are treated as a batch, however, as production time is long, each product is produced and managed individually.⁵

A challenge associated with this strategic decision is that if production volumes increase, it will be too time-consuming and costly to put specific effort into every single unit. Having that high flexibility will imply missed opportunities of standardization, leading to high costs, as seen in the product-process matrix by Slack et al. (2013). As jobbing processes require a high degree of employee knowledge, increasing production volumes, and the number of employees, might challenge ensuring that all operators possess the right knowledge.

An initial solution is to offer customization of fuel cell systems to a certain extent, however, the required flexibility for this customization should not result in too high costs. This could mean offering customization of fuel cell systems in cases where orders exceed a certain quantity, implying a move from the jobbing process towards more cost-efficient operations (Slack et al., 2013). Moving forwards, two separate assembly lines could be established, one for standard fuel cell systems that is not flexible, and one for customized orders where the layout can be flexible to shift according to specific orders. Contrastingly, as fuel cell stack production volumes are expected to increase more rapidly than for fuel cell systems, and as fuel cell stacks are more standardized than fuel cell systems, this production process should become more standardized. To summarize, this might imply a batch process for fuel cell systems and a mass production process for the fuel cell stacks.

2. The production layouts for fuel cell stack production and the PS200 system are functional: The production process layouts for fuel cell stack production and production

of the PS200 system were observed to be mainly of functional process character. The functional production layout for fuel cell stack production and the PS200 system enable PowerCell to utilize resources efficiently as similar resources are clustered.

A challenge associated with the functional production process layout is that while it increases resource efficiency, it makes product flows and planning production more complex. As argued by Slack et al. (2013), this is not an issue when the volume is low, and the variety is high. However, with increased production volumes, production might become more time-consuming and difficult to manage, and this might increase the risk of errors. Complex product flows will, furthermore, require increased cognitive effort from operators.

An initial solution to this is to, when production volumes increase, consider cell- and product layout to reduce complexity in flows. This will facilitate increasing flow efficiency in the production system, which reduces waste in terms of non-value adding time as stressed by Gremyr et al. (2020).

3. The production layouts for the PS100 system and production tests are fixed-position: For the PS100 system, a fixed-position layout is used as only one person works at the system at a single assembly station from beginning to end.³ Similarly, a fixed-position layout is used for the production tests – FAT, component, and leak tests – where systems are placed in the designated test area and the tests are then conducted on the stationary system. This layout implies high resource efficiency and, thus, a focus on cost-efficiency.

A challenge associated with the fixed-position layouts is that if production volumes increase, this decision of layout will become problematic. Product flow in fixed-position layout is almost non-existent, which means that production and movement of transforming resources will become complex and it might be difficult to get an overview of the stages in the production process.

An initial solution to this is to consider redesigning the PS100 system, for example, modularizing it. Furthermore, it might be beneficial if the PS100 system and the PS200 system are designed in a similar way, to facilitate standardization of components and the production process. If the PS100 system could be assembled in another way, clearer flows in production could be established, which will be beneficial if production volumes increase. An alternative is to phase out the PS100 system and focus on fuel cell systems that are more manufacturable.

4. Fuel cell stacks are activated in the lab area: When production of fuel cell stacks is completed, they are transferred to the lab area to be activated and tested by operators.⁶ This is to ensure that the fuel cell stacks work correctly and to detect any potential quality issues. The fuel cell stacks can after this be used in fuel cell system assembly or sold to the customer directly.⁷

A challenge associated with the activation of fuel cell stacks is that this process requires substantial time.⁶ If production volumes are increased, this challenge will be amplified, possibly inducing a bottleneck in the production process.

An initial solution to this is to consider redesigning the PS100 system, for example, modularizing it. Furthermore, it might be beneficial if the PS100 system and the PS200 system are designed in a similar way, to facilitate standardization of components and the production process. If the PS100 system could be assembled in another way, clearer flows in production could be established, which will be beneficial if production volumes increase. An alternative is to phase out the PS100 system and focus on fuel cell systems that are more manufacturable.

5. The production layout is kept flexible: In general, the production layout is characterized by its high flexibility to adapt to different customer requirements.³ Flexibility is of high importance in the production layout as new customer orders can entail different requirements on the production system.

A challenge associated with the flexible production layout is that if production volumes increase, it will become very costly and time-consuming to maintain the same level of flexibility in the production area. It will also be very difficult to plan the production and the capacity if always adjusting the layout to specific orders. The higher frequency of incoming orders will also make it difficult to prioritize which orders to adjust the production layout to.

As it will be very costly to maintain the same level of flexibility if production volumes increase, the level of flexibility in the production system must be decreased (Slack & Lewis, 2020). This could, for example, be done by utilizing separate production lines, as discussed in initial solution 1.

6. PowerCell has a relatively low technical level in the production in general but has implemented a comprehensive ERP system: As PowerCell recently started to aim for a shift from being a development-oriented company to being a producing company, the technical level of production is considered low regarding the three characteristics of process technology described by Slack and Lewis (2020): scale, automation, and coupling. However, a comprehensive ERP system called Monitor has been established enabling technical advancement.⁶ The lack of investments in technical advancement is a decision driven by cost-savings, as the production volumes are currently relatively low.⁵ Additionally, the relatively low technical level allows PowerCell to not be locked-in to certain technologies, remaining the flexibility for changes in the production.

A challenge associated with the low technical level is that if production volumes increase, it is, according to Slack and Lewis (2020), more cost-efficient to aim for a higher degree of scale, automation, and coupling in the process technology. However, increasing these characteristics leads to a lower robustness of the production system,

which requires a relatively stable production process with a low degree of variety. Furthermore, there is a challenge associated with ensuring that Monitor is updated with all available information, to fully utilize it. If production volumes increase and the technical level is not increased, the manual workload will increase severely, which will entail a longer production time. It might also increase the risk of quality issues due to the human factor. Another challenge in the organization is to move pieces of information between different systems, as this is currently done manually.⁷ For example, design and manufacturing drawings are constructed in a system that is not coupled to Monitor, thus, updates must be transferred manually. This means that systems risk not having the right information.

If production volumes increase, the production process must be standardized to a larger extent. As volume increases and variety decreases, Slack and Lewis (2020) propose that a higher technical level should be aimed for. A first step could be to further integrate Monitor, to ensure that it is utilized across the organization and that it is updated with correct information.⁷ Furthermore, a higher degree of coupling should be utilized between different systems, to ensure more reliable flows of information (Slack & Lewis, 2020). Another way to increase the technical level is to utilize digital screens in the production system to visualize the processes and facilitate synchronized flows.

7. Paused robotics development in fuel cell stack production: An ongoing development of robotics and automation in fuel cell stack production was paused.⁶ When the strategic decision about sourcing one type of fuel cell stack from Bosch was made, the development of automating the fuel cell stack production was paused due to the high costs of automation and the currently relatively low production volumes.

A challenge associated with pausing the robotics development in the fuel cell stack production is that it implies a decision to not currently automatize this production process. Certain respondents perceive this decision as a cancellation of automation, rather than a pause in the development. If production volumes increase, a higher technical level will be favorable, thus, with a higher degree of automation. An automation process is, according to Slack and Lewis (2020), often time-consuming, and pausing robotics development indicates that the automation process will take more time once resumed. This will probably constitute a larger issue if fuel cell stacks are produced in-house than if a decision is made to continue acquiring fuel cell stacks with high volume from Bosch. However, if only one type of fuel cell stack is acquired from Bosch, the volumes produced in-house will still, most likely, be large enough to require a certain degree of automation. As fuel cell stack production is expected to increase production volumes at a higher rate than the fuel cell system production, and could be considered closer to a standardized design, it is likely that automation will soon be needed.

A decision must be made regarding the future of in-house fuel cell stack production. If PowerCell wants to produce high volumes of fuel cell stacks in-house, it might be suitable to prepare for this by restarting robotics development, to avoid timely delays. If PowerCell wants to buy some fuel cell stacks and produce some of them in-house, a decision must be made regarding which stacks to buy and which to produce, in terms of volume. If the high-volume fuel cell stacks are sourced externally and in-house production handles lower volumes and higher variety, robotics might not be necessary to develop further.

8. FAT- and component tests are to a certain degree done using pre-programmed scripts: FAT- and component tests can be performed using pre-programmed scripts to a certain degree.⁹ This is done to achieve a dependable testing procedure easier to control in time and quality. This means that the tests can be performed without as much manual work, indicating a certain degree of automation.

A challenge associated with the FAT tests is that even though there is a pre-programmed script, the fuel cell systems still require manual handling with individual adjustments.³ This is because the fuel cell systems do not always have consistent quality.

As products become more standardized, the pre-programmed scripts should be updated and utilized to a larger extent.

9. Handheld devices are used in the warehouse: Warehouse employees have started to use handheld devices in the warehouse to scan components and see information about which items to pick.⁴ This enables higher speed in performing work tasks as the need for manual work decreases. It further increases quality as picking is done in a more structured way and inventory levels become more accurate.

No challenge has been associated with this strategic decision, and thus, no initial solution is proposed.

10. PowerCell has invested in a 3D-scanner to control incoming parts: Investments have been made in a 3D-scanner in the warehouse which facilitates control of incoming parts.⁷ This facilitates conducting quality control of incoming goods in less time and with higher quality.

A challenge associated with the 3D-scanner might arise if production volumes are increased, as many more components would arrive at the warehouse. As the process of checking a part with the 3D-scanner is relatively time-consuming, this will only be possible for a small amount of the incoming material.⁷ Thus, it can be difficult to know

⁹ K. Hartvig, personal communication, March 18, 2024

how to prioritize for the arrival control. These challenges imply a need for a more consistent quality of incoming material to be manageable.

To be able to know which parts to check, Monitor must be updated with the latest information regarding different components. Furthermore, if a certain supplier temporarily has quality issues, this information must also be available in Monitor, further indicating which components to control. Another solution to explore is that suppliers should perform certain tests before delivery, reducing the need for arrival control at PowerCell, hence, indicating a more proactive quality approach. This might induce higher costs for PowerCell, however, it reduces the time and cost spent examining components upon arrival and sending faulty components back to the supplier. Ensuring that suppliers test components before delivery might also be a way for PowerCell to make suppliers deliver the specified quality. Additionally, a more proactive approach toward quality management is also required to reduce the need for arrival control, to increase the quality of incoming material by, for example, improving the design and manufacturing drawings.

4.2.2 Strategic Capacity Decisions & Associated Challenges & Initial Solutions

The following section describes the strategic decisions made at PowerCell within the strategic capacity decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented. The content of this section is based on the theory presented in section 2.3.2 of this report, interviews, and observations.

11. Operators work day shift in production: Employees in production are working day shift, Monday to Friday, as the capacity added by more shifts is currently not required.⁵

A challenge associated with this strategic decision is that if production volumes increase, additional capacity will be needed. Keeping only the day shift will imply a need for more operators, equipment, and workstations. However, adding shifts would require at least some experienced operator at each shift to ensure the work is done correctly and that new operators develop knowledge of how to perform work tasks. Additionally, if night shifts are added, work tasks should be designed to require a low degree of cognitive effort from the operators.³

Evening and night shifts should be considered to increase capacity in production, if production volumes increase. However, this would require the testing facilities to increase capacity accordingly as the test labs otherwise would become a bottleneck.³ If, or when, adding night shifts, work instructions or detailed design and manufacturing drawings must be available to reduce the cognitive effort required by operators.

12. The level of capacity in the production is adapted to the forecasted production volumes: The current level of capacity in fuel cell stack and system production is set to

match the forecasted production volumes.³ The number of operators is adapted to the operators' levels of experience.

A challenge associated with the level of capacity in production is how to manage uncertain forecasts, as demand commonly fluctuates.⁶ For example, operators have been required to work overtime on certain occasions with peak demand, when customers have requested fast delivery.

As speed is a performance objective that respondents do not perceive as required to increase, one initial solution to the difficulties in managing uncertain forecasts is to increase the acceptance of longer lead times.⁷ This can be done by close communication with both internal and external customers, to ensure awareness. If longer lead times are accepted, it can be easier to achieve a more even production rate.

13. The level of capacity for FAT tests is five test labs with differing electric power levels, and there are no employees specifically dedicated to performing the FAT tests for production: There are five test labs where FAT tests can be performed, and these are shared between the Operations department, the Engineering department, and the Applications department.⁹ One is dedicated to products with up to 250 kilowatt, one for products with up to 160 kilowatt, and three for products with up to 30 kilowatt. The FAT tests are performed by employees working in either the Engineering department or the Applications department, as the Operations department does not have any employees in the lab area, despite their need for frequent usage of the lab.

A challenge associated with the capacity of test labs is that the FAT testing constitutes a bottleneck, as the required testing capacity is larger than the actual capacity.⁹ Furthermore, as production has no dedicated employees for performing FAT tests and share the resources with the Engineering department and the Applications department, it is difficult to plan and schedule testing activities in the lab area. Tests conducted with the Operations department's products are more predictable than the Engineering department and the Application department's products in terms of time required, because FAT testing of their products more often results in time-delays.⁹ Thus, the shared test labs affect the production system, as it leads to high variation in the testing process. The lack of dedicated personnel from the Operations department in the testing labs could result in a lack of sense of ownership for the tasks for the employees who perform the tests. This would obstruct the product flow and increase throughput time. Another challenge is the division of labs according to electric power, as this division does not currently reflect the demand. If production volumes increase, the Operations department's FAT tests will presumably constitute a larger part of the total FAT tests; thus, all current challenges discussed above will likely be amplified.

An initial solution to the challenges associated with the FAT testing is to revise the division of labs according to electrical power of the fuel cell systems. If possible, the

test labs could be generalized, meaning that each test lab could perform FAT tests on fuel cell systems of any electrical power. This would increase the flexibility in the testing activities, and delays would not obstruct the product flow through the production system. However, this solution would be costly, as the labs with capacity for testing 250 kilowatt and 160 kilowatt require special equipment and are thus more expensive than labs with capacity for lower electrical power.⁹ An alternative way is to only generalize the two labs with capacity for testing 250 kilowatt and 160 kilowatt, meaning that both the PS100 system and the PS200 system can be tested in both these test labs.

14. The level of capacity in the warehouse is set to match the demand in production: The current level of capacity in the warehouse is set to match the demand in production, which is dependent on customer demand.⁴ A certain capacity buffer is aimed for to always be able to perform tasks directly connected to production, such as arrival control on incoming material and material picking. However, there is never excessive capacity, as there are other tasks in the warehouse to be performed when demand in production reduces.

No challenge has been associated with this strategic decision, and thus, no initial solution is proposed.

15. One production site does everything, and this single site comprises three sub-sites: one warehouse, one production area, and one lab area: The whole production system is currently located in one facility. The production system is divided into three sub-parts located next to each other, a warehouse, a production area divided into fuel cell stack production and fuel cell system production, and a lab area.

A challenge associated with this strategic decision is that if production volumes increase, there will, eventually, be a need for capacity expansion. There will be a challenge to determine where and how to expand capacity, a decision comprising multiple aspects to consider as stressed by Slack and Lewis (2020). Firstly, if there should be one large facility that does everything, several smaller sites that do everything, or dedicated sites performing only certain tasks, by placing sub-sites at different locations. Secondly, where facilities should be located. Thirdly, if there are different requirements for expansion of fuel cell stack production and fuel cell system assembly, as fuel cell stacks have stricter regulations. Fourthly, establishing a new lab area entails challenges related to regulations and hydrogen infrastructure.⁷

When the maximum capacity at the current site is reached, a decision must be made regarding the capacity expansion, where and how to expand. This decision should be based on for example proximity to market and suppliers, infrastructural opportunities, legislations, availability of resources (Bellgran & Säfsten, 2010; Slack & Lewis, 2020). For example, if fuel cell stacks are further sourced from Bosch, a new fuel cell system

assembly site could be located close to one of Bosch's production sites.¹⁰ Additionally, countries with high economic incentives or established infrastructure for hydrogen solutions can be suitable locations for a new site.

16. Aiming for the production system to be mobile enough to relocate quickly: PowerCell aims to organize their production system in a way that enables them to quickly meet fluctuations in demand by relocating to different geographical locations.³ Thus, PowerCell aims to keep their fuel cell system assembly site mobile.

A challenge associated with this strategic decision is that it implies that many, presumably smaller, production sites are to be used rather than one bigger facility. However, no decision has been made regarding this yet.⁵ If a decision about a larger facility is made, the current mobility level of the production system might be unnecessary, and this excessive mobility might obstruct the development of the production process. Further, despite the fuel cell assembly stations being mobile, other parts of the production system might obstruct quick expansion to other locations.

To be able to set a suitable level of mobility in the production system, a decision must first be made regarding capacity expansion, as discussed in challenge 15. If the aim is to relocate frequently with many smaller sites, the current level of mobility of the production system might be suitable, however, if fewer and larger sites are aimed for, the level of mobility might be excessive.

17. Component tests and leak tests are done in the production area: As the component tests and leak tests are done earlier in the production process than the FAT tests and do not require as advanced equipment, they are performed in the production area.³ This enables a quicker testing process that is less affected by delays in the lab area.⁹ Additionally, this strategic decision enables operators to have more control over the component- and leak testing processes.

No challenge has been associated with this strategic decision, and thus, no initial solution is proposed.

18. The warehouse employees pick all the material for production and do an arrival control on some of the incoming material: To be able to ensure that inventory levels are correct, the warehouse employees are the only ones picking material for production.⁴ However, employees from different functions can modify inventory levels in Monitor as material is moved between different types of stock.⁷ However, this modification by different functions is done in an unstructured and ad-hoc manner, when required. For example, faulty components are registered in a so-called quarantine stock by the quality team. Furthermore, warehouse employees check the quality of incoming material upon arrival.

A challenge associated with material handling in the warehouse is that not all employees are aware that only warehouse employees can pick material.⁴ Another

challenge arises due to the possibility of other employees than warehouse employees modifying stock levels and transactions in Monitor.⁷ As these types of Monitor updates are done in a relatively unstructured way, there is a risk of faulty inventory levels when components are moved between different types of stock.

Regarding the material handling in the warehouse, communicate clearly throughout the organization regarding the decision that has been made. Furthermore, make another decision regarding the digital stock levels in Monitor, to ensure that warehouse employees are responsible for handling all types of inventory level modifications. This would probably reduce errors in inventory levels, as only dedicated employees handle the stock levels.

4.2.3 Strategic Supply Network Decisions, Associated Challenges & Initial Solutions

The following section describes the strategic decisions made at PowerCell within the strategic supply network decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented. The content of this section is based on the theory presented in section 2.3.3 of this report, interviews, and observations.

19. Aiming for an efficient rather than a responsive supply network: In choosing and managing suppliers, emphasis is placed on cost and quality, implying an efficient supply network rather than a responsive one.⁴

A challenge associated with the aim for an efficient supply network is that a responsive supply network is more suitable for PowerCell's situation, based on the current level of uncertainty. A responsive supply network would, according to Chopra and Meindl (2013), reduce lead times and enable a quick response to demand fluctuations. However, this increased flexibility would entail higher costs. This means that PowerCell currently has lower flexibility than required in their supply network, with long lead times. If production volumes increase and demand uncertainty decreases, the aim for an efficient supply network would be less problematic. However, PowerCell's current situation requires a high degree of flexibility from suppliers, as late changes in orders often are required.⁷

In their current situation, PowerCell requires a higher degree of flexibility from their suppliers than they currently have. Therefore, PowerCell should ensure that the required flexibility is contractually bound and not just assumed on an ad-hoc basis, to ensure that suppliers can meet late order changes. If production volumes increase and variety decreases, the demand uncertainty would likely decrease, and in that case, an efficient supply network should be aimed at, focusing on reducing costs and increasing quality (Chopra & Meindl, 2013).

20. Develops new fuel cell stacks and systems, producing stacks but assembling systems: PowerCell develops new fuel cell stacks and systems internally.² Further, they

produce fuel cell stacks and assemble fuel cell systems, sourcing standard components and sub-modules externally rather than producing everything in-house.⁶

A challenge associated with this strategic decision is that a clear direction must be chosen and communicated regarding the future core production business of PowerCell. Currently, there seems to be a certain misalignment in the employees' perception of this. For example, whether PowerCell should develop and manufacture both fuel cell-stacks and systems, or if the focus should be more niched. This decision will have consequences for how the production system will be formed, as fuel cell stack production and fuel cell system assembly have different requirements.⁷

A clear direction much be chosen about what PowerCell wants to excel at, then decisions regarding suitable production systems can be made. As the development of new fuel cell applications is considered PowerCell's core business, the main decision revolves around how to produce their products. For example, focusing on fuel cell stack production could entail more opportunities for automation, as this implies higher production volumes and possibly more standardization, than fuel cell system assembly. However, focusing on fuel cell system assembly might be of competitive advantages, differentiating PowerCell in the market. Furthermore, fuel cell systems might be more profitable than fuel cell stacks.¹²

21. Licensing production of one type of fuel cell stack to Bosch, and single sourcing it from them: Bosch holds the license for manufacturing a particular type of fuel cell stack, which PowerCell subsequently acquires from them.¹⁰ This partnership aims to achieve high quality and reduced production costs of this type of fuel cell, as Bosch has built capabilities for large-scale production.

A challenge associated with this strategic decision is that it seems like employees are unsure if acquiring these fuel cell stacks from Bosch is appropriate, as the fuel cell stack production is considered a core competence of PowerCell. Furthermore, it seems like the costs and time associated with producing the fuel cell stacks in-house has not been fully explored, meaning that acquiring fuel cell stacks from Bosch might not be the most cost-efficient with a longer time perspective.¹² Currently, establishing in-house production would imply substantial investments, posing a challenge. However, there is potential to reach economies of scale. According to Slack and Lewis' (2020) discussion about do-or-buy decisions, Bosch might reach economies of scale more easily than PowerCell, resulting in lower production costs, however, administrative costs and Bosch's profit margin must also be considered. Another challenge related to sourcing fuel cell stacks from Bosch is the risk of intellectual property leakage associated with the close partnership, as Bosch have an interest in the fuel cell market, thus, over-sharing technical details might be hazardous for PowerCell.² Furthermore, a challenge related to this sourcing decision is the quality of the product development. As the Engineering department, who is developing the fuel cell stacks, is not close to Bosch's

¹⁰ V. Åkerlund, personal communication, January 22 & March 14, 2024

production, continuous feedback and communication becomes increasingly difficult. This implies that PowerCell's core business of developing the new generation of fuel cell stacks will be challenging without receiving feedback and the possibility to trace and correct detected errors, as stressed by Slack and Lewis (2020). Additionally, it seems like employees are not sure if the decision to acquire fuel cell stacks from Bosch has a short- or long-term time horizon. This creates challenges in knowing how to develop other parts of the production system, making it difficult to know which resources and capacity to invest in.

Due to the differences in opinions about this strategic decision among employees, it seems like a thorough investigation is needed. This implies a thorough exploration of the different alternatives and should be done before production volumes increase. It is crucial to make this decision as it guides the development of the production system in a specific direction. There are three obvious alternatives: sourcing production of all fuel cell stacks from Bosch, producing all fuel cell stacks in-house, or sourcing certain fuel cell stacks from Bosch, for example, the ones with the highest production volume, and produce the remaining fuel cell stacks in-house.

22. A code of conduct is signed with new suppliers: When selecting suppliers, the new suppliers are encouraged to sign a code of conduct to ensure that they align with PowerCell's values and requested quality.⁴ On certain occasions, PowerCell instead considers the supplier's code of conduct equivalent to their own code of conduct.⁷

A challenge associated with this strategic decision is that suppliers are not always willing to sign PowerCell's code of conduct as they instead refer to their own code of conduct.⁷ This could make the supplier base more difficult to manage, as it leads to more administrative tasks. If production volumes increase, this challenge might become less prominent, as PowerCell could then have a stronger basis for negotiation.

To ensure consistency and reduce administrative work, try to get the supplier to sign PowerCell's code of conduct, rather than reviewing the supplier's own code of conduct.

23. Suppliers are evaluated and categorized as basic, preferred, or strategic, based on certain guidelines: Recently, PowerCell started to evaluate new and existing suppliers with a comprehensive framework, aiming to ensure that aspects such as desired quality and type of relationship are achieved.⁴

A challenge associated with this strategic decision is that increased production volumes will require more time spent on evaluating suppliers, if the number of suppliers increases. However, the evaluation can also aid in standardizing categorization of supplier. Furthermore, if evaluation is not done properly, there is a risk of keeping suppliers with quality issues, as emphasized by Luthra et al. (2020). The more investments that are made in these relationships, the more difficult it might be to decide to end the collaboration with that supplier.

Adapt the comprehensiveness of the supplier evaluation to the situation at hand; for example, if a critical component is to be sourced, a thorough evaluation is preferable.

However, if a commodity is to be sourced, it is not worth the time to do a thorough evaluation of this supplier, as it is interchangeable with other suppliers. Ensure that the corresponding relationship is established with the supplier depending on its category. Furthermore, for the suppliers of high strategic importance, ensure that the evaluation is followed up, for example, in terms of quality.

24. Keeping customers' products in stock until they are ready to receive them: For many orders, customers are not ready to start using PowerCell's products when they are ready to be shipped.¹¹ Thus, PowerCell has offered these customers to keep the goods in stock until the customers are ready to receive them. This is done to both meet and exceed customers' expectations, giving them the best customer service.

A challenge associated with keeping customers' products in stock is that PowerCell will not have enough space to store already-sold products if production volumes increase. This type of flexibility offered to customers therefore will be costly.

In the longer term, PowerCell should not offer storage of goods sold. However, there should be a transition period when PowerCell still offers this to a certain degree, not to decrease customer satisfaction. Furthermore, as production volumes increase, PowerCell must establish a more standardized way of working with delivery plans. This requires close communication with customers regarding their projects' progress, which Gremyr et al. (2020) stress the importance of.

25. Critical parts are single sourced and non-critical parts are multiple sourced: Parts are considered critical for production if they require substantial relationship specific investments in development or equipment, if they are expensive, or if the lead times are long.⁴ The critical parts are chosen to be single sourced from suppliers with whom partnerships are established, however, for parts that are critical due to their associated prices, alternative suppliers are sought for, to be used if required. Partnerships allow for close collaboration and communication, facilitating dependable deliveries. Although single sourcing is a strategic decision, the fuel cell market is relatively new, thus, there are not that many suppliers to choose from.⁴ Parts are considered non-critical if they are easy to source relatively quickly and that there are multiple available suppliers in the market, and for these components, multiple sourcing is chosen.

A challenge associated with the decision to single source is that it reduces the flexibility of scaling acquired volumes according to demand compared to multiple sourcing, as stressed by Jonsson and Mattsson (2017). With the current degree of demand uncertainty that PowerCell faces, a certain degree of flexibility in acquired volumes is required.⁷

While maintaining partnerships with suppliers for critical parts, PowerCell should actively seek out additional suppliers for critical components. This should be done to

¹¹ K. Samuelsson, personal communication, March 14, 2024.

provide backup options in case of supply chain disruptions or unexpected fluctuations in demand, while still leveraging the benefits of partnerships for dependable deliveries.

26. Long-term development projects together with customers: As many customers are new to the fuel cell market, they do not always know what they need, and therefore, they require applications that are highly customized.¹¹ Furthermore, the customers' timelines are typically long, thus, long-term collaboration is needed. Therefore, PowerCell often develops these products in projects with the customers. Upon delivery, PowerCell can help the customer install the products. This set-up offers flexibility to the customers and enables PowerCell to provide them with dependable deliveries. This set-up requires a certain degree of flexibility in the production system.³

A challenge associated with this strategic decision is that if production volumes increase, the same level of flexibility to meet customers' demand will become very costly and require many employees dedicated to these types of projects.

If production volumes increase, PowerCell can only offer this level of flexibility to a certain degree, as discussed in initial solution 1.

4.2.4 Strategic Quality Management Decisions, Associated Challenges & Initial Solutions

The following section describes the strategic decisions made at PowerCell within the strategic quality management decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented. The content of this section is based on the theory presented in section 2.3.4 of this report, interviews, and observations.

27. No defined desired level of quality: The Engineering department are not always sure how specific to be in product development, certain things are over-specified and certain ones are under-specified.² This is reflected in the design and manufacturing drawings, where specific measurements and tolerances, or their criticality, are not always clearly stated.⁷

A challenge associated with the lack of a defined desired level of quality is that it leads to design and manufacturing drawings that are sometimes insufficient for production.⁶ This induces quality issues. Furthermore, suppliers do not get sufficient specifications on what to produce, which also leads to potential quality issues in incoming material.⁷ If the design and manufacturing drawings lack detailed information about measurements and tolerances, it is also difficult to control arriving material as warehouse employees will not know what to look for. Contrastingly, the lack of a defined desired level of quality leads to certain things being over-done, having higher quality than required, so focus is sometimes mis-placed.² The lack of a defined desired level of quality additionally leads to different types of Muda, such as defects because of under-specification and over-processing because of over-specification.

A clear definition of the desired level of quality must be chosen at PowerCell, as this is crucial in an organization (Gremyr et al., 2020). This is important as a basis for all internal processes, to align the organization and facilitate cross-functional work. For example, if a clear definition is made, it will be easier to construct design and manufacturing drawings that facilitate manufacturing of components and products.⁶ This would enhance cross-functional teamwork and handovers between the Engineering department and the Operations department, as a common goal is clearly stated and aimed for.

28. Quality efforts are driven by standards and legislations of the different customer segments: PowerCell's quality efforts are driven by customer requirements for quality standards and legislations, leading to an internal prioritization of a level for quality that fulfills these specific standards.⁷ One example is that the aviation industry requires a high level of traceability of the products and their components.¹²

A challenge associated with quality standards is how to choose which standards to adhere to. The current way of working is more ad-hoc and responding to specific customer requirements.⁷ Ensuring adherence to quality standards is essential for customer satisfaction, serving as an order-qualifier, however, if not done following a strategy, there is a risk of a very scattered portfolio of standards that requires a lot of effort to maintain. The time invested in meeting these specific standards may not always yield the same level of value as alternative quality-focused tasks that could be prioritized instead. Additionally, a challenge is to integrate the quality standard work in the organization, not viewing it as simply a checklist. The current challenge is, thus, to strategically choose which quality standards to adhere to, while the upcoming challenge will be to maintain the chosen quality standards.

Establish a strategy for which quality standards to adhere to, to ensure a solid, coherent, base of standards. Aim for integrating the standards into the organizational way of working, to facilitate maintaining and auditing them. To meet specific customer requirements, smaller add-ons to the base of standards can enable fulfillment of more quality standards suitable for different customer segments.⁷ This can result in a comprehensive portfolio of standards, without the need for excessive workload.

29. The quality team is part of the Operations department: The quality team was formed only a year ago, and put under the Operations department, possibly putting a primary focus on production and purchasing for the quality work.⁷ However, quality meetings are held frequently with representatives from other departments to achieve an organization-wide quality focus.⁵

A challenge associated with this strategic decision is that it induces a risk of not having organization-wide quality focus.⁷ Thus, it requires well-functioning cross-functional communication, which also currently is a challenge. Additionally, it can complicate efforts to ensure a clear understanding within the organization of the importance of integrating quality standards effectively.

Ensure that the importance of quality work is clearly communicated throughout the organization, to achieve a mutual understanding. Organization-wide effort is, as emphasized by Dean and Bowen (1994), crucial to be able to provide customers with products that they need. Furthermore, the quality principle teamwork is stressed as an enabler for the two other quality principles: customer focus and continuous improvement, in an organization (Gremyr et al., 2020).

30. Basing the quality management work on the ISO 9001 standard: An internal prioritization for PowerCell is to achieve the ISO standard 9001 regarding quality management.⁷

A challenge associated with the ISO standards is to integrate these into the organizational work rather than viewing them merely as a checklist.⁷

Focus on integrating standards into the organizational way of working.

31. Reactive quality approach in production where faults are discovered and reported: Most faults, either in design or from production, are discovered during production or testing.⁷ These issues are reported to the quality department and the faulty product is put in a so-called quarantine area, to be handled, for example by re-work or returning them to the supplier. This implies a reactive approach to quality work.

A challenge associated with the reactive quality approach in production is that if production volumes increase, handling quality issues like this will be challenging. It will lead to disruptions to the production process that could have been avoided if a more proactive approach had been utilized. Discovering quality issues during the production process leads to a large amount of time-consuming re-work, or in some cases, scrap. However, in PowerCell's current situation, some respondents perceive the frequent product updates constitute a barrier to implementing a more proactive approach to quality work in the production process. Another challenge regarding quality management in production arises due to the relatively long assembly time for fuel cell systems. Operators leave the workplace multiple times, including at the end of workdays and over weekends, before the product is completed.⁵ This presents numerous opportunities for errors to occur, and these are typically addressed with a reactive quality approach, prolonging the production time even more.

Aim for a more proactive quality approach, to prevent quality issues from arising in the first place (Bellgran & Säfsten, 2010). For example, focus on improving design and manufacturing drawings, to avoid time-consuming re-work and ensure that quality is built in. Furthermore, ensure that components are quality-checked before assembly. Even though there are frequent product updates, it is still crucial to work with proactive quality management, as, if there are many changes, these must be dealt with directly. Poka-yoke is one proactive quality approach that can be used to reduce the number of errors and ensure that when errors occur, they are identified and handled quickly

(Black, 2008). For instance, this approach could be applied in the assembly of fuel cell systems to guarantee error-proofing when the production process is paused and restarted.

32. Testing material upon arrival in the warehouse implies a move toward a more proactive quality approach: An arrival control on incoming material has been implemented in the warehouse to detect quality issues earlier in the production process, moving toward a more proactive quality approach.⁷ However, the quality issues in the incoming material are partly due to the sometimes-insufficient design and manufacturing drawings, and partly due to insufficient quality from suppliers.⁶ Therefore, the arrival control is also reactive, as quality could be secured even earlier in the process.

A challenge associated with the arrival control is that if production volumes increase, more faulty components will likely pass, as all components cannot be checked properly. This means that production will receive material that might have defects, resulting in time-consuming re-work and unnecessary costs.

Ensure that design and manufacturing drawings are correct so that the supplier has the best possibility of delivering high-quality components. Furthermore, work together with the suppliers to find the desired level of quality required for these design and manufacturing drawings, for example, clarify which tolerances are the most critical (Liker, 2005). Secure that the suppliers comply with the agreed quality. One way of doing this is to explore the opportunity of certain tests being done at the supplier's location, which also enables a more proactive quality approach.

33. Reactive quality approach in testing as the whole product is assembled before tested: Despite the PS200 being module-based, the whole system is assembled before FAT testing it.³ This is done to ensure that the demanded quality is met, however, this implies a reactive approach as quality issues are discovered late in the production process.¹²

A challenge associated with this type of reactive approach to testing is that faults discovered during the test will lead to disassembly of the whole product and much time spent on searching for the source of the error.³ Testing the entire products, all modules together, might be unnecessary and require excessive capacity of the lab area, as not all modules might require that type of lab equipment. Furthermore, this approach implies that testing is done at the last stage of the production process, thus, faults discovered here could lead to a large amount of re-work. However, in PowerCell's current situation, the frequent product updates obstruct optimizing the testing procedure.³

¹² A. Bodén, personal communication, February 20, 2024

PowerCell could review the FAT tests to see if certain modules could be tested in the production area rather than in the lab area. If only the fuel cell module must be tested in the lab area, the mounting process for attaching the fuel cell system to the LIM wagon could be simplified, which would reduce the degree of non-value-adding work.

34. Focusing on multiple available customer segments: PowerCell wants to take on any customer, except those within the automotive segment, as this is licensed to Bosch.¹ Hence, they aim to be flexible enough to meet the requirements of many different customer segments. This strategic decision was made because different customer segments have different development of demand, certain segments experience substantial growth right now, while others might go through a similar phase at a different time.¹¹ Therefore, to not miss any market opportunities, PowerCell focuses on multiple customer segments simultaneously, a strategy enabled by the currently relatively small market size.

A challenge associated with focusing on multiple customer segments is that, as PowerCell and the market mature, there is a risk that PowerCell cannot fulfill the needs of all these customer segments, depending on how the requirements develop. Furthermore, when Bosch's license to serve the automotive segment expires, a decision must be made regarding if PowerCell should start to sell products to this additional customer segment.¹²

As customer segments develop, track the customers' requirements and see if standard products could be developed, either for each customer segment or in accordance with customer segments that have similar requirements. However, the aviation segment will probably still require a high degree of customization.¹² If customer requirements differ severely across segments, this will challenge the production system. Therefore, a decision must then be made regarding whether to stop serving a certain segment or to divide parts of the operation to solely focus on this segment. Furthermore, depending on how competitors in the market develop, and which customer segments they serve, PowerCell might want to choose a certain position where they are competitive.

35. Customization to suit any customer need: PowerCell want to be flexible to meet any customer need, resulting in a very high degree of customization.¹

A challenge associated with the high level of customization is that, as production volume increases, variety should typically decrease to stay on the natural diagonal (Slack & Lewis, 2020). Deviation from the natural diagonal implies that the organization either has too high or too low flexibility, which is costly. Thus, if PowerCell continues with the current level of customization when production volumes increase, the high level of flexibility will be very costly. Additionally, if customer requirements are misinterpreted, the high degree of customization could lead to Muda in the form of over-processing, if the product has excessively high quality. Another

challenge is that customers are not always aware of what they need, potentially requesting certain product characteristics that their application does not require.¹⁰ This could mean that PowerCell, on certain occasions, customizes more than necessary. Additionally, if production volumes increase, serving the aftermarket will become challenging the more customized the products are.

As discussed in solution 34, see if standards could be developed for each customer segment. The level of flexibility must in the longer term be reduced to handle increased production volumes, which will, according to Slack and Lewis (2020), lead to opportunities for increased cost-efficiency. However, as customers presumably will still require a certain degree of flexibility, it is important to try to push the efficient frontier, described by Slack and Lewis (2020). Mass customization is one way of handling this, by, for example, exploring modular designs to a larger extent. Utilizing modules will enable standardization in the production process while still maintaining flexibility to meet differing customer requirements. Furthermore, as discussed in solution 1, customization could be offered when customer orders exceed a certain quantity. Another aspect to consider is to ensure that customer requirements are fully understood, as customers will presumably ask for the highest possible quality even though their application might not require it.¹⁰

36. Mainly focusing on external customers rather than internal ones: Due to the relatively new commercialization of PowerCell's products, the primary focus is on meeting external customer needs.¹ Occasionally, this can be at the expense of meeting internal customer needs due to limited resources.⁷

A challenge associated with the external customer focus is that it obstructs collaboration in the organization, as stressed by Modig and Åhlström (2015). For example, if internal customer-supplier relationships are not emphasized, material handovers will not be adapted to the recipient. This can cause issues in downstream groups, which can be seen at PowerCell, where certain products are developed in response to specific customer requirements, sometimes compromising manufacturability.⁶ Furthermore, if the Sales department does not clearly specify which product they have sold to the customer, there will be room for error in interpreting the customer order, obstructing producing the correct product. This issue will likely be amplified if production volumes increase; if internal customers are not prioritized, handovers between functions will not meet the desired level of quality, thus, leading to inefficient cross-functional collaboration with prolonged lead times. Hence, if internal customers are not prioritized, the external customer might not be able to receive their product with the required speed, dependability, and quality (Modig & Åhlström, 2015).

It is important for PowerCell to foster a culture where internal suppliers and customers are considered in every process, as this is a prerequisite for external deliveries of high quality, according to Modig and Åhlström (2015). The internal customer is a pathway

to the external customer; hence, it must be prioritized. Each department must consider what the downstream department needs to be able to deliver a product according to the customer specifications.

37. Production files quality deviation reports to the quality team, who investigates and then forwards it to the correct recipient: Quality deviation reports are used as a means of communication between production and product development, to give feedback on design issues and improve product quality.⁷

A challenge associated with quality deviation reports is to find the appropriate level of which issues to report.⁷ This means that there is no defined desired level of quality. The quality deviation reports can therefore be subject to bias between different operators, potentially meaning that some employees report things that are of acceptable quality, or the other way around. Overemphasizing quality in the reports could, according to Sandy (2020), result in waste and time delays.

Define a desired level of quality to ensure that everybody is aligned and know which issues to bring up in quality deviation reports.

38. A coordinating role between the Sales department and the Operations department translates customer needs into actual production information: A coordinating role has been established to help translate the customers' requirements regarding specific orders, which are often a bit vague as the customer does not always know what they want.¹ The customers' requirements are translated into production information, such as specific part numbers, to ensure dependable delivery.⁸

A challenge associated with this role is that coordination between the Sales department and the Operations department is difficult, due to frequent product updates and customers not knowing what they want.⁸ For the coordinating role to function as intended and translate sales orders into concrete product data, the orders must be precise in terms of product requirements and specifications.⁶ If the customers' requirements are not properly translated, the orders risk having the wrong part numbers, leading to customers not receiving a product that meets their requirements. Furthermore, there is a risk of re-work or long lead times if other components must be ordered from suppliers.

Due to the frequent product updates, it must be clearly communicated within the organization which product revisions are to be sold and produced. Furthermore, these product revisions should be connected with specific part numbers, which could be done through a product configurator. Furthermore, this product configurator must be coupled with Monitor, and Monitor should be updated with accurate part numbers. Thus, everyone should know where to find the product information and be able to rely on the information being accurate.

39. *Cross-functional teamwork through project meetings:* In certain product development projects, such as the Annual Release projects, the Operations department have a representative, facilitating alignment with other functions, such as the Engineering department and the Sales department.⁵ The aim of this collaboration is to improve the products' quality.

A challenge associated with the cross-functional teamwork between the Operations department and the Engineering department is that it is based on specific projects rather than recurring, more general, meetings.

Introduce more regular meetings between the Operations department and the Engineering department, not solely linked to specific projects but also for general discussions in the organization. More regular meetings would not necessarily mean more meetings in total, but rather a revision in how meetings are held and with what agenda.

40. *Driving some innovative projects with suppliers:* Innovative projects to improve PowerCell's products are to a certain extent pursued with suppliers.² One example is the cooling module of the PS200 system, which has been developed in close collaboration with a supplier to suit PowerCell's needs.⁴

A challenge associated with this strategic decision is to know which suppliers to pursue this type of innovation projects with, to be able to maximize the value added. As such a collaborative project could lead to increased product quality, as emphasized by Gremyr et al. (2020), it is important to not choose the partner solely based on the price.⁷

To be able to succeed with the innovative project, joint problem-solving and a focus on mutual success is crucial by having a partnership relationship with the supplier (Slack & Lewis, 2020). Therefore, when these types of projects are pursued with suppliers, the supplier relationships should be viewed as long-term. PowerCell should continue doing these types of projects to receive a competitive technological edge. For example, start to develop more pre-assembled sub-modules together with suppliers to exploit both their and PowerCell's core competencies. This would also serve as a way of reducing the complexity in fuel cell assembly. Additionally, collaboration with suppliers can be used as a way of proactive quality management, by increasing the product quality from the start.

41. *Employees in the Operations department file change requests to the Engineering department:* When production has feedback on the product design, for example, the manufacturability of products, they discuss this with the Engineering department, and then file change requests to the Engineering department.⁷ The change requests are standardized forms to fill in. Then, the Engineering department prioritizes the requests and acts accordingly, for example by changing the design or finding another way to handle the issue, to improve the product quality.

A challenge associated with the change requests is that this approach to improvement work is beneficial when used as intended, however, a challenge could be to ensure that the requests are understood and prioritized correctly. Furthermore, it can be challenging to determine whether the change requests from production are based on a lack of clear work instructions or insufficient design and manufacturing drawings.

Develop internal standards to ensure internal alignment regarding what quality to strive for. Continue to establish this type of feedback system in the organization and ensure a consistent way of working with it.

42. Close collaboration is pursued with customers, due to the high uncertainty regarding customer needs: As customers often are relatively unsure of their own needs, both in terms of what they need and when they need it, PowerCell has a close collaboration with the customers to find the best solution.¹¹ Technicians from the Applications department are dedicated to specific customer projects and propose a design that suits the customers' needs at the right time.

A challenge associated with the close collaboration with customers is that with increasing production volumes, it will not be possible to have this close collaboration regarding every customer project. For new customers entering the fuel cell market, this type of guidance from PowerCell will probably be needed.¹ Therefore, the number of customers requiring close collaboration regarding orders will increase.¹¹ However, as customers become recurring, and requirements start to resemble each other, fewer of these customers will require this type of attention for each order, and it will be easier to standardize offerings. To summarize, the number of both new and recurring customers will increase, however, these two groups will require different levels of collaboration regarding their orders.¹¹

When developing customized products, PowerCell could place more focus on modifying existing products rather than developing wholly new ones. This would require less resources and time, as standard products could be used.¹¹ It also facilitates the standardization of the production process, as, if the Applications department uses standard products, it implies higher production volumes in the production process.

43. New role in the Operations department that will prepare for production: A new role has been established in the Operations department to facilitate production by for example reviewing the bills of materials, ensuring that the right components and part numbers are connected to the different product revisions.⁷

A challenge associated with this role is that the frequent product updates can make the preparation for production complicated.⁶ Additionally, the data is manually inserted in to Monitor, which can lead to errors. If complete design and manufacturing drawings are not received from the Engineering department, it will be difficult to connect part numbers to product revisions.⁷

There should be more frequent communication and updates between the Operations department and the Engineering department (Wheelwright & Clark, 1992). This will facilitate preparing for production. Additionally, if plans related to product updates are shared, the Operations department could more easily plan purchasing activities and production. Furthermore, to reduce the risk of errors, aim for a higher degree of coupling between the system used for design and manufacturing drawings and Monitor (Slack & Lewis, 2020).

44. Certain usage of process flow charts: Some process flow charts are available on the intranet, used to visualize the processes in the organization in a coherent way and to adhere to the ISO 9000-series.⁷ However, this is not fully organized, and the process flow charts are sparsely updated. Furthermore, the different process flow charts do not follow the same format and are mainly used upon audits.

A challenge associated with the process flow charts is to work with them in a comprehensive way and to acknowledge and encourage the usage of them, as they are currently not utilized to their full potential.⁷ The current lack of process view, reflected in the sparse usage of process flow charts, might obstruct organizational cross-functionality, as stressed by Gremyr et al. (2020). Furthermore, it seems like not all employees are aware of where to find information which should be available in the process flow charts. One example of such an information gap is that there seems to be a general lack of understanding about the testing process that is performed in the lab area. Another challenge is that many of the process flow charts are not updated, making them less dependable, and in certain cases, obsolete.⁷

Utilize the process flow charts to become more process oriented and try to enhance understanding of different processes and procedures in the firm, as stressed by (Keleman, 2003). Ensure that processes are established and subsequently, that process flow charts are made for these. To begin with, main process owners should guarantee comprehensive documentation and regular updates of their processes. Following this, employees overseeing various sub-processes should also do this, ensuring all processes are thoroughly documented.

45. Bottom-up improvement suggestions are encouraged: PowerCell has a culture of improvement, where many suggestions emerge bottom-up rather than top-down.⁷ This approach seems to be mainly driven by employees' engagement, rather than formalized decisions or in a systemized manner. However, some formalized forums are established, such as lesson learned sessions upon completion of projects.

A challenge associated with the informal bottom-up improvement culture is that, although there is a large potential for impact, this might require employees to drive change themselves. This might lead to missed opportunities for change, if employees do not have the time or courage to drive these changes themselves. Additionally,

difficulties could occur if change proposals are not handled in a systemized way, for example, if several employees work on either similar change ideas or contradictory ones.⁷ Increasing production volume implies that the organization grows, and this could obstruct the culture of bottom-up improvements if not formalized. Furthermore, it seems like employees are not fully aware of organizational goals, which can lead to difficulties in proposing improvement ideas.

Before the organization grows too much, ensure that forums for improvement ideas are formalized to facilitate a continued bottom-up improvement culture. Furthermore, an anonymous forum, such as a mailbox in the office, could be established to ensure that all employees feel comfortable in contributing. Communicate clear goals and milestones to reach these goals and point improvement ideas in a desired direction. The improvement work should be driven in a systemized manner, facilitating for every employee to contribute. 5S, as described by Elbert (2013), or kaizen events could be explored as ways of working with continuous improvement.

46. Using 5S for improvements in the warehouse and production: PowerCell has introduced the Lean Production methodology 5S with the ambition of improving and reviewing the warehouse and the production.³ This is a way of achieving higher flow efficiency in the production system.

A challenge associated with using 5S is to ensure it is implemented comprehensively throughout the organization, as the last steps are more holistic with the aim of sustainable change, according to Elbert (2013).

PowerCell should continue to work with 5S and strive for holistic implementation. This is beneficial as 5S can be used as a tool for stabilizing and standardizing processes, which can facilitate increased flow efficiency.

47. Putting emphasis on resource efficiency: The primary focus in the production system is on resource efficiency rather than flow efficiency, which can be seen for example in the lab area, where the aim is to maximize the usage of the testing equipment rather than optimizing the flows.³ Another example is material kitting, which is a way of improving quality in production, however, the kitting is done with time-controlled planning sometimes resulting in queues, indicating a focus on resource efficiency.⁴ The focus on resource efficiency is a way to reduce production costs.

A challenge associated with the focus on resource efficiency is that if production volumes increase, this approach introduces queues and inventory in the production system, as stressed by Slack et al. (2013). Furthermore, as Gremyr et al. (2020) argue that flow efficiency can help improve product quality, focusing on resource efficiency might lead to missed opportunities in terms of quality.

It would be beneficial in terms of quality and lead time to put a stronger emphasis on flow efficiency with synchronized flows in the production process. However, this can be challenging as it might induce certain costs of excessive capacity. A balance should be found between resource- and flow efficiency, aiming at keeping both high, as stressed by Gremyr et al. (2020). One way is to emphasize continuous improvements in the production system and to aim for reducing the seven Muda. Pull production systems and JIT could be explored as ways of placing a focus on synchronized flows, which will be beneficial. This is important even though there is relatively low stability in the production process.

4.2.5 Strategic Development & Organization Decisions & Associated Challenges

The following section describes the strategic decisions made at PowerCell within the strategic development and organization decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented. The content of this section is based on the theory presented in section 2.3.5 of this report, interviews, and observations.

48. Putting emphasis on product innovation rather than process innovation: Due to the newness of the product and the fuel cell market, focus is put on product innovation rather than process innovation. This is done with the aim of developing the best possible product, maximizing product performance.² Further, the focus is put on responding to customer needs and being flexible to meet changing requirements. This corresponds to Innovation stage 1 in the product process innovation curve by Utterback and Abernathy (1975).

A challenge associated with the focus on product innovation is that as production volumes increase, PowerCell will need to move toward more process innovation to ensure consistent quality in production. This implies a shift from innovation stage 1 to innovation stage 2, as proposed by Utterback and Abernathy (1975). This will require at least a few product designs that are mature enough to have relatively large production volumes. This change will also imply moving from performance-maximizing with high flexibility to a stronger focus on cost-efficiency. Thus, a challenge is to manage this change toward more process innovation to run operations more cost-efficiently.

Be aware of the stages of innovation, proposed by Utterback and Abernathy (1975), and what characterizes them, as these can explain both PowerCell's current and upcoming situations. Acknowledge the need for emphasizing different performance objectives in the different stages, for example, that flexibility is needed in the first stage but not as much in the subsequent stages. Thus, do not make too large investments in being extremely flexible as this will not be as needed in the future. Furthermore, the subsequent stages encompass a stronger cost focus than the first stage.

49. *Two-way, ad-hoc, rich, and late, communication between the Operations department and other departments:* As described by Wheelwright and Clark (1992), communication between two departments can be characterized by four dimensions. The communication between the Operations department and the Engineering- and Sales department is two-way; the Engineering releases product updates frequently and the Operations department communicates in the form of requirement lists for new products, change requests, and quality deviation reports.⁷ Additionally, the Sales department notifies the Operations department about customer orders and the Operations department accepts the order and then proceeds with manufacturing orders. The communication is ad-hoc in that there are no frequent formal meetings between the groups. However, the quality team has recently established biweekly meetings with product owners and customer support, discussing quality deviations.⁷ The communication is done using rich media, usually via face-to-face communication, and documents for formal requests.² Furthermore, communication is typically late rather than early from the Engineering department to the Operations department, there is not much communication between different product releases.⁶

A challenge associated with the communication characteristics is that cross-functionality is not fully achieved. The lack of recurring formalized communication and the late communication results in product updates from the Engineering department that have not always been discussed with the Operations department.⁶ This could induce manufacturability issues and issues for the purchasing team, as lead times for components are typically relatively long.⁴ It can also mean that certain components that are not needed in the new product revision are still sourced. Furthermore, the communication characteristics between the Sales- and the Operations department lead to challenges in ensuring that products sold are specified correctly and are manufacturable.⁶

There is a need for more formalized meetings and information exchange between departments, as communication is currently relatively ad-hoc. It is also important, as stressed by Wheelwright and Clark (1992), to establish communication as early as possible in the processes; for example, if the Engineering department updated the Operations department regarding product development, it would simplify the purchasing activities. This type of early communication would also lead to more opportunities for receiving feedback on the product design, thus possibly improving product quality. Furthermore, a standardized meeting structure should be established, with systemized ways of escalating issues in the organization.

50. *Product development and production mainly according to sequential engineering:* Different steps of the product development and manufacturing processes are in general not done in parallel, but rather one step after the other, in a traditional, sequential engineering, manner.⁷ The information is shared mainly upon completion of different

stages of development rather than continuously, and prototyping is mainly done solely by the Engineering department rather than in collaboration with production. However, certain aspects of integration are present, reflected in the product revisions not being fully complete when released, but this is not an organized way of pursuing concurrent engineering.

A challenge associated with this is that utilizing sequential engineering typically leads to insufficient product specification and, subsequently, product modifications and manufacturability issues, as stressed by Syan and Menon (2012). This can be seen at PowerCell, due to the sparse communication between the Operations department and the Engineering department between product updates. Additionally, releasing incomplete products might seem like a step towards concurrent engineering, however, this seems to be driven by reducing the time to market rather than to implement a thorough feedback loop.

Try to integrate the different parts of product development, prototyping, and manufacturing and exchange information frequently, to work more with concurrent engineering (Syan & Menon, 2012). Utilize the prototyping stage to thoroughly test new products and get feedback from production on it, to ensure complete products are released.

51. Manufacturability has previously not been embedded in product development: Most products are difficult to produce as the aim of product development has been to maximize performance or meet customer requirements rather than to make the products easy to manufacture.³ One reason is that most standard products originate from previous Applications projects that aimed to meet specific customer needs.¹¹ Furthermore, internal customers are typically not as highly prioritized as external customers.⁷

A challenge associated with this is that if production volumes increase, the issue regarding manufacturability will likely be amplified and result in excessive production times and risk of quality issues. Currently, manufacturing products requires a lot of expertise and cognitive effort from operators, and problem-solving is needed on an ad-hoc basis.⁶ As the organization grows, it might be difficult for new operators to handle these types of issues. Furthermore, the lack of manufacturability might make it difficult to standardize the production process into clear production steps, as stressed by Wheelwright and Clark (1992).

Try to work with DFMA, to enhance the manufacturability of products (Gupta & Kumar, 2019). For example, continue exploring modularity in products, perhaps sub-modules could be utilized alongside the larger modules comprising the PS200 system. More modularity would increase flexibility in a relatively cost-efficient manner, aiming for mass customization by combining different standard sub-modules into customized products. Furthermore, increasing modularity might facilitate the Applications

department's projects, as it would make it easier for them to modify standard products rather than building wholly new products. It could, for example, be investigated which parts of the standard products that the Applications department typically needs to modify and try to make these easier to disassemble from the products. DPD can also be investigated, trying to standardize the first parts of the production process and differentiating products later in the process (Bortolini et al., 2023). Another alternative could be to utilize ATO, as described by Jonsson and Mattsson (2017), by producing modules to stock and then assemble these in accordance with customer orders.

52. Most products that are considered standard are previous Applications projects: Products considered standard are commonly derived from Applications projects developed for specific customers.¹¹ This is because it became apparent that they functioned in other applications as well, leading to reduced product development costs.

A challenge associated with standard products derived from specific customer orders is that there is a risk that these products might not be what complies the most with customer requirements. There is also a risk that these products were not designed to be easily manufactured. If production volumes and the number of customers increase, if PowerCell's standard products do not align with the desired requirements of a majority of customers, many will request some level of customization.

Aim for customizing products by modifications of standard products, rather than developing completely new products for each customer project. With more customers, it becomes more important that the products considered standard respond well to most of the customers' requirements, as PowerCell will not be able to be as flexible as they currently are in the future.

53. Although components are standard, fuel cell system assembly requires a substantial number of components, leading to a complex assembly: The fuel cell systems are built of standard components; however, they require a lot of these components.⁶ This leads to a complex assembly and the operators require a lot of knowledge, apart from the design and manufacturing drawing, to assemble the fuel cell system. This enables customization, as components can be combined in various ways.

A challenge associated with this is that the substantial number of components required for fuel cell system assembly requires much manual handling, which is time-consuming and poses a risk for quality issues.⁶ If production volumes increase, the number of operators will likely increase, and then, it will be challenging to have work tasks that require that level of cognitive effort.³ Furthermore, having many components results in an increased workload for the purchasing team and reduces the opportunity for consolidating volumes when sourcing.⁴ It also entails more complexity in the warehouse.

Aim for reducing the total number of components in the product design, and to find more common components, for example, using one type of screw in multiple products or parts of the production process. Using common components will enable consolidation of volumes, thus facilitating price negotiation with suppliers (Slack & Lewis, 2020). Furthermore, pre-assembled sub-modules can potentially be bought directly from suppliers, facilitating the assembly process and reducing PowerCell's production time.

54. The PS200 system is module-based: The PS200 system was designed to be divided into three modules, facilitating an easier assembly that can be divided between different operators.² This enables flexibility, both for operators and for offering customers modified versions of the PS200 system.¹¹

No challenge has been associated with this strategic decision, however, modularize products to a larger extent, for example, by ensuring that all products are modular. Furthermore, sub-modules can be explored.

55. Operators are broadly specialized in working with stacks, systems, or testing, but have general knowledge within those areas: Employees in the production system work either with stack production, system assembly, or testing activities.⁵ However, within these areas, they can perform multiple tasks.

A challenge associated with this is that if production volumes increase, it can be challenging in terms of production time and quality to maintain the same level of general knowledge among operators. The high degree of generalization typically leads to more errors in production and a substantial part of work is commonly non-value-adding (Slack et al., 2013). Currently, operators in the production system spend a lot of time on problem solving, as tasks are relatively complex, which reduces the time spent on productive work.⁶ This is due to the newness of the products and the required flexibility, however, if production volumes increase and the level of flexibility decreases, a sustained high degree of generalization could obstruct productive work. However, in PowerCell's current situation, the level of generalization corresponds well to the high flexibility needed in the production system.

Develop the workforce in accordance with the successive standardization of the production system and the stages of innovation, as discussed by Utterback and Abernathy (1975). Thus, the operators will need to be more specialized as production volumes increase.

56. No detailed work instructions in production: There are no detailed work instructions in production, partly because the aim is to have enough detail in the design and manufacturing drawings, and partly because the operators currently have a high degree of knowledge in how to build the products.⁶ Furthermore, as products are frequently

updated, it would be time-consuming to create and update work instructions accordingly.³

A challenge associated with this strategic decision against using work instructions was based on the expectation that design and manufacturing drawings would be self-explanatory, however, that is not currently the case.⁶ Therefore, even though operators have a high degree of knowledge, it is challenging, reducing the time of value-adding work. If production volumes increase, the number of operators will likely increase. Without detailed work instructions, this will probably lead to more quality issues and a prolonged production time as operators must memorize the production steps. Furthermore, if additional shifts are implemented, issues can arise in shift handovers and excessive cognitive effort required during the night shift.³

In PowerCell's current situation, work instructions could be explored as a way of establishing internal standards, facilitating organizational alignment. However, when additional employees or shifts are required, work instructions are needed to ensure consistency in the production process.

57. Frequent product updates: The Engineering department releases new product versions frequently, one annual release per year and multiple smaller product revisions.² This is done partly in response to quality issues and partly to meet additional customer requirements. Furthermore, some products that are released are not fully complete yet, as a short time to market is aimed for.⁶

A challenge associated with the frequent product updates is that it requires a high degree of flexibility in the production system. The purchasing team must frequently ask suppliers for changes in orders, and incoming components can be obsolete upon arrival.⁴ In the warehouse, it can be difficult to track which components are needed and which are not needed, and the frequent product updates complicate the inventory transactions in Monitor. Furthermore, in production, if a product update is released during completion of a specific customer order, a question arises regarding whether to ship the previous release or re-work and ship the new release.⁸

It should be clearly communicated throughout the organization what implications a product update has for the production system; for example, which material is needed, what is to be produced, and what to do with material used in the previous product revision.⁷ Furthermore, there should be an internal standard regarding how to manage ongoing orders that are affected by a product update.

4.2.6 Strategic Production Planning & Control Decisions, Associated Challenges & Initial Solutions

The following section describes the strategic decisions made at PowerCell within the strategic production planning and control decision area. Furthermore, challenges associated with these decisions and initial solutions to these challenges are presented.

The content of this section is based on the theory presented in section 2.3.6 of this report, interviews, and observations.

58. Time-controlled planning where each order is planned separately: Planning is done in a time-controlled rather than tact-based manner in the production system. One example of how time-controlled planning is utilized at PowerCell is in the lab area, where FAT testing schedules are established to plan which fuel cell systems will be tested when.⁹ Another example is the time-controlled planning of material picking, where a certain date is set for when the material should be available for production.⁴ This is done as work content is not yet consistent in the production system and, thus, to be able to adapt production to each order.

A challenge associated with using time-controlled planning is to synchronize flows, as this type of planning can cause an uneven workflow with fluctuating utilization (Bellgran & Säfsten, 2010). With PowerCell's products being non-standard, and unexpected events occurring frequently, a time-controlled planning method is challenging as the plans often need to be adjusted. Additionally, time-controlled planning makes it difficult to be flexible in production and adapt to unexpected events that occur. The time-controlled planning implies excessive time being spent on establishing time schedules that often must be revised.⁹ If production volumes increase, this challenge might become less important given that the products become more standardized. Then, there would be less uncertainty in using time-controlled planning.

Try to achieve higher flow efficiency by utilizing more aspects of tact-based planning, as plans currently need to be revised very often. Tact-based planning can also be beneficial when the production system is more standardized, as the predictability facilitates an even product flow. Tact-based is, according to Bellgran and Säfsten (2010), suitable to use when set-up times are short, which is the case for PowerCell and their mobile production system.

59. Production planning and control has recently switched from using MTO to MTS: The production system has previously worked in an MTO manner, however, during 2023 they switched to working according to MTS by producing products according to forecasts.⁵ This has not yet been fully adapted, leading to an unstructured hybrid approach.³ The decision was made partly to let operators practice building products, enabling a more consistent quality and smoother production flow, and partly to be able to quickly meet customer demand by having products ready in stock.⁵

A challenge associated with the decision to implement MTS is that it seems like employees have different perceptions regarding whether this approach is utilized or not. Some indicate that MTO remains the primary approach, while others highlight the utilization of MTS. Furthermore, MTS is, according to Jonsson and Mattsson (2017), suitable for large production volumes and low variation among products, which

contradicts PowerCell's current situation. Therefore, the utilization of MTS is currently challenging, entailing high costs and the risk of obsolete inventory, as products are frequently revised. If production volumes increase, using MTS might become a suitable approach given that products are more standardized or modular designs are further implemented. Another challenge is that one of the reasons for implementing MTS was that operators should learn how to produce the products with consistent quality, however, the total number of products will still be the same, unless products become obsolete and scrapped. Furthermore, the implementation of MTS has contributed to PowerCell having a substantial inventory value.⁵

Find a hybrid approach that is suitable for PowerCell's situation. For example, prioritize standardizing certain modules that are typically not customized. These modules can then be produced in an MTS manner, while modules that are often modified can be produced according to MTO. Then, an ATO approach could be used to assemble the stock-kept modules. However, if MTS is further utilized, order points and order quantities should be established for the products.

60. Invested in a tool for fuel cell stack production to prepare for increased production volumes: PowerCell recently invested in a highly specialized tool dedicated to processing the plates in fuel cell stacks, to facilitate speed and quality in fuel cell stack production.²

A challenge associated with this investment is that it contradicts the strategic decision of pausing automation of other parts of the fuel cell stack production. This contradiction stresses the importance of deciding regarding the direction of future fuel cell stack production, which was emphasized by multiple respondents. Depending on which type of production, in-house or sourced externally, is chosen for future fuel cell stacks, this could potentially be an excessive investment. However, it contributes to enhancing the quality of the in-house fuel cell stack production.²

A decision must be made regarding how future fuel cell stack production should be conducted, to see if additional investments should be made in the internal production process or not.

61. A push production system is utilized with certain aspects of pull: The production system is mainly based on time-controlled planning, for example in FAT testing and material picking, indicating a primary focus on a push approach.⁵ However, in fuel cell stack production, the line stocking approach is a way of replenishing according to usage of material, meaning that a pull system is used for this process.⁴ Utilizing a push approach in the production system can be a result of the high degree of customization, making it possible to adapt to the highly customized orders.

A challenge associated with this is that it can be difficult to use push production when plans frequently must be revised. Not adapting the material flow to the actual

consumption can lead to inventories and queues in the production system, as emphasized by Bellgran and Säfsten (2010). This might lead to excessive planning and over-doing certain things, thus, the two Mudas over-processing and overproduction.

Implement aspects of pull production to avoid Muda and to expose errors in the production process. A pull production system can be suitable regardless of the degree of customization. For example, PowerCell could limit the number of kitting wagons or LIM wagons in the production system. Then, an empty wagon would act as a Kanban signal, as described by Tarantino (2022), indicating a need downstream in the production process and initiating a picking operation or the mounting of a new fuel cell system on the LIM wagon. Furthermore, if all wagons are full, this would visualize a bottleneck in the production process.

62. Material picking is done by kitting components for the fuel cell systems: Warehouse employees kit material for the fuel cell system production.⁴ The kitting is done according to manufacturing orders, and depending on its size, the kits contain material for either the entire manufacturing order or for certain production steps. The production team leader requests material to be picked from the warehouse according to pre-set dates based on information from the ERP-system Monitor. The kitting is done to ensure that operators have the correct material at the right time, increasing quality and dependability.

A challenge associated with the material kitting is the dates set for completion of this activity, as these are not always accurate, due to unexpected events occurring.⁴ Thus, complete kits waiting to be used in production form queues. If production volumes increase, this type of material kitting means that more material could possibly form queues and an alternative way of kitting material might be needed. Another challenge related to material kitting is that it is time-consuming for warehouse employees to pick individual screws and nuts needed for the kits (Black, 2008).

If certain components in the products are standardized, it will be possible to have small stocks at each workstation with the most common components, which can be replenished according to line stocking as described by Jonsson and Mattsson (2017). This could potentially reduce the control of the consumption of components, leaving room for errors in production as operators will not have the exact material to be used for each production step. However, it reduces the time spent on picking material.

63. Material picking is done in a picker-to-material manner: Warehouse employees pick material in a picker-to-material manner.⁴ This is due to the production system being relatively new and the warehouse area not being that large.

A challenge associated with the picker-to-material approach is that if production volumes increase, and if the warehouse area is expanded, this approach might be too time-consuming.

If the warehouse area is expanded, aspects of material-to-picker could be implemented to reduce the time spent on material picking. Methods such as pick by voice and pick to light, as described by De Vries et al. (2016) can be explored to increase quality and productivity of the picking process.

64. Material picking is done with line stocking in the fuel cell stack production area: A small inventory of material is placed in the fuel cell stack production area.⁴ Warehouse employees pick material for the fuel cell stack production continuously, as material is used, refilling the inventory when needed. This is done to ensure that operators always have the correct material.

A challenge associated with the line stocking approach in fuel cell stack production is that it reduces the warehouse employees' control of inventory levels.⁴ When a faulty component is discovered in the separate fuel cell stack production area, this might not always be reported to warehouse personnel who can update inventory levels in Monitor accurately.

The system for handling inventory transactions in Monitor in all parts of the production system should be standardized, to ensure that inventory levels are accurate. This will be of especially high importance if production volumes increase.

65. Fuel cell systems are mounted on LIM wagons for the testing activities: When fuel cell systems are assembled and ready to be FAT tested, they are mounted on LIM wagons.³ This process takes approximately two hours and is done by the operators in production. Then, testing employees proceed with the FAT tests.⁹ This is done to test the fuel cell system in its entirety, to ensure the highest quality.

A challenge associated with mounting fuel cell systems on LIM wagons is that it is time-consuming and does not add any value to the product.³ Furthermore, the mounting process is physically challenging as the fuel cell systems are heavy.⁹ If production volumes increase, this challenge will be amplified. Furthermore, with increased production volumes, increasing capacity of the lab area might be required, and if the mounting process is not improved accordingly, this could become a bottleneck. Additionally, as products mature, testing all modules as a final assembly in the lab area might be unnecessary, being time-consuming and costly.³ Mounting all modules on LIM wagons could also be considered a Muda in the form of over-processing.

As discussed in solution 33, it should be explored if every module must be tested in the lab area. If only fuel cell modules are tested in the lab area, LIM wagons could presumably be smaller, and the mounting process would become quicker and less physically demanding. An alternative way of facilitating the mounting process is to have the fuel cell systems mounted on the same wagon throughout the whole production system; thus, assembling it on the same wagon that it is tested on. This would save time

and make it easier to transport the fuel cell system between different stages of the production process.

4.2.7 Mapping Strategic Decisions in the Proposed Integrated Framework

Below, in Figure 4.3, the identified strategic decisions are mapped in the Proposed Integrated Framework. The strategic decisions are positioned according to the strategic decision area they belong to and the performance objective they aim to achieve.

		Resource Development						Market Competitiveness
Performance Objectives	Quality	4, 9, 10	15, 18	19, 20, 21, 22, 23, 26	27, 28, 30, 32, 33, 37, 41, 44, 46	54, 55, 57	59, 60, 65	
	Speed	9	17	21	43, 45	49, 56, 57	59, 60, 64	
	Dependability	8	17	25, 26	38, 39, 42, 43		62, 64	
	Flexibility	1, 2, 5, 6	16	24, 26	34, 35, 40	48, 51, 54	58, 61	
	Cost	2, 3, 6, 7	11, 12, 13, 14, 15	19, 20, 21, 25	29, 31, 36, 47	49, 50, 51, 52, 53, 55, 56	61, 63	
		Production process	Capacity	Supply Network	Quality Management	Development & Organization	Production Planning & Control	
Decision Areas								

Figure 4.3: *Mapped strategic decisions in the Proposed Integrated Framework.*

4.3 The Most Prominent Challenging Areas Related to PowerCell’s Production System

The following section presents the most prominent challenging areas related to PowerCell’s production system, answering RQ3. These challenging areas were identified by conducting a thematic analysis of the challenges associated with each strategic decision presented in section 4.2 of this report. Consequently, overarching challenging areas could be recognized.

4.3.1 Insufficient Cross-Functional Communication

Several challenges associated with the strategic decisions indicate that there is insufficient cross-functional communication at PowerCell, affecting the interfaces between the production system and other departments. This is reflected in the meeting culture, where most cross-functional meetings are held on a project- or ad-hoc basis, as discussed in decision 49. Additionally, information from upstream groups to downstream groups is shared late rather than early, leading to challenges for the downstream groups. Furthermore, deliveries to internal customers are sometimes underemphasized in the organization, according to decision 36, leading to insufficient handovers between functions. This makes it difficult to deliver the right quality and makes internal processes more time-consuming, as the input to the process is not optimized for the process.

If production volumes increase and the organization grows, the challenge of insufficient cross-functional communication will amplify. For example, the lack of formal forums

for cross-functional discussions and improvements will be challenging, as the current situation requires that employees know each other well and are comfortable reaching out cross-functionally. When PowerCell has more employees, it is likely that employees will primarily reach out to their closest coworkers, risking organizational silos and reduced cross-functional discussions and improvements. Additionally, as discussed in decision 44, there is insufficient usage and acknowledgement of the process flow charts in the organization. As process flow charts could be a way of facilitating cross-functional work and understanding by informing employees regarding how different processes relate to each other, this could be a missed opportunity for increased cross-functional communication.

The ERP system Monitor is used as a common platform for sharing information in the organization, however, it is not yet fully utilized, as discussed in multiple decisions. There are several challenges that in some way relate to Monitor, for example, ensuring that everyone in the organization is aware of it and uses it. Furthermore, Monitor must be updated with accurate information, such as inventory levels and correct part numbers when product updates are released. If employees cannot trust that Monitor provides accurate information, they might be resistant to use it.

The insufficient cross-functional communication at PowerCell constitutes a prominent challenging area, as it affects the production system in numerous ways. Furthermore, this challenge will likely be amplified if production volumes are increased.

4.3.2 A Lack of Clear Production Strategy Obstructs Development of the Production System

According to respondents, it seems like some strategic decisions made related to the production system have been ad-hoc and without a clear overarching strategic direction. One example of a strategic decision of which the aim seems to be differently interpreted by respondents is the decision of sourcing one type of fuel cell stack from Bosch, as discussed in decision 21. Some respondents mean that this is done to reduce the costs of production of these fuel cell stacks in-house, however, some mean that is uncertain whether this decision is cost-efficient and that it is a risk to not keep the core competence of producing fuel cell stacks in-house. Another example of a decision without a clear objective is the decision to pause the development of robotics in fuel cell stack production. As the future production of fuel cell stacks is not decided about, pausing the robotics development indicate that automating the fuel cell stack production will need to be restarted and likely delayed if production volumes increase, as elaborated in decision 7. Contrastingly, investments have been made in special tools for the stack production, as discussed in decision 60, and thus, exploring in-house production of the fuel cell stacks. These examples indicate that there is a lack of decisions about how to direct the future production system; what to develop, what to produce, and what is actually considered the core competence of the company.

Furthermore, strategic decisions and organizational priorities seem to not always align with PowerCell's current situation. For example, cost is strongly emphasized, however,

according to Utterback and Abernathy (1975), a strong focus on cost-minimization is advised first in a later stage of development. If over-emphasizing cost-efficiency too early, it could potentially obstruct the performance-maximizing stage of development. Furthermore, when choosing suppliers, cost and quality are two important deciding factors, as discussed in decision 19, meaning that PowerCell aims for an efficient supply network. However, as argued by Chopra and Meindl (2013), the high demand uncertainty that PowerCell is facing indicates that a responsive supply network should be aimed for, to be able to flexibly and quickly get components. The efficient supply network is challenging for PowerCell as the frequent product updates entail a need to often change purchasing orders. Furthermore, having too strict cost-focus regarding the supply network can obstruct joint innovation with suppliers. Another performance objective that is strongly emphasized is speed, in terms of reaching the market quickly and delivering products to customers quickly. However, this focus seems, according to respondents, to potentially be over-emphasized, as customers are often not ready to receive the products when PowerCell are ready to deliver them, as discussed in decision 24.

The lack of a clear production strategy leads to difficulties in developing the production system, as it does not provide a clear direction to aim for. Thus, this is a prominent challenging area related to PowerCell's production system. Furthermore, this challenge will be amplified if production volumes increase, as the production system might not be developed in a clear direction, hence it might be difficult to handle the increased volumes.

4.3.3 Low Degree of Manufacturability of Products

Multiple challenges are related to the low manufacturability of products. The low degree of manufacturability affects the production system substantially, as it increases the production time, number of errors, and complexity of fuel cell system assembly. Furthermore, it requires high cognitive effort from operators in production. The complex assembly process is a result of each product composing a substantial number of components, as seen in decision 53, which also affects the warehouse employees, as it complicates the material picking process, as discussed in decision 62. One example of a product with low manufacturability is the PS100 system, as discussed in decision 3, which requires a dedicated operator to assemble it from beginning to end. This leads to a long production time and many situations where errors could occur, as the employee pauses and restarts the assembly multiple times before the fuel cell system is completed. Furthermore, some standard products originate from Applications projects and were developed according to specific customer requirements, as discussed in decision 52. Hence, these were developed more in accordance with market requirements than with operational capabilities.

The low degree of manufacturability constitutes a prominent challenging area, as it obstructs an efficient production process. Furthermore, if production volumes are increased and the low manufacturability of products remains, the challenges associated with this will likely be amplified.

4.3.4 The High Degree of Customization Obstructs Managing Increased Production Volumes

The high degree of customization, discussed in decision 35, affects the production system significantly, as it obstructs the standardization and automation of production processes. Instead, the high customization requires a high degree of flexibility in the production system, as discussed in decision 5. This is further reflected in the decision to serve multiple available customer segments, as discussed in decision 34, requiring a flexible production system. This decision induces a risk of not fully fulfilling the customer requirements of each segment. Furthermore, PowerCell is currently in an early stage on the product process innovation curve as proposed by Utterback and Abernathy (1975). Hence, PowerCell places a strong focus on product development, with frequent product updates, rather than process development, as discussed in decision 48 and 57, which obstructs standardizing the processes in the production system. Another aspect of the high degree of customization is that PowerCell prioritizes adhering to specific quality standards to meet specific customer requirements, as seen in decision 28.

If the production system should be able to handle increased production volumes in a cost-efficient manner, a lower degree of variety must be achieved, according to Slack et al. (2013). Therefore, it will be difficult to continue with the same high level of customization if production volumes are increased. Also, Slack and Lewis (2020) mean that a production system should increase its process technology usage, such as automated tasks, as the volume increases, however, this requires a reduction in variety. Furthermore, the long-term development projects with customers, as discussed in decision 26, will be costly if production volumes are increased.

The high degree of customization constitutes a prominent challenging area, as it obstructs the standardization of the production system, thus, obstructs shaping the production system in a way that can accommodate increased production volumes cost-efficiently. Hence, this challenge is likely to be amplified if production volumes are increased.

4.3.5 Inadequate Quality Management Efforts

Despite several ways of working with quality, PowerCell's production system lacks clear and comprehensive quality management work. This is reflected in the absence of a defined desired level of quality, as elaborated in decision 27. The lack of a desired level of quality causes misalignment in the organization, as it is not clear which quality to aim for in, for example, design and manufacturing drawings, which is the primary input to the production process. The sometimes-insufficient design and manufacturing drawings make it difficult for suppliers to know which quality is required, which in turn results in errors that could have been avoided with a defined desired level of quality. Additionally, this requires warehouse employees to put a lot of time into performing arrival controls and searching for errors that could have been avoided by a more detailed design and manufacturing drawing. Another challenge is the frequent product updates, which sometimes result in non-complete products being released, as discussed in

decision 57. Furthermore, the lack of a defined desired level of quality makes supplier evaluation, discussed in decision 23, challenging, as it is difficult to know what to require and what to evaluate suppliers on.

Another aspect of the quality management work is that PowerCell primarily has a reactive quality approach in the production system. This is reflected in production and in the FAT testing, as discussed in decisions 31 and 33. Certain aspects of proactive quality management have been introduced, such as the arrival control in the warehouse, which makes it easier to achieve higher quality. However, this can also be viewed as a reactive approach, as, if the design and manufacturing drawings were more specific, quality errors could be captured even earlier. The reactive quality approach poses challenges for PowerCell, as it leads to rework and error-searching when issues are detected.

Currently, a high degree of cognitive effort is required from operators in production, partly due to the lack of work instructions elaborated in decision 56, and partly due to the low manufacturability of products. The operators possess much technological expertise; however, the high degree of manual work increases the risk of quality issues. Furthermore, if production volumes increase and shifts are added, there will be a need to reduce the cognitive effort required from operators, to secure the highest quality.

The inadequate quality management efforts constitute a prominent challenging area for the production system, as respondents agree that quality must be a higher priority in the organization to be able to handle increased production volumes. Furthermore, insufficient quality affects the whole organization.

4.3.6 Non-Value-Adding Work in the Production System

According to respondents, much time in the production system is spent on non-productive work, such as problem solving due to unexpected situations occurring in the production process. For example, as errors often occur in the production process, operators spend much time searching for a way to solve these problems, an activity that does not add value to the product. If problems are solved on an ad-hoc basis without operators reporting them, there is also a risk of the same problem recurring, leading to additional time spent on problem solving.

PowerCell often adheres to specific quality standards required for certain customer projects. These standards require much work from PowerCell; however, they do not always contribute to the internal quality work at PowerCell, meaning that these quality standards mainly add value to the customer rather than to PowerCell's internal quality work.

Another example of a decision risking non-value-adding work at PowerCell is the time-controlled planning, described in decision 58, which requires the time schedules to be revised often. This means that much time is spent on changing schedules, which is considered non-value-adding work. Additionally, as PowerCell's production system has push production characteristics, planning must frequently be revised, leading to

Muda such as over-production and over-processing, as elaborated in decision 61. Furthermore, the decision to change from MTO to MTS, as discussed in decision 59, can lead to obsolete inventory due to the frequent product updates.

An additional area where there is a risk of non-value-adding work is the testing activities. Firstly, as fuel cell systems are mounted on LIM wagons, substantial time is spent on the mounting process, as elaborated in decision 65. Here, no value is added to the product, as it is only prepared for entering the lab area. During the FAT test, the whole fuel cell system is tested, as discussed in decision 33. Therefore, if an error is discovered, considerable effort is required to disassemble the fuel cell system, conduct error analysis, and subsequently undertake necessary rework based on the identified error. Then, after the FAT test is conducted, the fuel cell system must be detached from the LIM wagon, which is also a time-consuming activity that does not add any value to the product.

The non-value-adding work in the production system is a prominent challenging area, as it means that much time is spent on activities that do not contribute to adding value at PowerCell. If production volumes increase and this challenge is not addressed, it will be very costly to run the operations.

4.4 Proposed Strategic Direction for PowerCell

The following section provides guidance on strategic decisions PowerCell can make to overcome the identified prominent challenging areas presented in section 4.3, and to develop the production system in a way that supports increased production volumes.

4.4.1 Proposed Strategic Direction to Address the Insufficient Cross-Functional Communication

To improve the interfaces between the production system and other departments at PowerCell, several strategic considerations are proposed. First, formalized cross-functional forums should be established. For example, utilize regular meetings between functions to facilitate communication, collaboration and problem solving. This could improve cross-functional interaction in terms of level of frequency and timing, as discussed by Wheelwright and Clark (1992). These types of forums should be established between the Operations department and the Engineering-, Sales-, and Applications departments, as these are interfaces where challenges occur. Furthermore, PowerCell could work with structured feedback sessions, where groups can discuss previous interactions in terms of what went well and what can be improved. Another thing that can be explored is workshops, seminars, and team-building exercises to lower the barriers for cross-functional communication.

Second, PowerCell should aim to improve information sharing practices, by implementing routines and procedures for information sharing between groups. Encourage a culture of proactive communication where relevant information is shared early to avoid delays and challenges for downstream groups (Wheelwright & Clark, 1992). Furthermore, ensure that internal customers are prioritized, optimizing processes

to deliver the right quality to the downstream groups (Modig & Åhlström, 2015). Additionally, encourage the usage and acknowledgment of process flow charts to facilitate cross-functional understanding and collaboration (Kelemen, 2003). More acknowledgment of process flowcharts will further increase mutual understanding in internal customer-supplier relationships. Another thing that should be encouraged is the utilization of Monitor. Ensure that all employees are fully aware of the ERP system, Monitor, and are trained to effectively utilize its functionalities.

This strategic direction would ensure that a solid base for organization-wide communication is established before the organization grows too much. Furthermore, it would ensure that handovers are more suited for the recipient, which will also reduce the non-value-adding work, as discussed in section 4.3.5. It would make it easier to align and strive for the same goals, for example regarding a desired level of quality. It would also provide opportunities for bringing up topics that would not fit into the current modes of interaction, such as the requirement lists, change requests, and quality deviation reports.

4.4.2 Proposed Strategic Direction to Address the Lack of Clear Production Strategy Obstructing Development of the Production System

To be able to make suitable strategic decisions for the production system, it is important that the strategic objectives for the production system are defined and communicated clearly. This is important as respondents have expressed ambiguous perceptions regarding strategic decisions, and it is also a prerequisite for developing a comprehensive production strategy with organizational alignment. PowerCell should ensure that decisions are based on a comprehensive analysis and alignment with the overall business strategy. Additionally, the business strategy should be clearly formulated and communicated across the organization, to provide a basis for the production strategy. Furthermore, cross-functional collaboration among key stakeholders should be fostered to facilitate consensus-building and informed decision-making. Additionally, it is important that employees at all levels understand the strategic direction of the production system and are empowered to contribute towards its realization.

When defining the strategic objectives, it is of high importance that PowerCell evaluate their core competencies and determine which aspects of production should be retained in-house for strategic reasons (Chopra & Meindl, 2013). Here, factors such as technological expertise in the form of core competences, intellectual property, and strategic importance should be considered when making decisions (Chopra & Meindl, 2013; Slack & Lewis, 2020; Uygun et al., 2023). For example, for smaller components needed for fuel cell system assembly, PowerCell does not possess the technological expertise. Furthermore, these do not risk intellectual property leakage, and the components are of low strategic importance. Thus, the smaller components could be externally sourced, potentially in submodules, as discussed in previous sections. For fuel cell stack production, this is considered a core competence by most respondents, as PowerCell possesses world-class technological expertise in this area. If using a

supplier to produce the fuel cell stacks, the physical separation between product development and production will reduce the amount of feedback, risking losing the technological expertise. By sourcing some fuel cell stacks externally, there is a risk of intellectual property leakage. Additionally, fuel cell stacks are considered the most important part of PowerCell's products, thus, they are of high strategic importance. Therefore, fuel cell stacks should be considered to be developed and produced in-house. This is further strengthened by Bellgran and Säfsten's (2010) argument that a company developing a product but externally sourcing the production risks insufficient feedback and, therefore, an inferior product.

Additionally, PowerCell should ensure that strategic decisions align with their current situation. They should, for example, strive to determine which development stage they are currently in, in terms of product- and production development. Furthermore, they should be aware of which stages are ahead, and what these stages imply in terms of strategic objectives. For example, the first stage of development is characterized by uncoordinated processes, product innovation and manual work, requiring flexible organization (Utterback and Abernathy, 1975). However, the subsequent stages have a stronger emphasis on process development and cost-efficiency, wherefore flexibility typically is not as important. As PowerCell approaches the next stage of development, strategic decisions should be influenced by these aspects. Therefore, high flexibility has been needed in the production system, however, the degree of flexibility will need to be reduced to enable more cost-efficient operations. Thus, PowerCell's current emphasis on cost-efficiency might not yet be needed and could potentially obstruct developing the best product, however, it will be required in future stages of development. This does not mean that PowerCell should stop being cost-focused, however, they should beware that this could compromise reaching the best technical solution in their current stage of development (Utterback & Abernathy, 1975). If production volumes increase, it will be more important to focus on cost-efficiency.

Another performance objective that should be considered is speed, as this is currently highly emphasized. While speed is beneficial for both internal processes and reaching the market quickly, it is currently compromising quality, as product updates are sometimes released before completion. Furthermore, PowerCell are typically ready to deliver products before customers are ready to receive them, implying that speed is over-emphasized. Therefore, to achieve a more leveled production with less fluctuations in workload, tact-based planning could be used (Bellgran & Säfsten, 2010).

Another aspect of adapting strategic decisions to the current stage of development is to recognize the importance of supply network responsiveness, as PowerCell faces demand uncertainty and rapid product development. Therefore, PowerCell should aim for a responsive supply network approach, to have suppliers that are flexible to respond to late order changes, both in terms of quantity and type of goods (Chopra & Meindl, 2013). This implies shifting from a cost-focused approach to supplier selection towards a more balanced approach that also emphasizes flexibility and supplier collaboration. PowerCell should furthermore foster strategic partnerships with suppliers that are

considered critical to enable joint innovation and enhance stability in the supply network (Slack & Lewis, 2020).

This strategic direction would ensure that the production system and the production strategy develop in alignment with the business strategy. If the strategic objectives are chosen based on PowerCell's current stage of development and clearly communicated throughout the organization, employees could more easily strive toward common goals. Furthermore, if informed decisions regarding whether production activities are done in-house or externally sourced, core competencies can be exploited to their full potential, leading to a technological edge in the market.

4.4.3 Proposed Strategic Direction to Address the Low Degree of Manufacturability of Products

To address the low degree of manufacturability of products, there is a need to approach the challenge from two directions: in terms of product design and in terms of production preconditions. First, PowerCell should work with product design optimization with a close collaboration between the Engineering department and the Operations department to enhance the manufacturability of products. Implement DFMA principles to ensure that products are designed with production efficiency in mind, as described by Gupta and Kumar (2019). Prioritize design features that simplify assembly processes, reduce the number of components, and minimize the likelihood of errors during assembly (Wheelwright & Clark, 1992). Investigate if more sub-modules can be acquired directly from the suppliers, to make the production process less complex and to not drift out of focus by producing things that are not considered a core competence for PowerCell. This can be part of the partnerships discussed in section 4.4.2, where innovative projects could be driven with suppliers to develop sub-modules for the fuel cell systems. Furthermore, if utilizing a modular design to a larger extent, certain modules that are typically not customized could be produced using an MTS approach, while the fuel cell system assembly could be done upon receiving customer orders. Another thing that can be explored is DPD, as described by Bortolini et al. (2023), where the first parts of the production process are the same for all products, and the customization is done as late as possible. This allows for standardization of the first parts of the production process without compromising the ability to customize products.

Second, improve the preconditions for the production process. As redesigning products is time-consuming, the Operations department should not wait for full manufacturability of products, but instead try to improve manufacturability in other ways. PowerCell should try to enhance the production process in a way that facilitates manufacturing, to enable consistency in production and thereby increase quality. For example, develop work instructions to ensure consistency in production and reduce cognitive effort required by operators, as stressed by Pimminger et al. (2020). Initially, work instructions can be relatively simple in paper form at each assembly station (Pimminger et al., 2020). However, as production volumes increase, digital manuals connected to the design and manufacturing drawings could be explored to reduce the

effort needed in creating and updating the work instructions when products are revised. Digital work instructions can potentially result in faster task completion time and lower perceived cognitive effort, as stressed by Eversberg and Lambrecht (2023). Additionally, ensure visibility in the production process by visualizing the production process on digital screens, to increase awareness of products' progress through the production system. Also, explore and implement Lean Production principles to reduce waste in the production process, for example, continue implementing 5S to stabilize the production process.

If working on the manufacturability challenge from both directions, thus, both in terms of product design and in terms of improving the production preconditions, manufacturability could potentially be reached quicker than if the Operations department depend solely on the Engineering department delivering complete, manufacturable, design and manufacturing drawings. Furthermore, this could help in reducing production time and improving quality. Utilizing an MTS approach for modules and assembling them according to customer orders could facilitate working with leveled production. Furthermore, methods such as DPD and modular designs help PowerCell move towards mass customization, overcoming the trade-off between flexibility and cost in the production system, as described by Slack and Lewis (2020). This strategic direction requires close cross-functional collaboration between the two departments to ensure that the development is aligned. Furthermore, to ensure that products fulfill customer requirements, other relevant departments, such as the Sales department, should also be included in discussions regarding how the products should be designed.

4.4.4 Proposed Strategic Direction to Address the High Degree of Customization that Obstructs Managing Development of the Production System

To balance the high degree of customization and developing the production system, the challenge must be addressed from two perspectives: in terms of level of customization offered and in terms of production development. First, if production volumes increase, the offered level of customization should be revised, as it will be difficult to maintain the same level of flexibility cost-efficiently. Therefore, customization could be offered to a certain extent, for example, if customer orders exceed a certain quantity. It is also important to beware that, as customers are often unsure of their own needs, customers might request specific solutions even though they do not require them. Thus, the level of customization should be limited, and PowerCell should thoroughly analyze customer requirements before starting customer-specific projects. Furthermore, it is important to evaluate the feasibility and the cost implications of long-term development projects with customers, to be able to balance the customization with the financial sustainability of such projects. This is important as these types of projects require high resource allocation and decrease opportunities for economies of scale.

Second, the production system should be standardized where possible, yet still be able to manage a certain degree of flexibility. The first step is to collect and analyze data on

customer orders, by segmentation and prioritization of customer needs. As PowerCell is currently highly responsive to all customer requirements with many customer-specific projects, it is of high importance that PowerCell analyzes their customer segments to identify commonalities in customer requirements. Furthermore, it can be beneficial to prioritize these requirements according to the most recurring ones, to be able to standardize production of products that comply with these common customer requirements. PowerCell should also evaluate which parts of the products are typically common between different customer orders. For example, if one specific module is rarely modified, production of this module can be standardized, and possibly automatized if production volumes increase. Thus, parts of the production process with high volume and low variety should be identified and standardized (Slack & Lewis, 2020).

Additionally, PowerCell should aim to align product- and process innovation, in accordance with the product process innovation curve described by Utterback and Abernathy (1975). To uphold flexibility despite uncertain future customer demands, a mass customization approach could be adopted (Slack et al., 2013). This strategy allows for standardization of specific elements in the production system, which enables increasing production volumes effectively. Ensure that product innovation facilitates process innovation, as PowerCell is approaching a transition from a primary focus on product innovation to a primary focus on process innovation. This can, for example, be done by exploring modularization to a larger extent to enable standardization of certain processes in the production system, while keeping the flexibility to meet different customer requirements, as discussed in section 4.4.2. Furthermore, DPD can also be explored to be able to standardize the first parts of the production process but still be able to offer customization. Additionally, if production volumes increase, PowerCell should incrementally increase the utilization of process technology, such as automation. Investments in technology that can offer scalability and adaptability to changing production requirements should be prioritized, as future customer requirements are still uncertain.

This strategic direction will help PowerCell ensure that they can manage the degree of customization offered in a cost-efficient way. First, the level of customization should be reduced as production volumes increase, as it will not be possible to maintain the same level of flexibility. Segmentation and prioritization of customer requirements would help PowerCell understand their customers' needs and see patterns between different customer segments. This would facilitate standardizing production of products that comply with many customer requirements, which could help reduce the number of customer-specific projects. Therefore, flexibility could be reduced in the production system without compromising meeting customer needs. Furthermore, if utilizing modularization, parts of the production system could be standardized without substantially compromising the number of variants offered to customers. Thus, this strategic direction could help PowerCell find a suitable level of flexibility and to a certain extent overcome the trade-off between flexibility and cost-efficiency.

4.4.5 Proposed Strategic Direction to Address the Inadequate Quality Management Efforts

To address the inadequate quality management efforts, PowerCell should start by establishing a clear definition of a desired level of quality and communicating this in the organization (Gremyr et al., 2020). The desired level of quality can, for example, regard which tolerances are needed, and which are critical, or which specifications regarding customer orders are required to facilitate production. The definition should be formulated cross-functionally, including representatives from multiple departments, such as the Operations-, Engineering-, Sales-, and Applications departments, to ensure alignment. As quality deviation reports and change requests are already utilized in the organization to improve quality, a defined desired level of quality will facilitate working with these reports in a structured way.

Based on the defined desired level of quality, supplier collaboration and evaluation can be enhanced. PowerCell should clearly define quality expectations and evaluation criteria for suppliers. Furthermore, the supplier evaluation process should be adapted to the criticality of the supplier, as the current evaluation criteria are very comprehensive. This is to not spend unnecessary time on the evaluation process. PowerCell should work closely with suppliers to ensure a mutual understanding of the quality standards and regularly assess supplier performance to drive continuous improvement.

Additionally, PowerCell should establish internal standards for how to work with processes, to further align the organizational way of working. Work instructions for the production process should be created to ensure consistency in production, and training could be provided to operators to reduce the required cognitive effort and improve efficiency in production operations (Pimminger et al., 2020). Furthermore, alignment could be reached by, for example, increasing the usage of quality management tools such as process flow charts (Kelemen, 2003). If production volumes increase and the production system stabilizes, control charts could be explored as a tool to statistically investigate variation in the processes and to see where interventions are needed.

PowerCell should also set up a strategy for working with quality standards. To adhere to customer requirements, a clear direction for working with quality standards should be established, as this is currently done in an ad-hoc manner. If PowerCell forms a foundation composed of carefully selected quality standards that adhere to many customers' requirements, it would be possible to cover more customers' requirements with the same quality standards. Furthermore, this foundation could be extended by smaller add-ons which might overlap to a certain degree with the already existing standards.

Another area to consider is the transition to a more proactive quality management approach. PowerCell has started to implement some aspects of proactive quality management, however, this can be further emphasized. The frequent product updates should not obstruct focusing on implementing proactive quality management efforts

but should instead be seen as an incentive. One important aspect to consider is to improve design and manufacturing drawings according to a defined desired level of quality, to reduce the number of errors, both in incoming material and in the production process. Furthermore, the testing activities could be examined to see whether certain tests could be done earlier in the production process to facilitate the error-searching process and reduce the amount of rework. The Lean Production concept poka-yoke could be explored to proactively ensure that quality is secured throughout the production process (Black, 2008). For example, sensing devices could be implemented to ensure proper positioning of components in the fuel cell systems, alerting when errors occur. Fixed-value methods are another type of poka-yoke tools that signal when production steps are done correctly, and the product is ready to proceed to the next stage of the production process.

Lastly, PowerCell should systemize the continuous improvement culture. As PowerCell currently has a strong culture of bottom-up improvement, this is important to sustain if the organization grows. Therefore, improvements should be systemized to be able to leverage collective expertise in a formalized way. This could be done by including improvement work in employees' work task descriptions, meaning that this type of work is as important and structured as any other work task. Furthermore, forums could be established for improvement ideas, to ensure that every employee would have an opportunity to contribute to PowerCell's development. To be able to align the improvement ideas in a desired direction, it is important that management communicates clear goals and milestones to reach these goals.

These different areas constitute a strategic direction for PowerCell to be able to improve quality management efforts. Firstly, defining a desired level of quality would facilitate constructing design and manufacturing drawings, which would enable easier production and less quality issues, both from suppliers and internally. Furthermore, it would be easier for the Sales department to coordinate between customer requirements and operations resource capabilities. This clarity would minimize errors and misalignments in production processes. Secondly, internal standards would increase organizational alignment regarding quality work. Thirdly, if quality standards were treated in a more coherent manner, each standard would require less individual work, and it would be easier to integrate them into the organization. Fourthly, proactive quality management is important to detect and prevent quality issues earlier in the production process, to reduce the amount of waste and rework. Fifthly, and lastly, systemizing the continuous improvement culture would ensure that this is sustained if production volumes increase, and the organization grows.

4.4.6 Proposed Strategic Direction to Address the Non-Value-Adding Work in the Production System

To address the challenge of non-value-adding work, several aspects must be considered. Firstly, ensure that problem solving in the production process results in quality deviation reports, to prevent the same issues from recurring and operators from spending excessive time on problem solving. Secondly, as mentioned in section 4.4.4,

it is important to strategically select which quality standards to adhere to, to not spend excessive time on working on standards that are only required by one customer and does not add value to PowerCell as an organization.

Thirdly, PowerCell should try to minimize variations in the production process. As variations in the production process result in operators spending substantial time on solving problems, the variations should be minimized to reduce the degree of non-value-adding work. To understand which specific activities in the production system should be prioritized to reduce variations in, it is important to try to identify bottlenecks. If a desired level of quality is clearly defined, as discussed in section 4.4.4, this would help to decrease variation on a more general level in the production system. Furthermore, PowerCell currently uses some Lean Production tools, such as 5S. This could be further explored to be able to identify and eliminate non-value-adding activities, Muda, in the production process, such as unnecessary waiting, overproduction, or overprocessing. If utilizing 5S to a larger extent, processes could be stabilized, and variations reduced.

Fourthly, PowerCell should aim for tact-based planning with a pull production approach to reduce non-value-adding work. To address the frequent revisions of schedules, a more tact-based planning approach could be utilized, rather than the current time-based planning approach. For example, ensure that activities in the production process are synchronized with the rate at which products are required, which could facilitate leveled production (Bellgran & Säfsten, 2010). Furthermore, this could be accompanied by a pull production approach, emphasizing synchronized product flow to minimize overproduction and waste. One way of implementing aspects of pull production is to work with the wagons used in the production system. The wagons used for kitting in the warehouse, and the LIM wagons used for FAT testing, could be quantitatively limited. This would obstruct overproduction as only a certain number of wagons can be kitted at the same time, and only a certain number of LIM wagons could be ready for testing. An empty wagon becomes a clear pull signal, representing a kanban signal, in the production system and triggers a response (Black, 2008). This could potentially help reduce lead times in the production system and increase the degree of tact-based planning. Furthermore, if all wagons are kitted or in a queue for FAT testing, a bottleneck can be visualized, and the preceding stage in the production process should be paused.

Fifthly, and lastly, PowerCell should search for areas of improvement in the testing activities. They could investigate the possibility of redesigning testing activities, reviewing if every module must be tested in the lab area with the FAT test, or if this, in fact, is only required for certain modules. If only the fuel cell module must be tested in the lab area, focus could be placed on developing the other modules in a way that facilitates testing these in the production area. This would free capacity in the lab area,

allowing more critical modules to be tested. It might not be possible to do this in PowerCell's current situation, but it should be aimed at as products mature. Furthermore, if only certain modules are FAT tested in the lab area, the LIM wagons might be able to be modified to only carry separate modules, which would save time in mounting fuel cell systems on them. Even if the whole product would still need to be tested in the lab area to ensure the desired quality, separate module testing could facilitate this process. Additionally, it might be possible to revise the division of labs, as three of these are currently dedicated to products with low demand. Therefore, if labs could be generalized according to electrical power, it would be possible to utilize the lab equipment in a more effective way. However, generalizing all the labs would be costly due to advanced equipment. Thus, a starting point could be to generalize the two labs that currently test the products with the highest demand. Generalizing the labs would increase the flexibility in the testing activities, and delays would not obstruct the product flow through the production system.

This strategic direction would help PowerCell reduce the amount of non-value-adding work in the production system. If variations in the production process are reduced, it will be easier to standardize production, enabling consistent quality and reduced Muda (Gremyr et al., 2020). Furthermore, if a tact-based approach is utilized, it is easier to achieve synchronized flows and a leveled production (Bellgran & Säfsten, 2010). Furthermore, if modules could be tested separately, it would be easier to search for errors, reducing the time spent on non-value-adding error-searching on wholly assembled products. The mounting process on LIM wagons would be simplified, also saving time. Additionally, if some modules could be tested in the production area rather than in the lab area, the special equipment would not be used for modules that do not require it. Hence, these areas collectively reduce the amount of non-value-adding work.

5 Discussion & Conclusions

Due to the circumstances shaping PowerCell's current production system and PowerCell's current stage of development, it is not surprising that they lack a comprehensive and coherent production strategy, even though many strategic decisions have been made. It is important for PowerCell to recognize these strategic decisions and their implications to manage increased production volumes. Furthermore, it is important to address the identified prominent challenging areas and ensure that a comprehensive production strategy that is suitable for PowerCell's situation is established.

To answer RQ1, regarding which strategic decisions have been made that shape PowerCell's current production system, 65 strategic decisions were identified. Furthermore, RQ2 was answered by associating challenges with these strategic decisions and proposing initial solutions to these challenges. Based on the results to RQ1 and RQ2, it is apparent that many strategic decisions have been made, however, not in a comprehensive manner, and sometimes the decisions contradict each other. Furthermore, many of the strategic decisions have challenging implications for PowerCell, especially if production volumes increase. One example of a decision with many associated challenges is the decision to acquire one type of fuel cell stack from Bosch. Firstly, most respondents during interviews were unsure if this decision was thoroughly evaluated before it was made, and if it is the best solution for PowerCell, as fuel cell stack development and production are considered PowerCell's core competencies. Secondly, a contradictory decision was identified, where PowerCell made investments in an advanced tool for in-house fuel cell stack production, implying development of in-house production. Thirdly, there seems to be a lack of consensus regarding whether this is a long-term decision or not.

Based on a thematic analysis of the 65 identified strategic decisions, six prominent challenging areas were identified, answering RQ3: insufficient cross-functional communication, low degree of manufacturability of products, high degree of customization obstructs managing increased production volumes, inadequate quality management efforts, non-value-adding work in the production system, and lack of clear production strategy obstructs development of the production system. These challenging areas are not mutually exclusive but rather interrelated, as visualized in Figure 5.1 below. For example, insufficient cross-functional communication and the lack of a clear production strategy seem to partially cause and amplify the other challenging areas. Furthermore, they amplify each other; insufficient cross-functional communication makes it difficult to communicate organizational objectives and achieve a common understanding, and the lack of a clear production strategy results in a lack of a common basis for cross-functional discussions. Additionally, non-value-adding work seems to be a result of most of the other challenging areas, thus, if these would be solved, the level of non-value-adding work would be reduced.

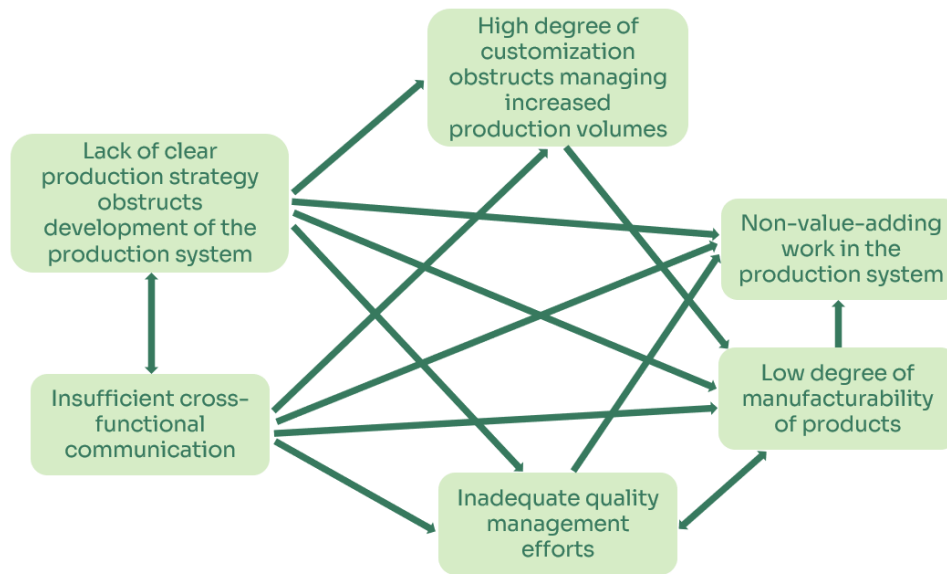


Figure 5.1: *Interrelations between the six prominent challenging areas.*

To answer the last research question, RQ4, six strategic directions were proposed based on the six prominent challenging areas. The strategic directions were proposed to provide a basis for PowerCell’s production strategy. As a starting point, PowerCell could prioritize addressing the challenging areas insufficient cross-functional communication and lack of clear production strategy, as these seem to be the causes of several of the other challenging areas. If these become less prominent, the others could become less prominent too. The overarching themes of the proposed strategic directions can be positioned in the Proposed Integrated Framework as seen below, in Table 5.1. However, concrete actions within these themes are not positioned in the Proposed Integrated Framework, and some of them do not belong to the same strategic decision area as the overarching theme. These are thoroughly described in section 4.4 of this report.

Table 5.1: *Overarching themes of the proposed strategic directions.*

Production Process	Capacity	Supply Network	Quality Management	Development & Organization	Production Planning & Control
<p>Enhance the production preconditions in a way that facilitates manufacturing</p> <p>Search for areas of improvement in the testing activities</p> <p><i>Further investigation required</i></p>	<p><i>Further investigation required</i></p>	<p>Evaluate core competencies and determine what to retain in-house</p> <p>Aim for a more responsive supply network</p> <p>Enhance supplier collaboration and evaluation</p>	<p>Standardize the production system where possible</p> <p>Define a desired level of quality</p> <p>Establish internal standards for processes</p> <p>Establish a strategy for which quality standards to adhere to</p> <p>Aim for a more proactive quality management approach</p> <p>Systemize the continuous improvement culture</p> <p>Ensure that problem solving results in quality deviation reports</p> <p>Minimize variations in the production process</p>	<p>Formalized cross-functional forums</p> <p>Implement policies and procedures for information-sharing between groups</p> <p>Ensure that the strategic objectives for the production system are defined and communicated</p> <p>Align strategic decisions with current stage of development</p> <p>Optimize product design for manufacturability</p> <p>Revise the level of customization offered</p> <p>Align product and process innovation</p>	<p>Aim for tact-based planning with a pull production approach</p>

Certain areas have been more thoroughly analyzed than others, as a consequence of the thematic analysis of the most prominent challenging areas. Hence, the strategic decision area capacity has not been treated as thoroughly as the other strategic areas, as not as many challenges were associated with it. It is recommended that PowerCell in establishing their production strategy utilizes the Proposed Integrated Framework as a basis, to ensure that a comprehensive production strategy is formulated. Each strategic decision area could be treated separately to a certain extent; however, coherence should be strived for. Furthermore, all strategic decision areas should be treated to constitute a comprehensive production strategy.

When creating a production strategy, it is of high importance to consider sustainability aspects, to ensure long-term viability. Sustainability should be addressed in the three dimensions of the triple bottom line: planet, people, and profit. Regarding the planet dimension, environmental sustainability, the production process should be shaped in a way that does not generate excessive waste or overuses natural resources. Therefore, if following the proposed strategic direction of this study, a more environmentally sustainable production system could be reached. Social sustainability, people, is here about ensuring that employees in the production system have sustainable working conditions, especially if production volumes increase. Furthermore, it is important to ensure that suppliers adhere to PowerCell's core values regarding social sustainability. Lastly, profit, economic sustainability, should be strived for when developing the production strategy, to ensure that it is economically feasible for PowerCell to work accordingly.

6 Further Research

In this study, strategic decisions that have shaped PowerCell's production system have been identified, along with challenges associated with these decisions. Furthermore, initial solutions were proposed. Based on this, the most prominent challenging areas were identified, and strategic directions were proposed as a way of addressing these. During the thematic analysis to identify the most prominent challenging areas, certain areas of the Proposed Integrated Framework were more thoroughly addressed than others. Therefore, to be able to create a comprehensive production strategy, it is advised that PowerCell further examines the areas that are not as thoroughly investigated. For example, further research should be conducted on the strategic decision area capacity to be able to make informed decisions about capacity expansion when needed. Additionally, the relationship between the prominent challenging areas is somewhat discussed in chapter 5 of this report, however, this could be further investigated to determine how actions within any of these would affect other parts of the production system.

This study has been conducted on a strategic level, meaning that solutions on an operational level are not proposed. To be able to develop the production system in accordance with the proposed strategic directions, it is advised to collect more operational data. For example, data could be gathered to determine statistically which are the most significant bottlenecks in the production system, which would aid in prioritizing which challenges to address first. It is furthermore recommended that PowerCell tries the proposed strategic directions operationally before determining the production strategy, to evaluate which strategic decisions are the most appropriate.

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