Enablers in the production system design process impacting operational performance

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ABSTRACT
This paper explores how the design process of the production system could be utilized to improve the operational performance during the production ramp-up and operation phases. A qualitative case study was carried out in a large process-type manufacturing company, focusing on three new production line launching projects. Different actions taken in the design process of the production lines were linked to their impact during the running operation phase and operational performance, which is measured by the metric of Overall Equipment Effectiveness (OEE) within lean manufacturing. The empirical findings provide a concrete example that activities in the design process impact on the OEE. A set of enablers in the production system design process at different systems-level, especially concerning the acquisition of new production equipment have been demonstrated that has potential to achieve the target operational performance. Finally, the concept of operational performance driven production system design process is proposed.

1. Introduction
As customers’ needs are rapidly evolving, manufacturing companies are pushed to reduce the manufacturing cost, deliver products in a shorter time, and ensure the right quality level. One of the potential solutions for manufacturing companies is to design or develop the production system to assist them in getting the desired level of operational performance from manufacturing operations (Bellgran & Säfsten, 2009; Choudhari et al., 2010; Koren & Shpitalni, 2010). However, how the decisions and activities taken during the design process of new production systems impact on operational performance is not clearly understood yet (Battesini et al., 2021). Despite several research conducted on connecting the product design process to operational performance (Arellano et al., 2019; Marodin et al., 2018; Pashaei & Olhager, 2019; Wurzer & Reiner, 2018), a lack of attention has been given to the production system design process (PSDP) and its impact on operational performance.

Referring to the production system life cycle, which consists of several phases—planning, design, constructing/installation, ramp-up, operation, and termination/upgrade (Attri & Grover, 2012; Wiktorsson, 2002), the design phase is the most vital,
as this is where the most critical decisions during the lifecycle are taken (Bellgran & Säfsten, 2009). In the design phase, crucial activities are performed, such as defining requirements, developing equipment specifications, designing or purchasing equipment from suppliers, planning the layout, designing internal and external logistics systems, etc. Managing these design-related activities is defined as the PSDP (Bellgran & Säfsten, 2004). In large manufacturing companies, activities related to launching a new production system are managed as a project, often referred to as ‘investment projects,’ ‘design projects,’ or ‘production line launching projects’ (Aurich & Barbian, 2004).

A new production system could be launched for several reasons, such as introducing new product into market, expanding capacity, fulfilling legal requirements to enter into a new market, etc. The potential benefit of an efficient PSDP is not only limited to shortening the time-to-market (i.e. from concept development to launch to the market) of new products and ramp-up time (Hayes et al., 2005; Pisano, 1997). It may also improve output, efficiency, quality, and profitability in the operation phase by eliminating the design error-related issues (Koren & Shpitalni, 2010). Therefore, the benefits of the efficient PSDP could be categorized into two perspectives: project management perspective (i.e. launch the product on due time to achieve time-to-market) and operational performance perspective (i.e. achieving the target operational performance when the production line is in ramp-up and operation phases). Considering these potential benefits, managing the PSDP could be viewed as a competitive advantage that is difficult for competitors to imitate (Bruch & Bellgran, 2012).

However, practitioners often face difficulties managing the PSDP because of its complexity and high uncertainty that requires involvement of multi-functional personnel (Bruch & Bellgran, 2012; Rösiö & Bruch, 2018). During the PSDP different solutions for the requirements of the intended production system are analyzed so that right specification is selected. In some cases, it becomes difficult for the practitioners to anticipate how the system solutions will actually behave during the operation phase due to absence of the actual physical production system. However, the pressure from top management to launch the product in market at due time, can hinder the proper analysis of how the system will behave during the running operation phase (Trolle et al., 2020). Also, due to the absence of a physical production system, in the design phase, practitioners also tend to spend less time on developing the specifications of intended production system and iterate the specifications later after the installation of the equipment (Rösiö & Bruch, 2018). Consequently, many changes are required after installation, causing a more extended ramp-up period and disturbances in the operation phase (Bellgran & Säfsten, 2009). Hence, practitioners need to find best practices to manage the PSDP that could launch the product into market on due time, and facilitate reducing ramp-up time and achieving intended operational performance.

Several research has been conducted on managing the PSPD. For instance, Andersen et al. (2017), De Kogel and Becker (2016), and Slim et al. (2021) tried to develop a systematic design process. Ahlskog et al. (2019), Bruch and Bellgran (2012), Rösiö and Bruch (2018), and Trolle et al. (2020) identified challenges associated with the PSDP. Bruch (2012), Lager and Frishammar (2010), Rönnberg-Sjödin (2013), and Rösiö and Bruch (2018), and Slim et al. (2021) identified tactics or action plans for managing
different activities within PSDP. The last decade of research addressed the lack of research on managing the design process (Andersen et al., 2017; Bruch, 2012; Rösiö & Bruch, 2018; Trolle et al., 2020).

Despite several earlier research (Bellgran & Säfsten, 2009; Choudhari et al., 2010; Koren & Shpitalni, 2010; Rösiö & Bruch, 2018) addressed that activities in the PSDP potentially impact the operational performance, no case study was found in the existing literature connecting the actions or decisions taken in the PSDP and its impact on the operational performance. In addition, some of the earlier research addressed to fulfill the functional requirements in the PSDP (Cochran, Foley et al., 2017; Rauch et al., 2016), however, achieving the target operational performance was not considered within the scope of functional requirements. Furthermore, by synthesizing existing literature, it is ambiguous to grasp if the suggested tactics mentioned for managing the PSDP are focusing on the project management perspective or on future operational performance perspective. Therefore, further research is required to determine how the PSDP could be managed considering future operational performance perspectives.

Based on the above argument, it is perceived that PSDP potentially impacts the operational performance of the intended production system. However, how the PSDP could be managed to achieve or assist the target operational performance was seldom addressed in the earlier research. This research aims at exploring how the PSDP could be managed to achieve a production system’s target operational performance. Hence, this research tries to identify the enablers in the PSDP that potentially impact operational performance so that practitioners can take proper measures on those enablers. Therefore, the following research question is set:

**RQ: What are the enablers in the production system design process impact operational performance in a production system’s ramp-up and operation phases?**

A case study was conducted in a process type manufacturing company where qualitative data were collected from three new production line launching projects to answer the research question. The operational performance is measured using the metric overall equipment effectiveness (OEE), which is widely used as a key performance indicator (KPI) for equipment or production lines (Gupta & vardhan, 2016; Tsarouhas, 2018). OEE, as a performance measurement tool, assists practitioners in estimating losses and identifying areas of major losses so that practitioners can take proper actions to improve efficiency (Gupta & vardhan, 2016; Shiau & Wang, 2021; Tsarouhas, 2018).

The rest of the paper is structured as follows: chapter 2 summarizes theoretical bases, chapter 3 presents the research methodology, and chapter 4 describes the empirical findings and results from the extensive case study. The discussion, including theoretical and practical implications, is found in chapter 5. Chapter 6 adds a summary and conclusion, including a proposal for the future research scope.
2. Theoretical background

2.1. The production system design process

The PSDP could be viewed as a decision-making process that supports the development activities of a production system and leads to the creation of a new production system (Bruch, 2012; Rösiö & Bruch, 2018). Bellgran and Säfsten (2009) described the PSDP as tasks of defining the problem, generating solutions, evaluating alternative solutions, and preparing the detailed design of the chosen solution. It ultimately results in an exact specification or description of the production system. Similarly, Alves and Carmo-silva (2009), Schuh et al. (2009), and Marzouk et al. (2012) defined the PSDP as a series of activities, from identifying system requirements to fulfilling those requirements. Fulfilling the requirements of the intended production system demands that a test run is performed, training on operating the equipment is conducted, and other essential aspects of the production system are taken into account. Cochran, Foley, et al. (2017) and Rauch et al. (2016) defined the PSDP as a mean of fulfilling the customer requirement by addressing the functional requirements, process parameters, and design parameter.

Rösiö and Bruch (2018) addressed that most literature considered PSDP limited to only preparatory design and detailed system solution design, missing capturing the critical activities needed to take place. Therefore, it needs to capture aspects ranging from preparatory design and detailed design (Bruch & Bellgran, 2013) to the realization and start-up of the physical production system. Figure 1 illustrates the framework of the PSPD that is considered in this article.

Figure 1. The production system design process (modified from Bellgran and Säfsten (2009)).
**Table 1. An overview of studies within the production system design process.**

| References                          | Theme of the study                                      | Key findings                                                                 |
|-------------------------------------|---------------------------------------------------------|-------------------------------------------------------------------------------|
| (Slim et al., 2021)                 | Lean thinking for production system design              | Proposed inclusion of lean principles to design a high performing production system/machine |
| (Trolle et al., 2020)               | Identification of challenges                            | Presented a set of challenges in production system design process              |
| (Rösiö & Bruch, 2018)              | Incorporating Reconfiguration in Design process         | Challenges and tactics related to incorporating design process presented       |
| (Andersen et al., 2017)             | Incorporating Reconfiguration in Design process         | A framework of designing reconfigurable production system is presented        |
| (Stark et al., 2017)                | Incorporating Industry 4.0 in design process            | Proposed a design approach for designing cyber physical production system      |
| (Rönberg Sjödin et al., 2016)      | Managing uncertainty in process development project    | Hypothesis proved quantitatively and suggested actions of managing uncertainty when purchasing equipment |
| (De Kogel & Becker, 2016)          | Incorporating lean in design process                    | Proposed design support tool to incorporate lean aspects in the design process |
| (Ahlskog, 2015)                    | Manufacturing technology development                    | Challenges and factors associated with manufacturing technology development projects identified |
| (Rösiö & Bruch, 2014)              | Production system design model                          | A model of production system design process developed and presented           |
| (Bruch & Bellgran, 2013)           | Managing information in design process                  | Characteristics of design information and its impact on design process presented |
| (Rönberg-Sjödin, 2013)             | Managing collaboration with equipment supplier in process development project | Challenges and suggested actions presented when collaborating with equipment supplier during equipment acquisition process |
| (Bruch & Bellgran, 2012)           | Managing information in design process                  | Type of design information, acquisition and sharing process of design information on equipment acquisition process presented |
| (Attri & Grover, 2012)             | Literature review on production system life-cycle       | Different production system life cycle model presented                        |
| (Aurich & Barbian, 2004)           | Incorporating flexibility of production line in production system design projects | A model presented to optimize the flexibility in production line development projects |
| (Cochran et al., 2002)             | Production equipment design process                     | Axiomatic design process used to incorporate lean principles when designing production equipment |


2.2. Frame of references of managing the production system design process

Literature papers were searched in Scopus using the search string (‘production system design process’ OR ‘manufacturing system design process’ OR ‘design process of production system’ OR ‘design process of manufacturing system’). The results showed 31 documents having 17 journal articles, among those, 11 were published between the period of 2000 to 2022. Using another search string (‘design process’ AND (‘production system’ OR ‘manufacturing system’) AND ‘operational performance’) resulted in only two papers, one of which is a journal article written by Sukhotu and Peters (2012). From these articles and using forward and backward snowballing sampling, other articles have been identified to serve the purpose of this research. A comprehensive summary of previous literature is presented in Table-1. The authors also referred to the article of Rösiö and Bruch (2018) that presented the latest comprehensive literature on managing PSDP.

Referring to Table 1, several researchers have discussed the phenomenon of managing the PSDP. Some concerns to collaboration needs for streamlined information flow and communication in the production system design (Bruch & Bellgran, 2012, Bruch & Bellgran, 2013). Others propose incorporating reconfiguration, flexibility, and lean thinking aspects already in the design phase to optimize production systems (Andersen et al., 2017; Mohammadi et al., 2014; Rösiö & Bruch, 2018; Slim et al., 2021). Yet another set of papers focus on identification of challenges in the PSPD (Ahlskog, 2015; Rönneberg-Sjödin, 2013; Trolle et al., 2020). Sukhotu and Peters (2012) developed a simulation-based mathematical model for a material handling system for reducing inventory levels as part of operational performance. Stark et al. (2017) tried to develop a design approach for designing of a cyber-physical production system.

The existing literature on the PSDP (presented in Table-1), focused on two categories: 1) managing the activities of the design process efficiently, 2) incorporating different manufacturing practices, such as lean, reconfigurability, and industry 4.0 aspects in the design process. Several of these studies have addressed that activities in the design process impact operational performance (Bellgran & Säfsten, 2009; Choudhari et al., 2010; Trolle et al., 2020). However, there are barely any detailed (case) studies connecting the activities in the PSDP with their impact on operational performance. In addition, understanding the impact on the operational performance concerning the context and features of the production system to be designed remains to be explored and understood further. Therefore, considering this research gap, the performed case study tried to connect the PSDP activities and their impact on the operational performance in later phases. To the best of the authors’ knowledge, in the existing literature, no literature review or article was found addressing enablers in the PSDP for achieving desired operational performance. Hence, this research tries to address the enablers in the PSDP and their impact on operational performance.

2.3. Operational performance and overall equipment effectiveness

In alignment with the sustainability aspects, companies nowadays measure their operational performance in economic, environmental, and social aspects. There are different dimensions for economic aspects of operational performance, such as product quality, product cost, deliverability, flexibility, reliability, etc., (Battesini
et al., 2021; Henao et al., 2019). Overall equipment effectiveness (OEE), originated from the concept of Total Productive Maintenance (TPM) within lean manufacturing, is widely used in industries to measure the performance of individual production equipment, production line, and even for whole factory’s production system (Gupta & Vardhan, 2016; Tsarouhas, 2018). By measuring three different metrics (availability, performance, and quality), OEE assists practitioners in identifying the number of certain types of losses so that the right actions are taken to improve the overall performance. Eventually, the improvements expand to other areas, that is, cost, delivery, flexibility, etc.

Several reasons can impact OEE: design error of equipment, uneven flow of materials and products, machine break down, maintenance work, lack of operators’ skills, management style of the production control system, etc., (Ahmad et al., 2018; Hagström, 2021). These reasons could be related to the activities of the production system design process, as during this process, a detailed specification of the production system is developed, and decisions are taken regarding how the intended system should function (Cochran, Arinez et al., 2017; Rauch et al., 2016; Slim et al., 2021). Though earlier literature did not directly link the activities in the design process and their impact on the OEE, it can be argued that many of the reasons for lower OEE could be overcome by adequately designing the production system. Hence, in this research, the operational performance of the production system is measured using the OEE parameter to identify how the actions in the PSDP impact the OEE.

2.4. Managing the production system design process- challenges and enablers for operational performance

Previous research highlighted several challenges and practices associated with managing the PSDP, like coordinating the whole production PSDP (Cochran et al., 2001) and requiring cross-functional involvement (Aurich & Barbian, 2004). Involving cross-functional experts in the project team provides broader perspectives for design consideration (Ahlskog, 2015; Cooper, 2011). Several challenges associated with the PSDP are mentioned in the literature. For instance, the lack of a systematic working structure to manage the complete design process (Andersen et al., 2017; Bruch, 2012; Rösiö & Bruch, 2018), management of information flow among different stakeholders during the PSDP (Bruch, 2012), and addressing functional requirements properly (Cochran, Arinez et al., 2017) have been pinpointed in earlier research.

For achieving the desired operational performance of the production line, it is crucial to align the activities of the PSDP with the manufacturing strategy (Machuca et al., 2011). Literature noted the early involvement of the production team in the design projects to address the functional requirements (Rönnberg-Sjödin, 2013; Rösiö & Bruch, 2018) as an enabler. The production team’s early participation during the PSDP provided vital input of shop-floor requirements, ensured defining proper equipment specification, and enhanced their commitment in the later stages of the project (Rönnberg-Sjödin, 2013).
To avoid additional challenges such as misunderstanding and uncertainty in information flow (Sjödin et al., 2011) during the PSDP, specific actions regarding the involvement of production equipment suppliers are suggested. For instance, maintaining strong collaboration with equipment suppliers (Abd Rahman et al., 2009; Lager & Frishammar, 2010; Rönnberg-Sjödin, 2013), collaborating on developing the equipment specification (Rönnberg-Sjödin, 2013), and assigning a contact person with sufficient technical knowledge to communicate with the equipment suppliers (Bruch & Bellgran, 2012).

As uncertainty is a crucial characteristic in the PSDP, it is advisable for production system designers to utilize lessons learned from previous similar projects and production lines (Hubka & Eder, 2012). In addition, Ahlskog (2015) highlights that the maturity level of new production technology also needs to be considered during the PSDP.

To sum up, the objectives of the PSDP could be divided into two categories. One is to manage the activities efficiently and finish the project on time with limited budgets and resources, which could be viewed as a project management perspective. Another is to design the production system to achieve the desired operational performance in the ramp-up and operation phases. Based on the literature review, enablers are identified as part of the PSDP that could potentially impact operational performance (Table 2).

### 3. Methodology

The research methodology adopted in this article is an exploratory case study. An exploratory study is suitable when the problem is not well understood due to insufficient prior research or knowledge, leading to further research opportunities (Van Wyk, 2012). A case study is suitable for explaining a phenomenon in a real-life context, and data collected through a case study can be rich and detailed, allowing an in-depth understanding of a phenomenon (Eisenhardt, 1989; Yin, 2017). Due to the lack of understanding the clear connection between the PSDP and the operational performance in the existing literature, this research explored a company’s PSDP as a case study. The case study was performed in a process type manufacturing company located in Europe where three completed production system design projects to launch new production lines were followed in retrospect. The case company has several production facilities worldwide and developed a stage-gate

### Table 2. Enablers of the production system design process impacting operational performance.

| Enablers                                      | References                                                   |
|-----------------------------------------------|--------------------------------------------------------------|
| Relationship with equipment supplier          | (Abd Rahman et al., 2009; Lager & Frishammar, 2010; Rönnberg-Sjödin, 2013) |
| Communication with equipment supplier         | (Bruch, 2012; Bruch & Bellgran, 2012)                       |
| Involvement level of production team          | (Rönnberg-Sjödin, 2013; Rösiö & Bruch, 2018)                |
| Specification of production equipment         | (Rönnberg-Sjödin, 2013; Rösiö & Bruch, 2018)                |
| Training quality for new production system    | (Ahlskog, 2015; Rönnberg-Sjödin, 2013)                      |
| Formulation of project team                   | (Ahlskog, 2015; Cooper, 2011)                               |
| Maturity level of manufacturing technology    | (Ahlskog, 2015)                                             |
| Utilizing lesson learned from similar production line | (Hubka & Eder, 2012)                                 |
model as standard practice for the design process of launching new production lines. A single department within the company manages the activities related to the PSDP coordinating with other functional departments.

3.1. Data collection and analysis procedure

The data collection was conducted through semi-structured interviews with professionals who had worked on the three selected projects. Qualitative data coming from interviews is suitable to investigate people’s perceptions, feeling, and basis for decisions (Säfsten et al., 2020). As the aim of this research is to understand how the PSDP was managed and its final outcome, hence, interviews were conducted to professionals involved in the projects to capture their perceptions and reasoning for decisions taken during the PSDP. The flexibility of the semi-structured interview approach provided a detailed understanding of a complex scenario (Fylan, 2005). It is to be noted that all participants had been working for more than seven years at the company. At least two researchers were involved in each interview to ensure triangulation and reduce observer bias in a total of 15 interviews. A summarized overview of the interviews is presented in Table 3, and a sample interview questionnaire is included in the appendix.

Before conducting the interviews, various project-related documents were reviewed, such as project charters, project timelines, current working procedures on project management, equipment quotations, etc. This step allowed an understanding of each project’s background to generate relevant questions during the interviews. The questionnaires were sent beforehand to allow the interviewees to prepare and recall memory. All interviews were recorded and transcribed. For increasing the reliability and validating the data, crucial information was cross-checked among different interviewees (Yin, 2017).

Following the case study method, the analysis followed guidelines of qualitative analysis (Strauss & Corbin, 1998) and case study protocols (Yin, 2017). Data for each case were analyzed separately and put together to perform a cross-case analysis. The interview data were analyzed using progressive coding techniques, consisting of three phases: open coding, axial coding, and selective coding (Strauss & Corbin, 1998; Williams & Moser, 2019), to generate meaningful information. The analytical process related to this study was as follows.

Table 3. Overview of data collection through interview.

| Project | Duration (min.) | Title of interviewed experts | Number of interviewees |
|---------|-----------------|------------------------------|------------------------|
| A       | 50–75           | Project managers             | 3                      |
|         |                 | First line managers          | 2                      |
|         |                 | Process engineer             | 1                      |
| B       | 40–80           | Project manager              | 2                      |
|         |                 | First line managers          | 2                      |
|         |                 | Technical project manager    | 1                      |
| C       | 45–65           | First line manager           | 2                      |
|         |                 | Ramp-up coordinator          | 1                      |
|         |                 | Project manager              | 1                      |
| Total   | 900             |                              | 15                     |
Step-1: At first, through open coding on thematic analysis, the actions or decisions taken in the design process were identified and how they impacted the ramp-up and operation phases. These actions or decisions in the design process were grouped to generate the enablers in the PSDP as part of progressive coding.

Step-2: After identifying the enablers from step-1, the strength of enablers was measured subjectively from interview data for all three case projects to perform cross-case analysis. For measuring the operational performance, data for OEE of the respected production lines were collected.

### 3.2. Project selection and case description

The case company is well reputed in its business and has production operations in multiple countries worldwide. Three completed projects for launching new production lines were selected, referred to as Project-A, Project-B, and Project-C. The following criteria was used to select the projects:

**Project status:**
the projects had to be in the operation phase for up to three years, expecting that the ramp-up and operation-phase difficulties could be understood and the interviewees could gather and share sufficient information about the projects.

**Complexity:**
complexity level refers to the difficulties in managing the project-related activities considering different types of activities, timelines, required resources, targets within the projects, etc. The company project managers determined the complexity level based on their experience.

**Operational performance level:**
this criterion refers to the production lines’ operational performance after running the production operations. The desired OEE levels in the projects to analyze were 1) Satisfactory OEE, 2) Not satisfactory OEE level, 3) Undefined OEE level or not measured, given data is not available.

| Category                              | Project-A       | Project-B       | Project-C       |
|---------------------------------------|-----------------|-----------------|-----------------|
| Product type                          | New             | Existing        | Existing        |
| Process type                          | New             | Existing        | Existing        |
| Tenure of commercial production       | 2 years         | 2.5 years       | 1.5 years       |
| Current OEE                           | Undefined (data is not available) | 50% | 33% |
| Performance level in operation phase  | N/A (OEE data is not available) | Satisfactory | Not satisfactory |
| Existing similar production line      | No              | Yes             | Yes             |
| Reason for new production line        | Supply new product to market | Increase capacity and supply to new market | Increase capacity |
| Complexity level in terms of managing project activities during early phases | Medium | Low | High |
For Project-A, the company launched the production line to supply a product manufactured by another company on a sub-contract basis. The company did not have much expertise in the product and lacked process-related information. The line ran for commercial production for the last two years until the study began.

For Project-B, a new production line was launched to supply an existing product already being manufactured to a new market. Before launching this new line, a few production lines had already been running for the same product, that is, they had the production process expertise. However, the new line’s capacity was doubled by increasing the capacity of one of the machines designed by the equipment supplier for the first time.

For Project-C, the line was launched to increase the company’s existing capacity, mainly focusing on supplying a new market. The production line has run for the last one and a half years. Before launching this production line, several production lines for the same product were already running. Therefore, they had the expertise in the production process. A new process technology was used in one process, optimizing the production space. Furthermore, the line speed was higher due to the need to increase the output of the line. Essential descriptive items related to the three projects are presented in Table 4.

4. Results

4.1. Enablers in the design process impacting operational performance

Following step-1 mentioned as the analytical procedure in the methodology (see Chapter 3.1), the enablers addressed in the existing theory (see, Table 2) were linked with their impact on the following ramp-up and operation phases, as presented in Table-5. The empirical investigation allowed for identifying additional enablers besides those mapped from reviewed literature. They were also linked to their consequent operational performance (Table 5). The identified enablers presented in Table 6 and Table 5 were further grouped as a part of the progressive coding technique mentioned in step-1 in the research design (see, Table 7).

4.2. Cross case analysis of the three production line investment projects

After analyzing the three production line launching projects individually, the three projects were compared and further analyzed to check how variations of the strength of identified enablers impacted on the operational performance (as described in step-2 in the methodology section). The enablers’ strength were identified based on the actions taken related to the enablers, and classified into two groups: strong (+++) and weak (+).

Strong (+++): indicates that the strength of the elements related to a specific enabler was found to be high.

Weak (+): indicates that the strength of elements related to a specific enabler was not found to be strong.

Detailed criteria to measure the strength of each enabler is presented in Table 8. The table describes what has been classified into weak and strong dichotomy for each element under every enabler. A summarized list of strengths of the enablers of all the three case projects is presented in Table-9.
Table 5. Additional enablers in the design phase impacting operational performance.

| Enablers/elements of enablers in the design phase | Relevant facts/causes in the design phase                                                                 | Consequence/ Result in the ramp-up and operation phases                                                                 | Related to Project |
|-------------------------------------------------|----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------|
| Product expertise                               | The information about the product quality deviation parameter was not reliable. (‘I got that information, wrong or right that I cannot say right...so we re-qualified the equipment...’) | Additional resources to change different parameters of the production process to ensure quality and avoid deviations.      | Project-A         |
| Process expertise                               | Lack of proper information about process requirements to supply in new market.                            | Unnecessary activities were performed for one year. (‘...they set high element than the other markets and I think we maybe could challenge that more in the beginning...one and half year we changed our way of cleaning because it was not necessary.’) | Project-B         |
| Equipment supplier’s competency                | Supplier’s competency was not satisfactory to solve technical issue. (‘...we have made big lessons learnt...we underestimate the complexity both we and machine supplier...[they] thought they have solved [technical disturbances] but it turned out during installation...this cost almost one year working with solve this’) | Technical disturbances in machine, time to solve technical disturbance increased, increased equipment down time.       | Project-A, Project-B, Project-C |
| Internal technical competence                  | Assigned skilled machine technician with working experience on similar type of machine. (‘...this special guy [technician within company] has been working with the same machine and machine type for 20 years...we haven’t managed this without him.’) | Identified root causes of technical disturbances and found solutions to reduced technical disturbances.                  | Project-A, Project-B, Project-C |
| Quality of Testing of equipment                | Higher test run time to find root causes of technical disturbances and to validate the identified solutions. | Less technical disturbances in operation phase. (‘They [production team] got a lot of training with all these test runs. So when the machine was handed over they could run it at high speed from the beginning.’) | Project-B         |
| Design of SOP (Standard Operating Procedure)   | SOP developed aiming to reduce training time of new operators. SOP was not adequate, equipment specification was not appropriate. (‘I think it was very big mistake. They thought that the line could be handled with the man only by 6 of operators...we need...perhaps even 8 at an average shift!’ (if you trained from standards then you learned to do the things in the right way, but if you don’t have standards for changeovers then it’s hard to do changeover in in the time...) | Training of the operator time reduced. Operators were not in proper place, changeover time increased, had to change equipment specification later. | Project-A, Project-C |
| Enablers/ elements of enablers in the design phase | Relevant facts/causes in the design phase | Consequence/ Result in the ramp-up and operation phases | Related to Project |
|---------------------------------------------------|------------------------------------------|--------------------------------------------------------|-------------------|
| Relationship with equipment supplier              | Design team had to work with the least preferred supplier due to business deal. | Delayed the start-up process. Safety aspects of the equipment improved. | Project-A         |
| Communication with equipment suppliers            | Supplier’s misunderstanding some of the requirements of the equipment.          | Several continuous improvement activities were performed in the equipment to improve safety, quality and technical issues that hampered planned production schedule. | Project-C         |
| Involvement level of production team Specification of production equipment | Full time future production manager appointed early. | Training of the operator time reduced, Ergonomic issue improved. | Project-A         |
| Specification of production equipment Training quality for new production system | Specification of the equipment was not accurate. | Created bottleneck in the production line causing less OEE | Project-C         |
| Formulation of project team                        | Multifunctional experts were involved in the project team.                  | Improved green, safety, ergonomics, maintenance aspects of production equipment. | Project-A, Project-B, Project-C |
| Maturity level of manufacturing technology          | New technology implemented for a specific process. | Increased learning time for operators and technicians, and increased downtime during equipment breakdown. | Project-C         |
| Utilizing lesson learned from similar production line | Bottleneck identified in the previous production lines reduced. | Improved OEE. | Project-B         |
Table 7. Enablers in the design phase impacting operational performance in ramp-up and operation phases.

| Enablers                                                                 | Elements of Enablers                                                                 | Impact in the ramp-up and operation phase                                                                 |
|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Product & process expertise                                              | Familiarity with the product                                                        | New product and new process require more time to learn. Lack of proper information about new product’s quality related deviation parameter may lead to unnecessary operations. Utilization of lesson learned from existing product and process offers continuous improvement opportunity. |
|                                                                          | Familiarity with the process                                                        |                                                                                                         |
|                                                                          | Maturity level of manufacturing technology                                           |                                                                                                         |
|                                                                          | Utilizing lesson learning from similar production line                               |                                                                                                         |
| Quality for testing and training                                         | Quality of training                                                                  | Proper training and testing of equipment increase confidence of operators and technicians to solve technical issues during operation phase. |
|                                                                          | Quality of testing of Equipment                                                      |                                                                                                         |
| Internal technical competence                                            |                                                                                      | Internal strong technical competency assists to solve different technical issues related to production equipment, for instance, finding root cause of disturbance, providing solutions, assist suppliers on implementing solutions, etc. |
| Involvement level of production team                                     |                                                                                      | Early involvement of production team (production manager, operators, lean experts, maintenance, etc.) and their competency provide opportunity to develop standard operating procedure, machine specification properly. |
| Formulation of project team                                               | Involvement of multifunctional experts                                               | Involvement of multifunctional experts in the project team provides input on different level.                   |
| Competency of production team                                            | Design of standard operating procedure                                              | Competency of the production team allows to design the equipment specification, training plan and standard operating procedure properly. |
|                                                                          | Specification of production equipment                                                |                                                                                                         |
| Communication with equipment supplier                                   | Suppliers’ understanding on requirements                                            | Proper communication with the equipment suppliers ensures their understanding about the requirements and specifications of equipment which reduces uncertainty and misunderstanding. |
| Relationship with supplier                                               |                                                                                      | Strong relationship with suppliers assist on developing equipment specifications, re-engineering of equipment (if necessary) and solving technical issues as a part of after sales service. |
| Supplier expertise on equipment                                          |                                                                                      | If supplier is constructing the equipment first time that may impact on solving technical disturbances during testing and ramp-up phase. |

4.2.1. Comparing operational performance

OEE was identified as a relevant indicator for comparing the projects’ performance during the ramp-up and operation phases. Data collected of the OEE of the installed production lines for Project-B and Project-C over time is presented in Figure 2. It should be noted that data on OEE for Project-A is not included since it was not available during the study. Results show that for Project-B, the target level of OEE was to reach 60% after two years of running. The target was nearly achieved, reaching 57% after two years, a number found satisfactory to the company management. For Project C, the target was to reach 50% OEE six months after start-of-production. However, only 20% OEE was achieved by that time, a number that was not found to be on a satisfactory level by the management. Hence, Project-C performed at a lower level than Project-B in reaching the target OEE.

Based on the cross-case analysis of Project-B and Project-C (see Table-9), some of the actions’ strengths in relation to the enablers were low for Project-C. These enablers were: 1) Quality of training and training of equipment, 2) Competency of the project team, and 3) Communication with the production equipment supplier. Similar
Table 8. Criteria for linguistics criteria for cross-case analysis.

| Enablers                | Elements of Enablers                              | Linguistic criteria                                                                 | Symbol |
|-------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------|--------|
| Product & process expertise | Familiarity with the product                      | Company have been already manufacturing the type of product                          | ++     |
|                         |                                                  | Company had not manufactured the type of product before                              | +      |
|                         | Familiarity with the process                      | Production teams are familiar with the manufacturing process                          | ++     |
|                         |                                                  | Production teams are not familiar with the manufacturing process                     | +      |
|                         | Maturity level of manufacturing technology        | Company is familiar (worked before) with the manufacturing technology               | ++     |
|                         |                                                  | Company is not familiar (never worked before) with the manufacturing technology      | +      |
|                         | Utilizing lesson learning from similar production line | Company had similar production line                                                | ++     |
|                         |                                                  | Company never had similar production line                                           | +      |
| Involvement level of production team |                                        | Production team were involved early in the design process                           | ++     |
|                         |                                                  | Production team were not involved early in the design process                        | +      |
| Formulation of project team | Involvement of multi-functional experts           | Involvement of team members from different functionalities during the design process | ++     |
|                         |                                                  | Lack of involvement of team members from different functionalities during the design process | +      |
| Competency of production team | Design of standard operating procedure            | Standard operating procedure was designed properly                                 | ++     |
|                         | Specification of production equipment             | Standard operating procedure was not appropriate                                    | +      |
|                         |                                                  | Specifications of production equipment were developed properly                     | ++     |
|                         |                                                  | Specifications of production equipment were not appropriate                         | +      |
| Internal technical competence |                                                  | Internal technical competency proved fruitful in the design process                   | ++     |
|                         |                                                  | Internal technical competency had no impact in the design process                     | +      |
| Quality for testing and training | Quality of training                              | Responded did not complain about training quality                                    | ++     |
|                         | Quality of testing of equipment                   | Responded felt that training quality was not sufficient                              | +      |
|                         |                                                  | Responded felt that testing of equipment was sufficient                             | ++     |
| Communication with equipment supplier |                                        | Responded complained about the quality of testing of equipment                      | +      |
|                         |                                                  | Responded did not complain about the communication issue with equipment suppliers  | ++     |
|                         |                                                  | Responded addressed that there was an issue with the communication with equipment suppliers | +      |
| Relationship with supplier |                                                  | Responded addressed that they have strong relationship with suppliers               | ++     |
|                         |                                                  | Respondents addressed that poor relationship with customers hampered the project    | +      |
| Supplier expertise on equipment |                                        | Respondent addressed that supplier understanding about requirement of equipment was to their expected level | ++     |
|                         |                                                  | Respondent addressed that supplier understanding about requirement of equipment was not to their expected level | +      |

Note: + and ++ respectively represent subjective assessment of implemented actions as described through the specified binary linguistic criteria for each action.
built the equipment for the first time in both investment projects. For both investment projects, the major equipment suppliers were the same. Additional specialized machines suppliers depended on production-line specifications which were not necessarily the same for the case projects. The pharma case company had a well-established (customer-supplier) relationship with the leading equipment suppliers. In both Project-B and Project-C, the production teams were already involved in an early stage of the design process, and skilled operators working in the existing (similar) production lines participated in the project.

Regarding the dissimilarities of the enablers found in Project-B and Project-C, the empirical data demonstrated issues in Project-C on 1) Quality of training of operators and testing of production equipment; 2) Design of standard operating procedure (SOP) and equipment specification, and 3) Supplier’s understanding of the equipment specification. Because of these issues, Project-C resulted in a lower OEE than the expected level of the ramp-up and operation phases. After gradually changing the SOP and the equipment specification in the operation phase, the OEE of production line C (Project-C) started to increase. For Project-B, however, the production team faced different types of

![Figure 2. OEE data for case project-B & project-C.](image)

| Enablers                        | Elements of Enablers                                      | Project-A | Project-B | Project-C |
|--------------------------------|-----------------------------------------------------------|-----------|-----------|-----------|
| Product & process expertise    | Familiarity with the product                              | ++        | ++        | ++        |
|                               | Familiarity with the process                             | +         | ++        | ++        |
|                               | Maturity level of manufacturing technology                | +         | +         | +         |
|                               | Utilizing lesson learning from similar production line    | +         | +         | ++        |
| Quality of training and testing of equipment | Quality of training                                      | ++        | ++        | +         |
| Internal technical competence | Quality of testing of equipment                           | ++        | ++        | +         |
| Involvement level of production team | Involvement of multi-functional experts                  | ++        | ++        | ++        |
| Formulation of project team    | Design of standard operating procedure                    | ++        | ++        | +         |
| Competency of production team  | Specification of production equipment                     | ++        | ++        | +         |
| Communication with equipment supplier | Suppliers’ understanding on requirements                | ++        | ++        | +         |
| Relationship with equipment supplier | Supplier expertise on equipment                         | +         | ++        | +         |
| Supplier expertise on equipment |                                                           | +         | +         | +         |

Note: (+++) indicates that the strength of the actions in the project related to the enabler was high. (+) indicates that the strength of actions in the project related to the enabler was low.
technical disturbances in the equipment after installation. The team handled these disturbances, investing a lot of time in training, identifying the disturbances’ root causes, and testing possible solutions. They reached comparatively close to the expected OEE level in the ramp-up and operation phases.

5. Analysis and discussion

5.1. Production system design process and operational performance

Analyzing the three case projects, Project-B resulted in a satisfactory level of OEE compared to Project-C. Some of the causes for lower OEE in Project-C were related to the design issues in PSDP activities. Linking to the strength of enablers (Table 9), Project-C had less strength on some of the enablers than Project-B. Therefore, it establishes how the PSDP management impacts operational performance. As mentioned in the literature, there is a lack of studies connecting the PSDP and operational performance. This case study validates that the PSDP impacts operational performance, supporting the earlier research of Bellgran and Säfsten (2009), Koren and Shpitalni (2010), Lager and Frishammar (2010), and Battersini et al. (2021).

In the theory section, by synthesizing existing literature, a set of enablers perceived to impact the operational performance were identified (Table-2). The empirical findings validate those enablers that need to be addressed during the PSPD to achieve target operational performance. The case study also recognizes the following enablers: product and process expertise, quality of testing production equipment, internal technical competency, competency of the project team, and suppliers’ expertise on equipment.

In suggesting involving the production operation team early in the design projects, our research underscores the competency of the production operation team in defining the equipment specification and designing the standard operating procedure (SOP). Despite the fact that having similar several production lines, Project-C resulted in lower OEE than Project-B because equipment specifications and SOP were improper. For all three case projects, it was found that different production managers worked differently when designing production lines within the same company. For instance, Project-C was suffered from the long required training time for new operators, whereas the Project-A system was designed so that new operators could learn within a short period. Standardized procedures of specifying the equipment and designing SOP were lacking in the studied projects. Hence, our research is in line with earlier research emphasizing that systematic working procedures for the production system design process are required (Ahlskog, 2015; Andersen et al., 2017; Rösiö & Bruch, 2018; Trolle et al., 2020).

From a customer perspective, maintaining a proper relationship with the equipment suppliers, for example, co-operating on the equipment specification, is suggested (Lager & Frishammar, 2010; Rönberg-Sjödin, 2013). Our research adds to this discourse by suggesting that the development of the internal technical competence (of the customer/producing company) needs particular attention since the equipment suppliers did not always show the adequate capability to solve technical disturbances. For all case projects, respondents addressed the issue of not receiving the desired technical support from the equipment suppliers to solve the technical disturbances. This might be due to several
reasons, for example, related to shortages in the suppliers’ expertise on the production equipment or lack of resources and capacity. In this situation, the case company’s internal technical competence proved to be both relevant and necessary for identifying the root causes of the equipment disturbances and developing solutions to these technical issues. Internal technical competence could also prevent the negative impact of the perceived weak relationship with the equipment suppliers found in Project-A. As put forward by one respondent: ‘[The supplier’s technician] was there looking [for what was wrong], but he was not so skilled [about mechanical properties] of the machine. These things [technical disturbances] were fixed by ourselves, not by [equipment supplier] support. They did some [activities] to avoid this problem, but it did not work’.

The scope of the studied production system design projects involved training the production team and testing the production equipment. The empirical findings presented in this paper indicated that the quality of both training and testing of equipment impacted the operational performance of the production line. It was noted that testing and training were considered a production team’s responsibility, resulting in less attention to these activities. According to one respondent from the production operation team: ‘[When something delays in the design process, training time is often compromised, which is not good]’. One respondent from the project management team mentioned, ‘[For the investment project we cannot take responsibility for how trained the operators are and how the standard way of working is. We can only take responsibility for the machines]’. The plausible reason for such discrepancy is that achieving target operational performance was not considered a success criterion for the production system design project in the case company. Therefore, training and testing of equipment need to be emphasized, and a proper training plan must be addressed within the PSDP.

Though earlier research addressed that the training time is related to the familiarity with new manufacturing technology and processes (Cantorna & Die, 2005; Kumar et al., 2018), the empirical findings add to this discourse. A similar scenario was found comparing Project-B and Project-C. For Project-C (where new technology was implemented and the company had similar production lines), new operators required a longer time to train themselves. Whereas for Project B, training time was not an issue as the production line was a duplicate of existing lines. However, for Project-A (where new technology was implemented and the company did not have similar production lines), new operators’ training time was fast as the standard working procedure was designed in such way considering the learning rate of new operators. Therefore, it indicates that, even for new technology implementation, there is a possibility to reduce the operators’ training time by taking proper measures when designing the equipment specification and standard working procedure.

Finally, Chirumalla (2017) categorized the production system design project based on the newness level of product and process. All three case projects had different characteristics in terms of newness level of product and process. When product, process and technology is new, it may cause lack of expertise of produce and process. During this adverse scenario, due to limited data, this research could not provide sufficient insight on how attention towards other enablers could result achieving desired operational performance that could be subject to further research.
5.2. Proposition: Operational performance-driven Productions system design process

Relating to the product design or new product development (Marodin et al., 2018; De Vasconcelos Gomes et al., 2022), the intended production system/line could be considered as a product and the production team as the customer. To ensure the customer’s need (i.e. the production department need), earlier studies (Rönnberg-Sjödin, 2013; Rösiö & Bruch, 2018) emphasized involving the production team early in the PSDP so that functional requirements are properly addressed. The case projects presented in this research followed similar tactics. However, the production lines still resulted in less OEE than the target level, and improvements to OEE happened during the later operation phase. A plausible reason could be that during the PSDP, the main focus remained on meeting the process requirements (i.e. the ability to produce the product to ensure quality). Improving performance or efficiency (i.e. OEE) is considered a later task for the production team after installing equipment.

Delivering products early into the market is considered a competitive advantage, however, managing the ramp-up time is still an issue for the companies. The empirical findings highlights that there is a lack of attention in the training activities, and a push from top management to deliver the product as soon as possible. Therefore, a new approach is required where the PSDP would be driven to achieve the target operational performance. The production team, project team, top management, and equipment suppliers need to address the future operational performance during the PSDP and take proper measures. The goal of the operational performance-driven PSDP will be to meet the respected KPI during different phases of the production system lifecycle. For example, time-to-market during the PSDP, time-to-volume during ramp-up phase and other KPIs, such as OEE, emission, safety, deliverability, quality, that are usually prioritized later on operation phase. It could result in a faster ramp-up, higher performance, and efficient production. The following figure 3 provides a sample example of operational performance-driven PSDP.
6. Conclusion, implication, and future research

6.1. Conclusion

This research explored how to manage PSDP to achieve the desired operational performance. The empirical study identified a set of enablers to address in the PSDP, (i) product and process expertise, (ii) formulation of the project team, project team’s competency, (iii) involvement of the production team, (iv) internal technical competency, (vi) quality of training and testing of equipment, (vii) supplier expertise on equipment, (viii) relationship with the equipment supplier, and (ix) communication with the equipment supplier.

Companies can achieve the target operational performance by addressing proper measures on these enablers during the PSDP. The cross-case analysis of the three case projects shows that projects that ensured proper measures of the enablers achieved the desired and higher OEE. In contrast, the project having low strength of the enablers resulted in lower OEE than the target level during the ramp-up and operation phases.

Utilizing the PSDP for achieving the desired operational performance has long been ignored in industries and academia. Hence, this research proposes an operational performance-driven PSDP concept, where the PSDP process will be driven to meet the target time for delivering the product to market and achieve the target operational performance during ramp-up and operation phases.

6.2. Theoretical implications

This research contributes to the theory building connecting the domain of operational performance management and technology management, specifically on the management of the PSDP. The empirical findings provide new insights on connecting the activities during the PSDP with their impact on operational performance. Linking specific production system design decisions and activities to the final operations performance is a challenging task, and here lies some of the novelty.

As mentioned before, there is a lack of understanding of how decisions related to designing production systems impact operational performance (Battesini et al., 2021), and empirical evidence of how PSDP impact operational performance. This research provided an empirical example of how actions in the PSDP impact operational performance, measured as OEE, and a set of enablers to address during the PSDP for achieving target operational performance. Consequently, this research builds on the understanding of how the production system design-related decisions and activities impact operational performance.

Finally, this research propose a new approach of operational performance-driven production system design process, where the PSDP will be considered an opportunity to improve operational performance.

6.3. Practical implications

The identified enablers and varying implementation of their underlying actions impact operational performance differently. Practitioners could use this to identify significant enablers for their production system design context and strive for more stringent
implementation of relevant actions. Based on the observations of this study, special attention should be given to developing internal technical competence, production operation team’s competency, and quality of testing and training. However, the main implication is the creation of a mindset and awareness of the importance of the PSDP on the final result.

6.4. Future research

As this study is limited to one case study in a process-type manufacturing company, more case studies could be performed in other industrial sectors. Further research is needed to determine how to direct the attention towards different enablers based on the characteristics of the new production-line design/launching projects in terms of newness of product, process, and technology. Practitioners could take proper actions even with a limited project budget and resources by further exploring the problem area and translating the new knowledge to suit the industrial applications. In addition, further research could be conducted to identify the inter-relation among the enablers and to prioritize the enablers using multi-criteria decision-making techniques or other means. Furthermore, this paper only considered OEE as operational performance; other operational performance parameters relating to different aspects of sustainability could be considered.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Abd Rahman, A., Brookes, N. J., & Bennett, D. J. (2009). The precursors and impacts of BSR on AMT acquisition and implementation. IEEE Transactions on Engineering Management, 56(2), 285–297. https://doi.org/10.1109/TEM.2009.2016070

Ahlskog, M. (2015). Supporting pre-development of new manufacturing technologies (Issue 194). Mälardalen University.

Ahlskog, M., Bruch, J., & Jackson, M. (2019). The fuzzy front end of manufacturing technology development. International Journal of Manufacturing Technology and Management, 33(5), 285. https://doi.org/10.1504/IJMTM.2019.103280

Ahmad, N., Hossen, J., & Ali, S. M. (2018). Improvement of overall equipment efficiency of ring frame through total productive maintenance: A textile case. International Journal of Advanced Manufacturing Technology, 94(1–4), 239–256. https://doi.org/10.1007/s00170-017-0783-2

Alves, A. C., & Carmo-silva, S. (2009). A review of design methodologies for manufacturing systems. MECAHITECH’09-1st International Conference on Innovations, Recent Trends and Challenges in Mechatronics, Mechanical Engineering and New High-Tech Products Development, 1–19.

Andersen, A. L., Brunoe, T. D., Nielsen, K., & Rösiö, C. (2017). Towards a generic design method for reconfigurable manufacturing systems: Analysis and synthesis of current design methods and evaluation of supportive tools. Journal of Manufacturing Systems, 42, 179–195. https://doi.org/10.1016/j.jmsy.2016.11.006
Arellano, M. C., Rebolledo, C., & Tao, Z. (2019). Improving operational plant performance in international manufacturing networks: The effects of integrative capabilities and plant roles. *Production Planning and Control, 30*(2–3), 112–130. https://doi.org/10.1080/09537287.2018.1534266

Attri, R., & Grover, S. (2012). A comparison of production system life cycle models. *Frontiers of Mechanical Engineering, 7*(3), 305–311. https://doi.org/10.1007/s11465-012-0332-5

Aurich, J. C., & Barbian, P. (2004). Production projects - Designing and operating lifecycle-oriented and flexibility-optimized production systems as a project. *International Journal of Production Research, 42*(17), 3589–3601. https://doi.org/10.1080/00207540410001696348

Battesini, M., ten Caten, C. S., & Pacheco, D. A. D. J. (2021). Key factors for operational performance in manufacturing systems: Conceptual model, systematic literature review and implications. *Journal of Manufacturing Systems, 60*(June), 265–282. https://doi.org/10.1016/j.jmsy.2021.06.005

Bellgran, M., & Säfsten, K. (2004). Production system design and evaluation for increased system robustness. *Second World Conference on POM and 15th Annual POM Conference*, 1–30.

Bellgran, M., & Säfsten, K. (2009). Production development: Design and operation of production systems. *Springer Science & Business Media*. https://doi.org/10.1017/COBO9781107415324.004

Bruch, J., & Bellgran, M. (2012). Design information for efficient equipment supplier/buyer integration. *Journal of Manufacturing Technology Management, 23*(4), 484–502. https://doi.org/10.1108/17410381211230448

Bruch, J. (2012). *Management of design information in the production system design process (Vol. 51, Issue 11)* (Mälardalen University). Doctoral Dissertations. http://www.diva-portal.org/smash/record.jsf?pid=diva2:592090

Bruch, J., & Bellgran, M. (2013). Characteristics affecting management of design information in the production system design process. *International Journal of Production Research, 51*(11), 3241–3251. https://doi.org/10.1080/00207543.2012.755273

Cantorna, A. I. S., & Die, I. (2005). The effect of the implementation of advanced manufacturing technologies in training in the manufacturing sector. *Journal of European Industrial Training, 29*(4), 268–280. https://doi.org/10.1108/03090590510597124

Chirumalla, K. (2017). Challenges in managing new product introduction projects: An explorative case study. *Proceedings of the International Conference on Engineering Design, ICED*, 2(DS87–2), 259–268. https://www.designsociety.org/publication/39580/Challenges+in+managing+new+product+introduction+projects%3A+An+explorative+case+study

Choudhari, S. C., Adil, G. K., & Ananthakumar, U. (2010). Congruence of manufacturing decision areas in a production system: A research framework. *International Journal of Production Research, 48*(20), 5963–5989. https://doi.org/10.1080/00207540903164644

Cochran, D. S., Arinez, J. F., Duda, J. W., & Linck, J. (2001). A decomposition approach for manufacturing system design David S. Cochran, Jorge F. Arinez, James W. Duda, Joachim Linck, v20, n6, 2001, pp371–389. *Journal of Manufacturing Systems, 20*(6), 371–389. http://linkinghub.elsevier.com/retrieve/pii/S02786125028001194

Cochran, D. S., Arinez, J. F., Collins, M. T., & Bi, Z. (2017). Modelling of human–machine interaction in equipment design of manufacturing cells. *Enterprise Information Systems, 11*(7), 969–987. https://doi.org/10.1080/17517575.2016.1248495

Cochran, D. S., Foley, J. T., & Bi, Z. (2017). Use of the manufacturing system design decomposition for comparative analysis and effective design of production systems. *International Journal of Production Research, 55*(3), 870–890. https://doi.org/10.1080/00207543.2016.1218088

Cooper, R. G. (2011). *Winning at new products: Creating value through innovation*. Basic Book.

De Kogel, W., & Becker, J. M. J. (2016). Development of design support tool for new lean production systems. *Procedia CIRP, 41*, 596–601. https://doi.org/10.1016/j.procir.2016.01.009

de Vasconcelos Gomes, L. A., Seixas Reis de Paula, R. A., Figueiredo Facin, A. L., Chagas Brasil, V., & Sergio Salerno, M. (2022). Design principles of hybrid approaches in new product development: A systematic literature review. *R and D Management, 52*(1), 79–92. https://doi.org/10.1111/radm.12476
Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review, 14*(4), 532–550. https://doi.org/10.2307/258557

Fylan, F. (2005). Semi-structured interviewing. In M. J & G. P (Eds.), *A handbook of research methods for clinical and health psychology* (pp. 65–78). Oxford University Press.

Gupta, P., & Vardhan, S. (2016). Optimizing OEE, productivity and production cost for improving sales volume in an automobile industry through TPM: A case study. *International Journal of Production Research, 1*, 54(10), 2976–2988. https://doi.org/10.1080/00207543.2016.1145817

Hagström, M. (2021). Demystifying the effectiveness in design of production systems. Chalmers University of Technology. Issue 0

Hayes, R., Pisano, G., Upton, D., & Wheelwright, S. (2005). *Pursuing the competitive edge*. John Wiley & Sons.

Henao, R., Sarache, W., & Gómez, I. (2019). Lean manufacturing and sustainable performance: Trends and future challenges. *Journal of Cleaner Production, 208*, 99–116. https://doi.org/10.1016/j.jclepro.2018.10.116

Hubka, V., & Eder, W. (2012). *Theory of technical systems: A total concept theory for engineering design*. Springer Science & Business Media.

Koren, Y., & Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems, 29*(4), 130–141. https://doi.org/10.1016/j.jmsy.2011.01.001

Kumar, R., Singh, H., & Chandel, R. (2018). Exploring the key success factors of advanced manufacturing technology implementation in Indian manufacturing industry. *Journal of Manufacturing Technology Management, 29*(1), 25–40. https://doi.org/10.1108/JMTM-03-2017-0057

Kurkkio, M., Frishammar, J., & Lichtenthaler, U. (2011). Where process development begins: A multiple case study of front end activities in process firms. *Technovation, 31*(9), 490–504. https://doi.org/10.1016/j.technovation.2011.05.004

Lager, T., & Frishammar, J. (2010). Equipment supplier/user collaboration in the process industries: In search of enhanced operating performance. *Journal of Manufacturing Technology Management, 21*(6), 698–720. https://doi.org/10.1108/17403811011064003

Machuca, J. A. D., Ortega Jiménez, C. H., Garrido-Vega, P., & De Los Ríos, J. L. P. D. (2011). Do technology and manufacturing strategy links enhance operational performance? Empirical research in the auto supplier sector. *International Journal of Production Economics, 133*(2), 541–550. https://doi.org/10.1016/j.ijpe.2010.12.010

Marodin, G., Frank, A. G., Tortorella, G. L., & Netland, T. (2018). Lean product development and lean manufacturing: Testing moderation effects. *International Journal of Production Economics, 203*(March), 301–310. https://doi.org/10.1016/j.ijpe.2018.07.009

Marzouk, M., Bakry, I., & El-Said, M. (2012). Assessing design process in engineering consultancy firms using lean principles. *Simulation, 88*(12), 1522–1536. https://doi.org/10.1177/0037549712459772

Mohammadi, Z., Shahbazi, S., & Kurdve, M. (2014). Critical factors in designing of lean and green equipment. *The Annual Cambridge International Manufacturing Symposium, September 2014*, 1–12.

Pashaei, S., & Olhager, J. (2019). Product architecture, global operations networks, and operational performance: An exploratory study. *Production Planning and Control, 30*(2–3), 149–162. https://doi.org/10.1080/09537287.2018.1534267

Pisano, G. P. (1997). *The development factory: Unlocking the potential of process innovation*. Harvard Business Press.

Rauch, E., Matt, D. T., & Dallasega, P. (2016). Application of axiomatic design in manufacturing system design: A Literature review. *Procedia CIRP, 53*, 1–7. https://doi.org/10.1016/j.procir.2016.04.207

Rönberg-Sjödin, D. (2013). A lifecycle perspective on buyer-supplier collaboration in process development projects. *Journal of Manufacturing Technology Management, 24*(2), 235–256. https://doi.org/10.1108/17410381311292322
Rösiö, C., & Bruch, J. (2018). Exploring the design process of reconfigurable industrial production systems activities, challenges, and tactics. *Journal of Manufacturing Technology Management, 29*(1), 85–103. https://doi.org/10.1108/JMTM-06-2016-0090

Säfsten, K., Gustavsson, M., & Ehnsiö, R. (2020). *Research methodology: For engineers and other problem-solvers.* Studentlitteratur AB.

Schuh, G., Lenders, M., Nussbaum, C., & Kupke, D. (2009). Design for Changeability. In ElMaraghy, Hoda A. *Changeable and reconfigurable manufacturing systems* (pp. 251–266). Springer London.

Shiau, Y. R., & Wang, S. Y. (2021). Key improvement decision analysis mechanism based on overall loss of a production system. *Journal of Industrial and Production Engineering, 38*(1), 66–73. https://doi.org/10.1080/21681015.2020.1841687

Sjödin, D. R., Eriksson, P. E., & Frishammar, J. (2011). Open innovation in process industries: A lifecycle perspective on development of process equipment. *International Journal of Technology Management, 56*(2–4), 225–240. https://doi.org/10.1504/IJTM.2011.042984

Slim, R., Houssin, R., Coulibaly, A., & Chibane, H. (2021). Lean system design framework based on lean functionalities and criteria integration in production machines design phase. *FME Transactions, 49*(3), 575–586. https://doi.org/10.5937/fme2103575S

Stark, R., If, T. D., Kind, S., & Neumeyer, S. (2017). Manufacturing Technology Innovations in digital modelling for next generation manufacturing system design. *CIRP Annals, 66*(1), 169–172. https://doi.org/10.1016/j.cirp.2017.04.045

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research techniques.* Sage publications.

Sukhotu, V., & Peters, B. A. (2012). Modelling of material handling systems for facility design in manufacturing environments with job-specific routing. *International Journal of Production Research, 50*(24), 7285–7302. https://doi.org/10.1080/00207543.2011.645512

Trolle, J., Fagerström, B., & Carin, R. (2020). Challenges in the fuzzy front end of the production development process SPS2020 (IOS Press), 311–322. . https://doi.org/10.3233/ATDE200169

Tsarouhas, P. (2018). Improving operation of the croissant production line through overall equipment effectiveness (OEE) A case study. *International Journal of Productivity and Performance Management, 68*(1), 88–108. https://doi.org/10.1108/IJPPM-02-2018-0060

Van Wyk, B. (2012). *Research design and methods Part I.* University of Western Cape.

Wiktorsson, M. (2002). *Performance assessment of assembly systems: Linking strategy to analysis in early stage design of large assembly systems.* KTH Royal Institute of Technology.

Williams, M., & Moser, T. (2019). The art of coding and thematic exploration in qualitative research. *International Management Review, 15*(1), 45–55.

Wurzer, T., & Reiner, G. (2018). Evaluating the impact of modular product design on flexibility performance and cost performance with delivery performance as a moderator. *International Journal of Operations and Production Management, 38*(10), 1987–2008. https://doi.org/10.1108/IJOPM-03-2017-0152

Yin, R. K. (2017). *Case study research and applications: Design and methods.* Sage publications.