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Development of Manufacturing Simulation Software for Production Managers

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Abstract

Performance measurement is indispensable to production management. Production management uses Key Performance Indicators (KPIs) to measure and control the production system. Similarly, manufacturing simulation software can be used to support their decision-making. Simulation allows for testing out various production scenarios to optimise production resources in a risk-free environment. However, what KPIs should production simulation software measure? And how should simulation software be developed to support production managers?

This thesis aims to explore the development of simulation software for production managers. This study is conducted via semi-structured interviews with 15 production and production development managers from various discrete manufacturing industries. In addition, a workshop with simulation experts is hosted to evaluate the applicability of the interview study findings.

The study's key findings reveal the diversity in performance management metrics across different companies in discrete and assembly production industries. While some common metrics, such as Overall Equipment Effectiveness (OEE), exist, their definitions and applications vary among companies. Additionally, production managers employ unique approaches (e.g., in managing personnel) to address production challenges and improvements.

To address these findings, the study proposes novel features for simulation software, including support for Key Performance Indicator (KPI) expressions, standardised data retrieval from the simulation environment, improved data presentation, and simulating workforce skill mix. Furthermore, it suggests incorporating features related to personnel management, such as a calendar system and work shifts, to address production managers' concerns effectively.

Keywords Simulation, Performance Measurement, Production Management, Key Performance Indicators, Management Controls, Industry 4.0

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Tiivistelmä

Suorituskyvyn mittaaminen on välttämätöntä tuotannon johtamisessa. Tuotantojohtaminen käyttää keskeisiä suorituskykyindikaattoreita tuotantojärjestelmän mittaamiseen ja ohjaamiseen. Vastaavasti tuotantosimulointiohjelmistoa voidaan käyttää päätöksenteon tukena. Simuloinnin avulla voidaan testata erilaisia tuotantoskenaarioita tuotantoresurssien optimoimiseksi riskittömässä ympäristössä. Mutta mitä suorituskykyindikaattoreita tuotantosimulointiohjelmiston pitäisi mitata? Ja miten simulointiohjelmistoja olisi kehitettävä tuotantopäälliköiden tueksi?

Tämän diplomityön tavoitteena on tutkia simulointiohjelmiston kehittämistä tuotantopäälliköille. Tutkimus toteutetaan puolistrukturoitujen haastattelujen avulla, joihin osallistuu 15 tuotanto- ja tuotannon kehittämispäällikköä eri valmistusteollisuuden aloilta. Lisäksi tutkimuksessa järjestetään työpaja simuloinnin asiantuntijoille, jossa arvioidaan haastattelututkimuksen tulosten sovellettavuutta simulointiohjelmistoon.

Tutkimuksen keskeiset havainnot paljastavat suorituskykyindikaattoreiden erilaisuuden eri yrityksissä erillis- ja kokoonpanotuotantoaloilla. Vaikka haastattelusta löytyi joitakin yhteisiä mittareita, kuten laitteiden kokonaistehokkuus (OEE), niiden määritelmät vaihtelevat yrityksittäin. Lisäksi tuotantopäälliköt käyttävät ainutlaatuisia lähestymistapoja (esim. henkilöstöhallinnossa) tuotantohaasteiden ja parannusten käsittelemiseksi.

Näiden havaintojen käsittelemiseksi tutkimuksessa ehdotetaan simulointiohjelmistolle uusia ominaisuuksia, kuten tukea keskeisten suorituskykyindikaattoreiden ilmaisuille, standardoitua tiedonhakua simulointiympäristöstä, parempaa tiedon visualisointia ja työvoiman taitojen simulointia. Lisäksi tutkimuksessa ehdotetaan henkilöstöhallintoon liittyvien ominaisuuksien, kuten kalenterijärjestelmän ja työvuorojen, sisällyttämistä, jotta simulointiohjelmisto tukisi tuotantopäälliköitä parhaiten.

Avainsanat Simulointi, Suorituskyvyn Mittaaminen, Tuotannon Johtaminen, Keskeiset Suorituskykyindikaattorit, Tuotannon Kehittämistoimenpiteet, Industry 4.0

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Preface and acknowledgements

I want to thank Professor Lauri Saarinen and my thesis advisor MSc. Fernando Ubis and Jarkko Soikkeli for their good advice and supervision.

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Helsinki, 15 September 2023
Mikael Saksi

Abbreviations

ANSI	American National Standards Institute
AI	Artificial Intelligence
Cpp	Production Part Cost
DES	Discrete Event Simulation
ERP	Enterprise Resource Planning
ESG	Environmental, Social and Governance
GDP	Gross Domestic Product
IRR	Inter-rater Reliability
ISA	International Society of Automation
ISO	International Organization for Standardization
JIT	Just-in-Time
KPI	Key Performance Indicator
ML	Machine Learning
MICR	Manufacturing Intelligence Control Room
OEE	Overall Equipment Effectiveness
PD	Production Development
PDM	Production Development Manager
PM	Production Manager
Pp	Production Pace
RQ	Research Question
TOC	Theory of Constraints
VC	Visual Components
WIP	Work in Progress

1 Introduction

As John Hauser et al. from MIT Sloan stated, "You are what you measure!" (Hauser and Katz Gerald, 1998). The premise of their article discusses the importance of choosing suitable organisational metrics to drive the behaviour of managers. They argue that counterproductive metrics can lead to suboptimal decision-making, which does not support the company's long-term profitability. Manufacturing organisations are also highly dependent on appropriate performance metrics; as stated by Hon, "performance measurement is indispensable to a manufacturing enterprise." (Hon, 2005).

The manufacturing industry significantly influences global greenhouse emissions and value addition. It is estimated that 21 % of global greenhouse gas emissions are attributed to the manufacturing industry (United States Environmental Protection Agency, 2023). Simultaneously, 16 % of global value addition as a proportion of Gross domestic product (GDP) falls on the manufacturing industry (The World Bank, 2023). Hence, even marginal improvements in this industry can significantly improve global sustainability and resource consumption.

In fact, Industry 4.0 (I4.0) is a vast technological revolution, which represents a vital opportunity to address these challenges faced by the global production industry. According to Zhou et al. the German electrical industry estimates that I4.0 will increase industrial productivity by a staggering 30 % (Zhou *et al.*, 2015). Simulation is considered an "an enabling technology of I4.0 for managing complex systems" and plays a vital role in developing this revolution (de Paula Ferreira *et al.*, 2020)

Production managers (PMs) play a pivotal role in the daily operations of manufacturing enterprises. Similarly, production development managers (PDMs) are crucial in developing the efficiency and productivity of the manufacturing system. Simulation software (part of I4.0.) presents an opportunity to support their decision-making without disturbing the actual production system. Simulation software can be used to test out specific what-if scenarios in a risk-free environment. Moreover, it can help save resources, avoid commission mistakes, and analyse the current state of the production system. However, two questions remain: What should production simulation measure? And how can production simulation support production management?

This thesis addresses these concerns by investigating how simulation software can be developed to support production managers. More specifically, the aim is to investigate and identify the Key performance indicators (KPIs) simulation software that should help to cater to challenges faced by production management (relationship between KPIs and simulation is discussed in section 1.1). Simultaneously, the nature of the production manager's work is studied to understand other functionalities that simulation software should offer to support their decision-making. Ultimately, new software features are proposed to steer the development of statistics and analytical features of the Visual Components (VC) simulation software.

Understanding what KPIs should be implemented in production simulation is currently highly topical from the point of view of I4.0. Machine Learning (ML) and Artificial Intelligence (AI) are hot topics of this revolution (Agrawal *et al.*, 2020). The opportunity to employ ML and AI in production simulation software is very relevant. However, without suitable KPIs and data collection methods in simulation, ML and AI tools lack the necessary input and feedback data to optimise these multi-objective production problems. Hence, understanding which KPIs (=objectives) should be implemented in simulation and how data should be collected in the software paves the way for the effective application of these powerful I4.0. optimisation tools (Agrawal *et al.*, 2020). Similarly, employing the digital twin concept requires understanding real-world performance management. Hence, this thesis also aims to address these I4.0. concerns by understanding which KPIs should be harmonised between the real world and the digital twin.

This research is conducted as semi-structured interviews with 15 production managers and production development experts. Moreover, this research entails a workshop with simulation experts from VC to evaluate the applicability of the interview study to the software. These findings are then used to propose new software improvements and features per the insights gathered from the interviews and workshop with industry experts.

This study includes four research questions (RQs) through which the abovementioned topics are investigated. The research questions are:

- **RQ1.** What output KPIs do production managers (PMs) and production development managers (PDMs) track to monitor production performance?
- **RQ2.** What management controls do PM and PDMs have to control and improve the production system?
- **RQ3.** Which production management KPIs do simulation experts recommend developing in simulation software?
- **RQ4.** Which production management controls do simulation experts recommend developing in simulation software?

The remainder of this introduction (section 1.1) explores the framework used in this study, which reveals the interconnections between KPIs, management controls, production managers and the production system. This framework guides the rest of the thesis and aids the reader in understanding the various inter-relations between the research topics in this study.

1.1 Production management framework

The framework used in this study is shown in Figure 1, which demonstrates the focus of research questions 1 and 2. This framework is adopted from Jovan et al., where a closed-loop production management paradigm is presented (Jovan and Zorzut, 2006). As shown in Figure 1 below, the framework components consist of the company management, the PM, the PDM, the production system, Key Performance Indicators (KPIs) and management controls. Additionally, external disturbances and energy and raw materials impact the production system.

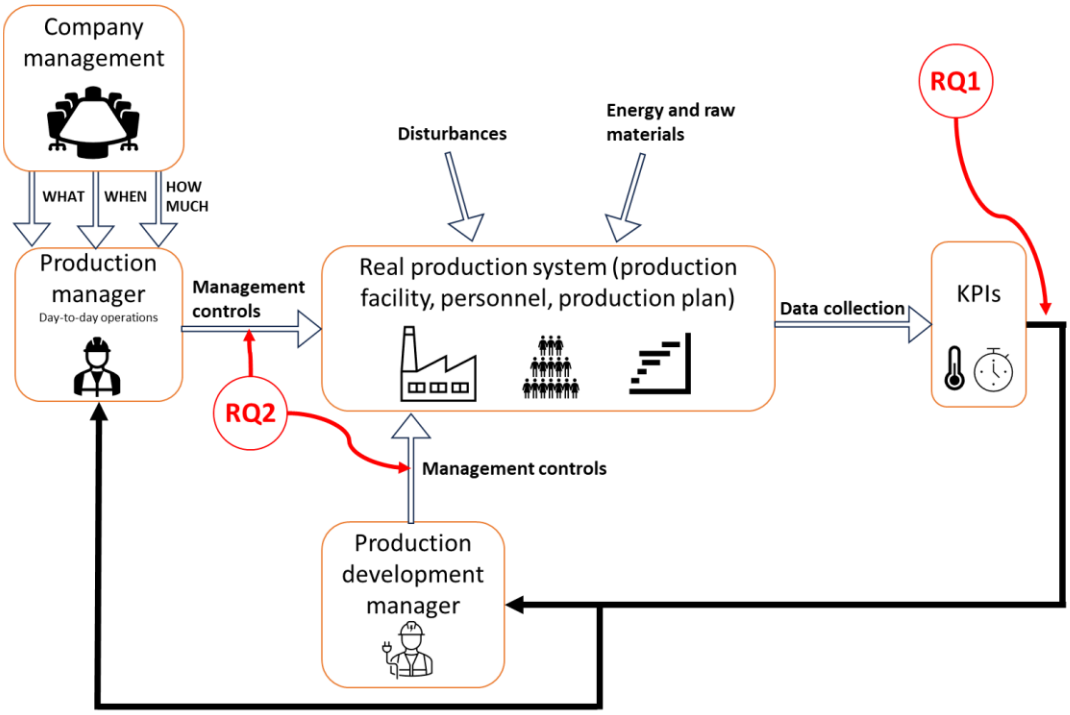

Figure 1: Production Management Framework in the Study (adapted from (Jovan and Zorzut, 2006))

Figure 1 above shows how the company management passes requirements on the PM, which can be in the form of product quality and product type (WHAT), the deadlines for executing production (WHEN), and the production volume (HOW MUCH). The company management may also exert other requirements on the PM, such as worker safety, environmental considerations, cost reductions, etc.

1.1.1 Role of production manager

The role of the PM is to run the day-to-day operations in the factory. The PM is responsible for meeting the demands set by the company's management. The PM influences the personnel in the factory, and they can also alter the production plan. Moreover, the PM can change the workflow and production processes within the production system. The PM also typically aims to identify potential areas of improvement within the factory frequently.

1.1.2 Role of production development manager

The role of the PDM has some overlaps with the PM. It is also worth noting that a single individual takes on both positions in some companies. The PDM does not control the workers and production plan; however, they support the PM by continuously improving the production system. These improvements can include procuring new production technology (e.g., automated welding cells) and improving existing production processes (e.g., updating work instructions and opening bottlenecks). Although both roles overlap in terms of continuous improvement within the production system, the PDM is not typically directly responsible for the execution of the production plan and does not control the personnel within the factory. In larger organisations the PDM may work in a division separate from the PM's division.

1.1.3 Role of KPIs

Furthermore, a vast amount of data is collected in various forms from the production system. This collected data is then used to form KPIs. Both the PM and PDMs then use these KPIs to understand the current state of the production system. The managers can use this knowledge to employ corrective actions if the production system is running below its target performance. Similarly, the KPIs can generate insight for finding potential areas of improvement within the factory. These KPIs are explored via the interview study.

Moreover, the data from KPIs may also be saved and hence cumulate over time. This cumulated data provides historical information on production, which can be used to form trends, seasonal fluctuations and even statistical process control applications.

1.1.4 Role of management controls

Management controls are deemed the operational activities that PM and PDMs can undertake to improve or correct the production system. Improvement actions refer to activities that focus on continuously improving the production system. These are particularly important in maintaining the competitiveness of the manufacturing enterprise. On the other hand, corrective actions refer to operational actions that managers can take in the case of a production malfunction or external disruption. These management controls are also explored via the interview study.

1.2 Production simulation framework

The production simulation environment is presented and followed in Figure 2 below, alongside the focus areas of research questions three and four. Note that research questions three and four, shown in Figure 2 below, apply the interview study findings.

The framework in Figure 2 below consists of the simulation user, the digital production system, and the output data that the simulation presents to the user. In this framework, the simulation user models a twin of the real production system digitally and then uses this output data or feedback to reconfigure the layout. Ultimately, this feedback is then used to improve the design of a greenfield layout or make improvements to a real production line via the insights from the simulation. In this regard, the two frameworks presented in Figure 1 and Figure 2 are alike, as both the simulation user and the PM/PDM use the information from their production system as feedback to configurations it.

The workshop with VC simulation experts explores these research questions three and four.

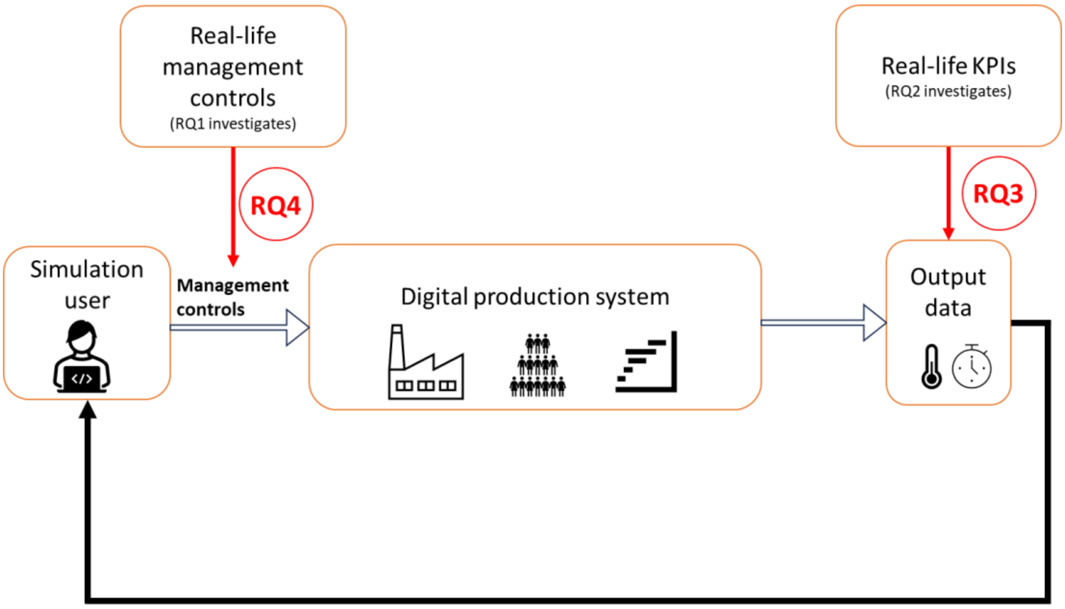

Figure 2: Production Simulation Framework in the Study

2 Production management in literature

This section provides the reader with an overview and understanding of the current literature covering various production management topics relevant to this study. KPIs in production management are reviewed in section 2.1, production improvement philosophies are examined in 2.2, production management controls in section 2.3 and simulation in production management is reviewed in section 2.4. Finally, section 2.5 provides a synthesis of the literature and acknowledges the research gaps this study aims to address.

2.1 KPIs in production management

This section, 2.1, reviews the literature on KPIs in the context of production management. More specifically, the importance, state-of-the-art, categories, hierarchy, ideal properties, and purpose of KPIs in production management are reviewed.

2.1.1 Importance of KPIs in production management

The first reason KPIs and metrics are essential for production management is that it is difficult to control an activity that cannot be measured (Hon, 2005). As stated by Hon, “performance measurement is indispensable to a manufacturing enterprise.” (Hon, 2005). In the same realm, improving a production system without relevant metrics is near impossible, as Kaplan summarised: “No measures, no improvement” (Gunasekaran and Kobu, 2007). Hence, to control and improve the multi-faceted and complicated activity of manufacturing, necessary KPIs will need to be in place to understand the production system’s current state and performance. These metrics can point us to the direction of the system's disturbance or a potential improvement area.

Furthermore, KPIs are vital as they provide relevant insight from the vast data available. As stated by Jovan et al., a PM's main challenge is “how to extract relevant information from his vast amount of data to make fast and correct decisions”. (Jovan and Zorzut, 2006). As stated by their name, **key** performance indicators indicate the most valuable and relevant data to the PM to facilitate their decision-making.

Moreover, some studies highlight the importance of manufacturing performance measurement to maintaining a company’s global competitiveness (Amrina E. and Yusof S. M., 2011) (White, 1996). Amrina et al. state that manufacturing companies must frequently review their performance with appropriate KPIs to ensure competitiveness (Amrina E. and Yusof S. M., 2011). Additionally, having the appropriate KPIs in place allows companies to evaluate the current state of manufacturing performance and acts as a compass to “indicate directions of needed improvement” to ensure future competitive livelihood (White, 1996).

Furthermore, KPIs are also crucial in a manufacturing enterprise as they drive its organisational behaviour. KPIs are not only used to track performance at a company level but also to track the performance of individuals such as PMs, cell managers or machine operators. The article's premise by Hauser et al. is that employees within the organisation will aim to optimise/maximise whatever they are being measured by (Hauser and Katz Gerald, 1998). Similarly, Skinner and Wheelwright suggest that those things that “get measured gets attention, particularly when rewards are tied to measures” (White, 1996). If incorrect KPIs are selected, then it may lead to counterproductive behaviour. For instance, assume that the performance of the PM is evaluated on the production volume they can maintain. This type of KPI can lead to excessive inventory levels, as the PM wants to ensure maximum utilisation of the production line, which may be sub-optimal to the performance of the larger organisation.

Finally, the selection of organisation-wide KPIs facilitates the comparison of factories within the same organisation. As stated by Grencik, a common of metrics “allows for benchmarking between facilities in different countries or continents” (Grencik, 2009). Hence, KPIs allow for comparison between different parts of the organisation whilst facilitating a common language through the employment homogeneous performance metrics.

2.1.2 State-of-the-art production management KPIs

In current literature, a wealth of information exists in the field of KPIs within manufacturing and production management. For instance, the ISO 22400-2: Manufacturing Operations Management – Key Performance Indicators standard lists 34 KPIs, which are KPIs “that they have been used in various industry sectors for some time” (International Organization for Standardization, 2014). The KPIs listed in this standard are Manufacturing Operations Management (MOM) KPIs, which is an “intermediate level within the functional hierarchy of a manufacturing enterprise”. Manufacturing operations and control is level three in the functional hierarchy of activities in a manufacturing organisation as per ISA 95, as shown in Figure 3 below (ISA, 2005). This document aims to provide standard definitions of these common KPIs to facilitate communication about production performance between various organisations and industries. This ISO standard notes that although the KPI definitions are readily understandable and straightforward, different industry experts may interpret the KPIs differently (International Organization for Standardization, 2014).

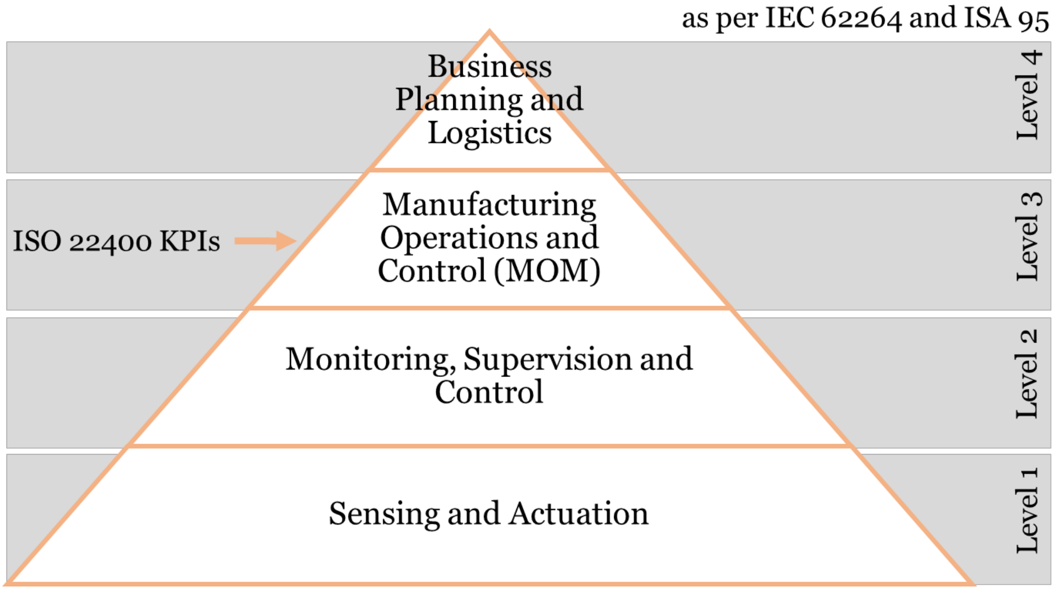

Figure 3: Functional hierarchy of activities in a manufacturing organisation (ISA, 2005)

Another study by Contini and Peruzzini investigated a set of KPIs for manufacturing companies in the context of modern digital transition and Industry 4.0 (Contini and Peruzzini, 2022). More specifically, this study aimed at developing a set of KPIs, which are indicators of production sustainability. This article states that “having a set of sustainability performance indicators is a prerequisite for effective performance management” (Contini and Peruzzini, 2022). The study was conducted via an extensive literature review, and the sustainability performance metrics were divided into economic, environmental, and social KPIs. The result of the research included 48 social, 30 environmental and 39 economic KPIs. For instance, KPIs included payment ratio, work accidents, land use, transportation costs, etc.

KPIs can also vary from industry to industry (Cristea and Cristea, 2021). Hence, several studies have aimed at developing a suitable set of performance metrics for a specific industry. For example, the study by Cristea and Cristea proposed a set of 32 KPIs for measuring the operational performance in the flexible packaging industry (Cristea and Cristea, 2021). The research was conducted as a survey, including a literature-based review and semi-structured interviews with industry experts. The found KPIs were categorised into main KPI areas: production, quality, financial, customer contentment, employee satisfaction and environmental protection. In addition, the importance of individual KPIs was investigated to establish the weights of the industry-specific indicators. Other industry-specific studies include augmented reality in the automotive industry (Jetter *et al.*, 2018), quality KPIs in the pharmaceutical industry (Torkko *et al.*, 2014) and building construction performance indicators (Ali *et al.*, 2013).

Another study by Andersson and Bellgran claims that OEE and productivity are two of the most used performance metrics in operations (Andersson and Bellgran, 2015). The study explores the complexity of using both measures in production improvement. Although OEE was found to be a relevant driver for process stability, it was not found to be an appropriate measure in measuring productivity. The study shows, via a case study, how an improvement in productivity worsens the OEE metric, as the ideal cycle time of the bottleneck resource was reduced.

Furthermore, other shortcomings of the OEE metric include its complexity concerning the triple factor definition (availability, performance, and quality), which complicates its understandability and definition (Andersson and Bellgran, 2015). Moreover, this study claims that empirical findings indicate that the interpretation of categorisations of planned and unplanned time and the definition of ideal cycle time vary from company to company. Similar issues are also persistent with the productivity measure. The definition of productivity also varies from organisation to organisation, but it can also vary within different company levels. The study, however, outlines that well-defined productivity and OEE metrics, when combined with other complementary metrics, can be highly effective at measuring improvements in production performance (Andersson and Bellgran, 2015). The complementary measures include Production Pace (Pp) and Production Part Cost (Cpp).

2.1.3 KPI categorisations

Several studies have investigated the KPIs and metrics in production management and manufacturing. For instance, the survey and taxonomy of strategy-related performance measures by White explores and summarises non-financial KPIs in manufacturing (White, 1996). This study showcases that current literature presents many alternative categories for production KPIs. The study, however, selects the following KPI categories: quality, cost, flexibility (volume and process), delivery dependability, and speed (delivery speed and lead time). The study justifies the selection of these KPI categories as they “seem to have been most widely accepted in manufacturing strategy literature”. It is worth noting that these KPI categories reflect a manufacturing organisation’s strategic objectives. In addition, this study highlights that companies that have established a specific manufacturing competitive priority should prioritise these measures (e.g., companies that compete with quality should have more quality-related metrics).

Moreover, this study provides another four classifications for manufacturing performance metrics. The classifications can be used as a metric to explore different performance measurement systems and to group individual KPIs. The four classifications are summarised in Table 1 below.

Table 1: Four Classifications of Manufacturing Performance Metrics (White, 1996)

Data source	**Where is the data obtained?**
Internal	The data source is within the organization.
External	The data is from outside the organization.
Data type	**Is the data based on opinions and estimates or on independently observable facts?**
Subjective	The data is based on an estimate or an opinion.
Objective	The data is based on observable facts not involving opinion.
Reference	**How is the data referenced?**
Benchmarked	The data is compared to other organisations.
Self-referenced	The data is compared within the organisation.
Process orientation	**Where does the measurement of the data occur?**
Input	The data is measured at the process input.
Output	The data is measured at the process output.

Another study by Hon explores the performance and evaluation of manufacturing systems (Hon, 2005). This study is extensive, as it reviews the historical evolution of performance metrics, types of performance metrics in a manufacturing organisation, properties of these metrics, their purposes, their categorisations, and performance metric frameworks. Firstly, the study categorises performance metrics into cost, quality, productivity, time, and flexibility based on an extensive survey completed by (Hon and Serna, 2005). Within each of these categories, it presents several standard metrics used to measure the performance of the manufacturing system.

2.1.4 KPI Hierarchy

Moreover, Peklenik recognises that performance metrics within a manufacturing organisation can also be classified by a 5-level hierarchy (Peklenik, 2003). The ascending order of the hierarchy is a single machine, manufacturing cell, flow line, factory, and production network. Each of these entities refers to the level of the manufacturing system, where the lowest level is a single machine (or workstation), and the highest level is an entire production network. This production network is a supply chain network with inter-organisational factors and external suppliers.

Furthermore, Kang et al. have described another type of hierarchy for manufacturing KPIs, distinct from the one presented by Peklenik, as shown in Figure 4 below (Kang *et al.*, 2016). The data inter-dependency of the KPIs defines this hierarchy, and their three categorisations include supporting elements, basic KPIs and comprehensive KPIs. Supporting elements refer to data directly collected from the shopfloor (e.g., scrap quantity, actual transportation time, actual unit idle time, etc.). This data can then derive basic KPIs (Kang *et al.*, 2016). Basic KPIs provide insight into the performance of larger entities or systems within the production system and include such KPIs as availability, worker efficiency, rework ratio, and mean-time-to-failure (MTTF). Finally, basic KPIs can be used to derive comprehensive KPIs, which include Overall Equipment Effectiveness (OEE), Net Equipment Effectiveness (NEE), and Line Throughput Rate.

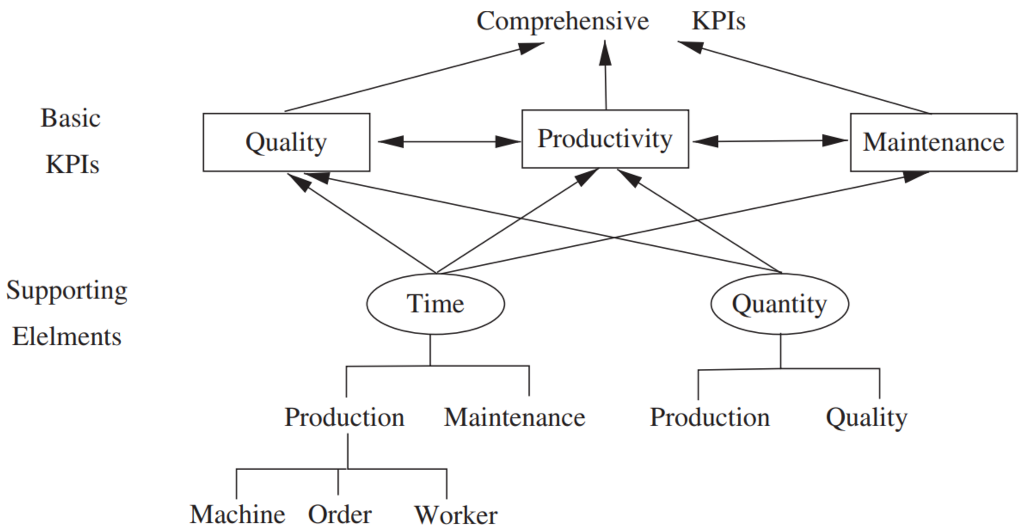

Figure 4: Hierarchy of KPIs including supporting elements, Basic KPIs and Comprehensive KPIs (Kang *et al.*, 2016)

2.1.5 Ideal properties of KPIs

In addition, the article proposes properties of ideal performance metrics (Hon, 2005). The first ideal property of a performance measure is simplicity (Hon, 2005). This refers to the ease of collecting the data for the metric and its interpretability. Andersson and Bellgran also state that performance measures should be easy to understand and collect (Andersson and Bellgran, 2015).

According to the literature, another ideal property of a performance metric is its predictive ability. Predictive ability refers to how forward-looking the metric is in terms of time. For instance, the total order on hand is a forward-looking metric, as it guides planning activities (Hon, 2005). In addition, pervasiveness is another ideal characteristic of a performance measure, which refers to how well the metric can be applied at different levels of the manufacturing hierarchy (e.g., machine, cell, line, factory, and network level).

2.1.6 Purpose of KPIs

Additionally, the study discusses the purpose of manufacturing performance metrics based on a book by Meyer (Marshall W. Meyer, 2003). The purpose of these metrics can be summarised into three distinct perspectives: time, organisational, and human perspectives. These categories are described and summarised in Table 2 below.

Table 2: The three perspectives to performance metrics (Marshall W. Meyer, 2003)

Time perspective	
Look forward	The metric is looking forward and can be used for planning purposes (e.g., future orders at hand).
Look back	The metric is looking in past performance (e.g., what was the production volume last month).
Organisational perspective	
Roll up	The metric can be constructed by collecting data from lower-level units and summarising this altogether.
Roll down	The metric can cascade down from the top to individual functions in the manufacturing organisation.
Human perspective	
Motivate	The metric can be used to individuals within the organisation to achieve or exceed a goal (e.g., production manager gets rewarded if they can achieve a certain production output).
Compensate	The individual employee within the company is compensate for the work they have done (e.g., number of hours worked equals a certain compensation).

2.2 Production management philosophies

As outlined in section 1, this study focuses on the practical day-to-day management controls that PMs can take to improve and control the production system. Although these practical shopfloor-level actions are the focus, production management philosophies are essential to review due to their strong presence in manufacturing organisations. This section is worthwhile for the reader to explore because, in addition to understanding the day-to-day actions that workers in the manufacturing organisation can take, it is also essential to know how these production philosophies guide the decision-making in production improvement.

The purpose of these production philosophies is to provide a framework which will guide production improvement decision-making in the manufacturing organisation. The philosophies do not necessarily directly provide the production organisation with the actions it needs to take but are more holistic frameworks that aid in problem evaluation and improvement.

Although numerous distinct production philosophies exist, this brief review focuses on the Lean and Theory of Constraints (TOC) production philosophies. The review focuses on these as they are prominent production philosophies that various companies widely adopt within the batch and assembly production industry (Muthiah and Huang, 2006). Although only Lean and TOC are discussed, other production improvement philosophies include agile manufacturing, mass customisation, and total quality management (TQM).

2.2.1 Lean improvement philosophy

The Lean production concept can be described as a "philosophy, as a set of principles and as a bundle of practices" (Čiarnienė and Vienažindienė, 2012). The core concept of Lean is to reduce waste and maximise value creation for the customer in the manufacturing organisation. On the shop floor, minimising waste includes overproduction, overprocessing, motion, defects, waiting, inventory, and transportation (Jasti and Kodali, 2015). These various types of waste are shown in Figure 5 by workers, materials, and machines. Simultaneously, Value Stream Mapping (VSM) is used to ensure that each step in the production process provides value to the customer (Čiarnienė and Vienažindienė, 2012).

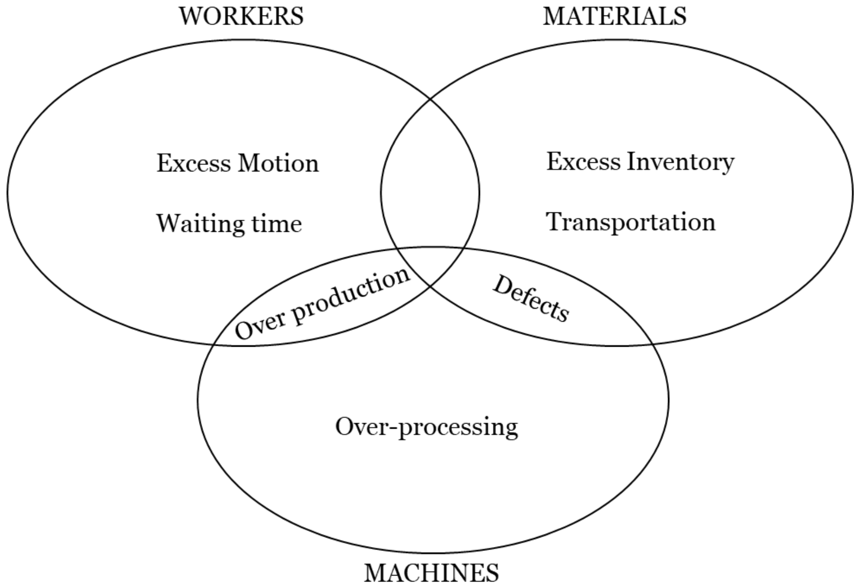

Figure 5: Seven types of waste in Lean by Workers, Materials and Machines (Čiarnienė and Vienažindienė, 2012)

Other principles in Lean include establishing a smooth and continuous production flow in the value stream and implementing a pull production system (Duque and Cadavid, 2007). Ensuring a smooth and continuous production flow improves the efficiency of the production line. The pull production system means that products are not 'pushed' to the customer, but rather, the production chain is linked in a way that manufacturing commences only once they are needed (Duque and Cadavid, 2007). Moreover, Lean principles establish a culture of continuous improvement (i.e., Kaizen) and specify customer value (Čiarnienė and Vienažindienė, 2012).

Several tools are used to implement Lean production principles. These tools include Just-in-Time (JIT), which can be considered a production concept as grouped in the *Hand of Factory Planning* by Wiendahl et al.. JIT aims to deliver raw materials, WIP and products at just the right time (neither too early nor too late) to minimise waste in the form of inventory. Other tools in implementing Lean include Kanban (visual control production and inventory level system), 5S's (to organise the workplace) and Poka-yoke (to reduce the occurrence of mistakes or defects). With this philosophy and tools, it can be argued that Lean "is one of the most important concepts that help enterprises to gain competitive advantage in the world market" (Čiarnienė and Vienažindienė, 2012).

Several studies have investigated and discussed relevant KPIs to measure Lean performance and the extent of Lean implementation. For instance, Gene Fliedner provides examples of performance metrics that Lean practitioners can use to (1) "[for] better understanding or monitoring the current system state", (2) "the metrics permit control activities", and (3) "the metrics can be used for internal or external stakeholder reporting purposes" (Gene Fliedner, 2018). This study categorises the Lean performance metrics by time, cost, quality, flexibility, and sustainability.

Another study by Duque and Cadavid explores the relationship between Lean activities and metrics (Duque and Cadavid, 2007). The study aims to integrate the various Lean metrics in different stages of the production philosophy's implementation. The implementation and, hence, metrics are classified by (1) elimination of waste, (2) continuous improvement, (3) continuous flow and pull-driven systems, (4) multifunctional teams, and (5) information systems. The purpose of the selected metrics is for company performance benchmarking and to provide "input to control charts and establish improvement goals for report periods" (Duque and Cadavid, 2007).

Finally, Karlsson and Åhlström develop a model that aims to evaluate the "changes taking place" to introduce the Lean production framework (Karlsson and Åhlström, 1996). The study identifies the Lean philosophy principles, which include (1) elimination of waste, (2) continuous improvement, (3) zero defects, (4) Just-in-time, and (5) pull instead of push. Other categories include multifunctional teams, decentralised responsibilities, integrated functions, and vertical information systems. Each category includes 'determinants', which are theoretical indicators of Lean implementation, alongside more practical 'measures', which can be used to measure these determinants.

2.2.2 Theory of constraints (TOC)

The Theory of Constraints (TOC) is a management philosophy whereby the most limiting factor in the production system is identified, which stands in the way of achieving a particular goal in the enterprise (Şimşit *et al.*, 2014). TOC is also commonly applied in manufacturing, where the constraint can be called the bottleneck. TOC inherits the Five Focusing Steps, which describes the process of improving the production system by i) identifying the system constraint, ii) exploiting the system constraint, iii) subordinating everything else to the constraint, iv) elevating the constraint, and v) repeat the process (Şimşit *et al.*, 2014). As the bottleneck in the production is improved, another process in the production process naturally becomes the new bottleneck. Hence, the Five Focusing Steps are always applied to the new bottleneck, so the TOC philosophy is called a continuous improvement process (Pacheco *et al.*, 2021).

Throughput accounting is a form of accounting that incorporates the TOC philosophy (Bragg, 2007). It differs from traditional accounting (focused on product level) as throughput accounting is focused on the system level. In traditional accounting, all expenses associated with the production of a specific product are allocated to the product by various means (Bragg, 2007).

The gross margin at the product level is obtained by taking the product selling price and subtracting all production expenses allocated to the product.

Contrastingly, throughput accounting almost wholly ignores the gross margin at the product level and instead emphasises maximising the whole system's profitability (Bragg, 2007). It is assumed that most production expenses are incurred at the system level (i.e., fixed costs of maintaining the production facility) independent of how many units are produced. For instance, a traditional accounting system would allocate the depreciation costs of a specific machine to the product level expense. However, producing more products would lead to negligible machine depreciation costs compared to running the whole facility. Hence, in line with throughput accounting, the system output should be maximised to ensure the highest profitability (variable costs only include direct material).

2.3 Production management controls

This section aims to shed light on existing management controls and improvement programs in the literature. This is different from section 2.2 as this section focuses more on practical and tangible activities applicable on the shop floor. In contrast, production methodologies are more frameworks guiding production improvement decision-making.

Past literature has investigated improvement programs that manufacturing organisations and managers can use to improve production performance. For example, the study by De Meyer and Ferdows lists a total of 39 improvement programs which were established by researchers in the US, Japan, and Europe (De Meyer and Ferdows, 1990). De Meyer and Ferdows state that this list of improvement programs is not extensive, as it is viewed that several other improvement programs not included in this list also exist. Improvement actions from this study deemed most relevant to production management are summarised in Table 3 below.

Moreover, this study also investigates the influence of these improvement programs on performance indicators. For instance, the study concludes that implementing statistical quality control processes positively influenced the quality performance indicators. Similarly, performance measured in terms of on-time delivery was positively affected by better purchasing management, capacity expansion, and plant relocation.

Another study by Lagacé and Bourgalt also investigated improvement programs and their effect on various dimensions of organisational competitiveness in Canada (Lagacé and Bourgault, 2003). More specifically, the study investigated this topic via PMs. This study targeted PMs as PMs were seen to be deeply involved in implementing the improvement program, but they also had “good overall knowledge of the firm”. The improvement programs were divided into three sections: responsive time, elimination of waste and economies of scope, as shown in Table 3 below.

Gelders et al. also list manufacturing improvement activities found through a survey study in Belgium (Gelders *et al.*, 1994). The study found a total of 25 improvement activities. These improvement activities, however, were not described in more detail other than their name. The various manufacturing improvement activities are also shown in Table 3 below. In addition, this study also presents several manufacturing improvement programs, which include a worker participation program, statistical process control (SPC), set-up time reduction (SMED), etc.

These three studies mentioned above reveal potential management control items; however, they are somewhat outdated and may not represent modern manufacturing practices. Digitalisation, Industry 4.0., and the Internet of Things are all developments that these studies may not fully capture. Unfortunately, newer literature provides little to address modern-day management controls of PMs; hence, this study aims to address this gap. Addressed research gaps are discussed more at the end of the literature review in section 2.5.

Table 3: Improvement programs and management controls found in literature relevant to production management.

Study	Improvement programs, actions, and activities	
(De Meyer and Ferdows, 1990)	❖ Direct labour motivation ❖ Manufacturing reorganization ❖ Worker safety ❖ Automating jobs ❖ Recondition physical plants. ❖ Closing plants ❖ Statistical quality control ❖ Giving workers a broader range of tasks ❖ Giving workers more planning responsibility	❖ Supervisor training ❖ Purchasing management ❖ Reducing the size of the manufacturing workforce ❖ Introducing robots ❖ Reducing set-up time ❖ Preventative maintenance ❖ Reduction of size of manufacturing units ❖ Capacity expansion ❖ Plant relocation
(Lagacé and Bourgault, 2003)	**Responsive time:** ❖ Set-up time ❖ Production flow optimization ❖ Cellular layout ❖ Stock management ❖ Relations with suppliers ❖ Production to order **Elimination of waste:** ❖ Maintenance management ❖ Quality control ❖ Zero-defect ❖ Workstation re-organization	**Economies of scope:** ❖ Flexible equipment ❖ Product development method ❖ Product simplification ❖ Workforce flexibility ❖ Employee involvement
(Gelders *et al.*, 1994)	❖ Process quality ❖ Process availability ❖ Set-up times ❖ Lot sizes ❖ Administrative lead-times ❖ Automated information ❖ Automated processes ❖ Integration information systems ❖ Internal communication ❖ Raw material inventories ❖ Final product inventories ❖ Work-in-process ❖ Manufacturing lead-time	❖ Product oriented layout ❖ Process flexibility ❖ Performance reporting ❖ Rework/scrap ❖ Communication with customers ❖ Safety ❖ Capacity ❖ Forecast demand ❖ Planning cyclus ❖ Communication with suppliers ❖ Faster decision process ❖ Others

2.4 Simulation in production management

This section investigates the purpose of simulation in production management, various types of production simulation software, and studies that aim at developing multiple aspects of production simulation software.

2.4.1 Purpose of simulation for production management

As described by Chung, in the context of industrial and manufacturing engineering systems, “simulation modelling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system” (Chung, 2004). In manufacturing, simulation can be used to test specific scenarios without altering the actual system. In other words, simulation can be used to examine and compare alternative designs or investigate existing system issues (Hosseinpour and Hajihosseini, 2009). Moreover, simulation can be used both in the system’s design and during its operation (Mourtzis *et al.*, 2015).

Simulation has several benefits to an organisation. Firstly, simulation is a tool that grants low-cost, secure, and fast manufacturing system analysis (Mourtzis *et al.*, 2015). It allows engineers and decision-makers to test a system before its implementation. For instance, mistakes in specific factory layouts can be realised through manufacturing simulation rather than on the shop floor, leading to cost savings and quicker system commissioning time. Secondly, manufacturing simulation benefits include reduced equipment damage and lower personnel training costs (via operator training simulator) (Hosseinpour and Hajihosseini, 2009).

Moreover, simulation can also be used as a communication tool for stakeholders with a limited understanding of the manufacturing system. For example, visual simulation tools allow for more effective communication of manufacturing line problems to stakeholders, such as company management, who may have limited experience in shop floor operations. Finally, simulation can provide manufacturing organisations with greater flexibility in re-designing their manufacturing system, which is increasingly vital due to the “dynamic nature of the market and its fluctuations (Mourtzis *et al.*, 2015). Chung states that “benefits have resulted in simulation modelling and analysis projects in virtually every service and manufacturing sector” (Chung, 2004).

Hosseinpour and Hajihosseini also discuss various problem areas within production management, which simulation can address (Hosseinpour and Hajihosseini, 2009). These applications were found via a comprehensive literature review, and applications include but are not limited to bottleneck analysis, throughput analysis, establishment of inventory policies, material flow control strategies, reliability analysis of predictive maintenance, queue sizes, estimation of the utilisation of equipment and personnel, or time-in-system analysis (Hosseinpour and Hajihosseini, 2009).

2.4.2 Types of production simulation

Mourtzis et al. provide some categories for classifying simulations (Mourtzis *et al.*, 2014). Simulation models can be classified by their randomness into either stochastic (repetition of simulation leads to different results) or deterministic (repetition of simulation leads to the same result). An example of a stochastic simulation is the Monte Carlo simulation technique (Kassen *et al.*, 2021). Moreover, simulation models can be classified as static or dynamic by their dependence on time. Dynamic models (dependent on time) can be classified into continuous or discrete simulations. Other classifications include the simulation's data organisation into grid-based and mesh-free structures. VC can be classified as a dynamic discrete event simulation (DES) program.

Furthermore, Mourtzis's extensive literature review provides an understanding of the distinct manufacturing simulation domains, which allow for the distinction of various software tools (Mourtzis *et al.*, 2014). These manufacturing simulation domains include factory layout design and production planning, robotics, material flow, energy consumption and environmental impact, systems planning and control, ergonomics, product design, customer demand and market developments, manufacturing networks design, planning and control, process design, planning and verification (Mourtzis *et al.*, 2014). These domains of simulation are summarised in Figure 6 below.

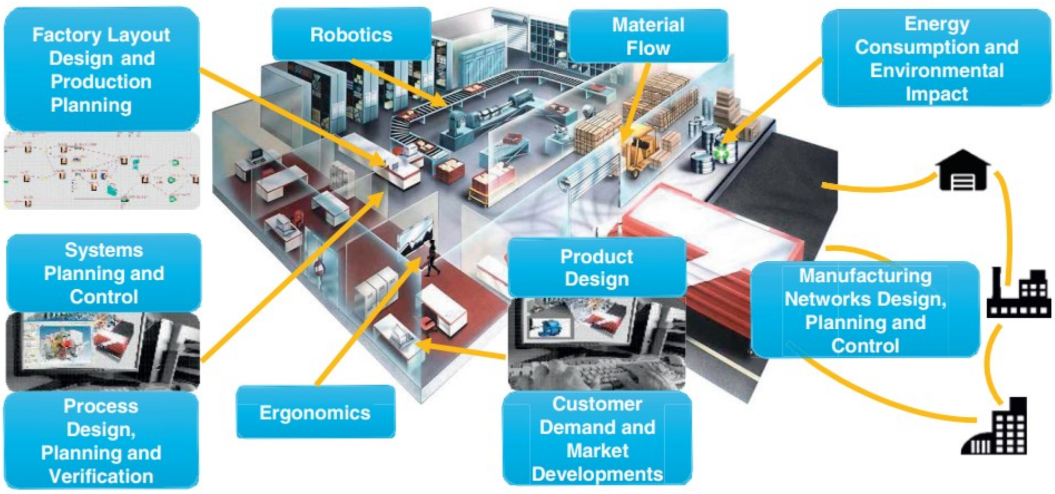

Figure 6: Manufacturing Simulation Domains (Mourtzis *et al.*, 2014)

2.4.3 Development of simulation software for production management

According to Huynh et al., various research literature explores the applications of Discrete Event Simulation (DES) in specific case studies (Huynh *et al.*, 2020). However, there is limited research on DES in manufacturing performance management. This study aims to develop a simulation model which calculates production KPIs from a dynamic simulation. These results can then benchmark manufacturing performance management in the actual system. Moreover, this study details the technical implementation of the model in which the output data is presented in a Manufacturing Intelligence Control Room (MICR), as shown in Figure 7 and Figure 8 below. KPIs calculated in this study via ThingWorx industrial IoT software include availability, performance, OEE and daily throughput. The choice of KPIs is not explicitly justified in this study.

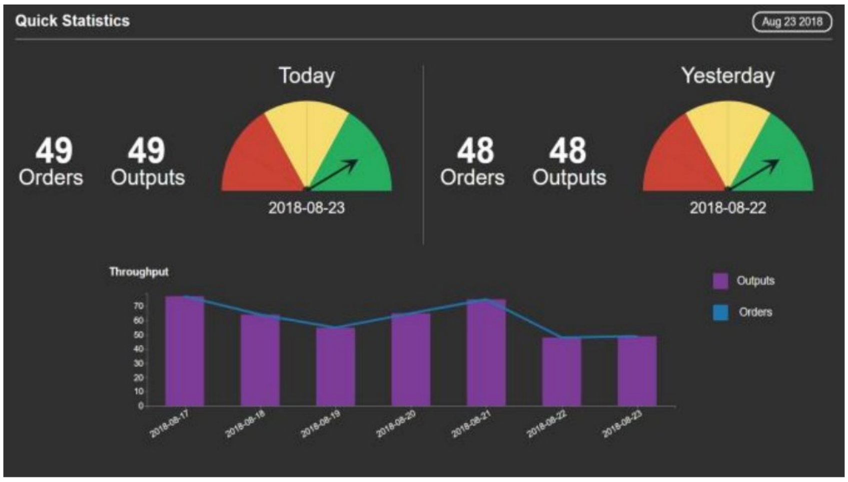

Figure 7: Simulation linked to MICR dashboard showing throughput (Huynh *et al.*, 2020)

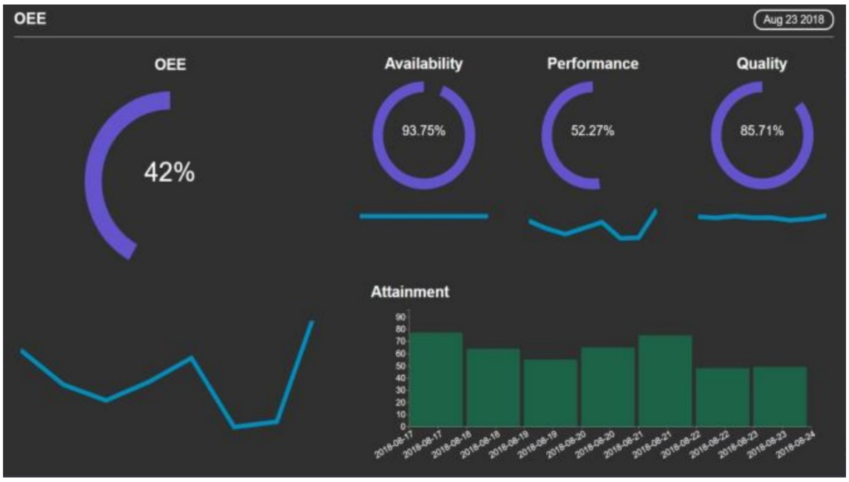

Figure 8: Simulation linked to MICR dashboard showing OEE (Huynh *et al.*, 2020)

In addition, this study investigates how specific parameters within the production system can be optimised (Huynh *et al.*, 2020). This optimisation task uses the GAWizard application within the Siemens Tecnomatix plant simulation software. Optimisation objectives mentioned in the study include makespan, throughput and buffer sizes between machining and assembly stations.

Another study by Popovics et al. developed a generic data model framework named EasySim, which was adopted to fit the ISA-95 framework shown in section 2.1.2 Figure 3 (Popovics *et al.*, 2016). The study presents the class diagrams for the developed system and states that the generic data structure is interchangeable from one simulation program to another. For instance, the data model is applied in both Siemens Plant Simulation software and C#. The study also investigates the validity of the newly developed generic data structure.

Furthermore, the study by Kassen et al. develops a generic simulation model which uses enterprise resource planning (ERP) software as input data (Kassen *et al.*, 2021). This generic simulation model development aims to reduce the costs of building a digital shadow for SMEs. The premise is that SMEs do not have the resources and money to create simulation models, which are considered rather expensive. Hence, input data from the ERP system would allow for low-cost simulation model development. In addition, this study lists the KPIs, which the generic simulation model calculates, which include run time, setup time, cycle time, process time, production lead time, utilisation, and machine productivity. The study, however, does not explicitly justify the choice of these simulation KPIs.

2.5 Gaps and limitations in literature

Current literature has a wealth of information on production KPIs, their categorisations, hierarchies, purposes, etc. Also, studies on improvement programs in manufacturing organisations have been investigated and their effectiveness, for instance, on various dimensions of competitiveness. Current literature also provides case studies utilising production simulation for specific industry applications. Moreover, few studies detail the technical development of production simulation software (e.g., integration of simulation into production performance management, generic data structure applicable to the ISA-95 standard, and even an integration of simulation with ERP software).

Despite these studies, gaps in literature still exist, which this study will aim to address. Literature offers a wealth of distinct KPIs that have been reported in empirical surveys and extensive literature reviews. However, current literature does little to provide insight into which KPIs production managers actually use from this vast selection of KPIs. Furthermore, this study attempts to uncover the characteristics and relative importance of the KPIs to production managers.

Moreover, this study's unique angle is to take the perspective of industry experts and customers via an interview study in developing production simulation software. More specifically, the research gaps addressed in this study include:

1. Understanding what KPIs PMs and PDMs track on the shop floor. In addition, this interview study will also try to understand the reasons behind measuring specific KPIs, as well as their prevalence.
2. Understanding what day-to-day management controls PMs and PDMs have to improve and control production. This field has limited information; hence, this study aims to add knowledge about the more practical and tangible actions of PMs and PDMs.
3. Understanding which KPIs should be developed in production simulation software. Current literature offers limited information concerning justifying the selection of production KPIs in simulation software.
4. Understanding what new functionality should be developed in production simulation software to facilitate decision-making for production management.

3 Methodology

3.1 Research design and justification

The empirical study can be split into two parts, as shown in Figure 9 below. The first part deals with the KPIs that PMs and PDMs use in their field. This phase also includes investigating the management controls these managers take to improve or correct the production system. The focus of this section is on answering research questions one and two. This first part can be further divided into critical segments: recruiting interviewees (3.1.1), conducting interviews (3.1.2), and analysing interviews (3.1.3).

The second part of the study investigates the practicality and feasibility of the findings in simulation. This section aims at answering research questions three and four. This part deals explicitly with which KPIs should be implemented in manufacturing simulation software. Secondly, this section investigates which management controls should be added to the manufacturing simulation software. This section is divided into two main phases, which include the methodology for conducting the workshop (3.1.4) and analysis of the workshop findings (3.1.5).

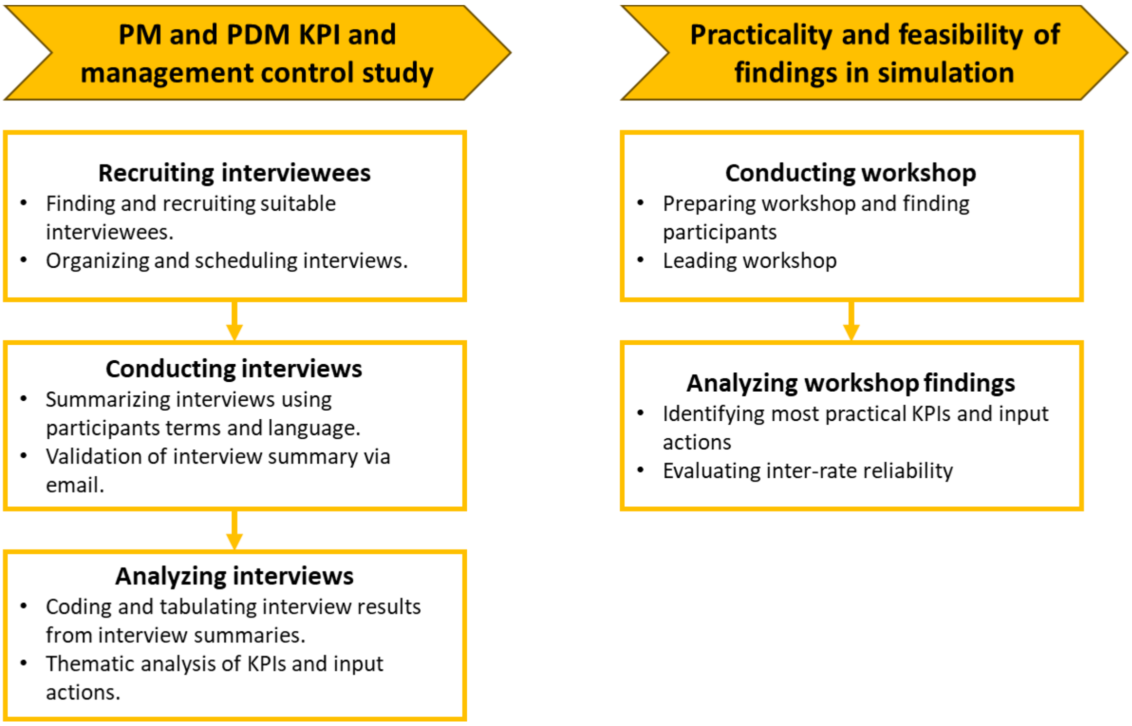

Figure 9: Outline of key phases in the empirical study.

3.1.1 Recruiting interviewees

The process of recruiting interviewees for the study started by listing out all potential a) contacts who may be suitable for the study or b) contacts who may know someone within their organisation who is suitable. Most interviewee leads were gathered through the customers and known contacts within Visual Components (VC). Several VC sales and simulation expert team members were consulted for potential interviewee leads. A few potential leads were listed based on personal contacts. A total of 24 leads were generated in the process. Leads in discrete manufacturing industries were targeted, as this is the clientele and application of the VC software.

The leads were primarily contacted by email. This email contained a short introduction of the researcher and an introduction to the study, including its purpose and aim. The interview guide with the potential questions was also attached to the email to provide more clarity on the topic in question. The interview guide sent to the interviewees can be found in Appendix A. The explanation of the study and attached interview questions were kept concise but informative to ensure that the lead could identify a suitable participant for the interview in their organisation. The lead's personal evaluation of the participants' or their suitability for the study was relied on.

Moreover, the leads were also called wherever possible to increase the reply rate. It was noted that calling potential leads increased the rate of replies considerably and resulted in more interviews. The phone calls included an introduction of the researcher and a reminder of the email sent to the recipient. After calling, several leads commented that they had forgotten to reply to the email but were nonetheless willing to participate in the study. Out of 24 leads, 18 responded, and 12 interviews were accepted, as shown in Figure 10.

The five left-out interviews were not organised due to several reasons. Two of these leads never found a suitable candidate in their organisation for the interview. Another lead was deemed unsuitable for the study as they had no management experience as PM or PDM. Moreover, another lead reported that their PM was dealing with the aftermath of a fire at their workplace and could not participate in the study. The last left-out participant was not included due to a missed email.

The 12 interviews included a total of 15 interviewees and 11 different companies. PumpCo1 and PumpCo2 were from the same organisation; however, PumpCo1 was in production development, whereas PumpCo2 was with a PM. In addition, RoboticsCo included three participants in one interview. All other interviews included only one participant.

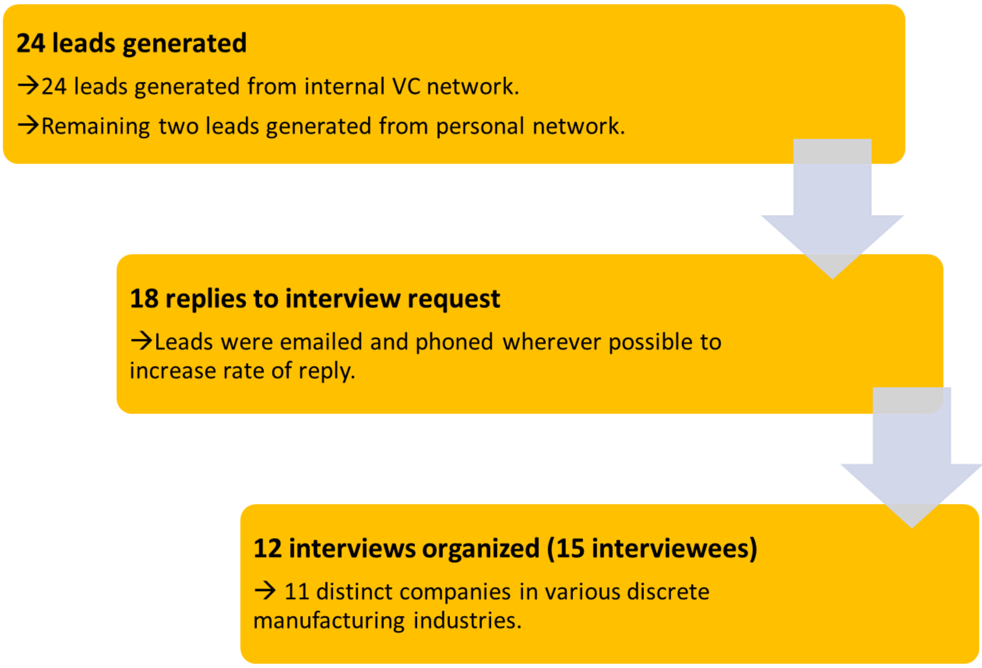

Figure 10: Recruitment process for interviews

The roles of the interviewees are displayed in Figure 11 below. Nine interviewees could be categorised as PDMs based on their current position, representing 60 % of the participants. The study also includes five working as PMs, representing 33 % of participants. Based on interview responses, one participant seemed to be actively taking on the role of PM and PDM simultaneously, representing 7 % of participants.

Furthermore, the study participants were not only classified by their official job title. The job titles in different organisations varied for the same role. For instance, for some companies, the role of a PDM was 'manufacturing technology director', whereas for others, it was 'industrial director' or simply 'production development manager'. Hence, the participants were classified by which category they primarily fit based on the description of their role in the interview. These roles were defined in sections 1.1.1 and 1.1.2.

It is also worth noting that although the participants were classified primarily as PDM or PM, a few interviewees mentioned having experience in both fields. For instance, the FirearmCo interviewee was currently a PDM; however, he had worked as a PM in his previous role. Contrastingly, the PumpCo2 and CabCo interviewees were currently PMs; however, they both had an extensive background in production development.

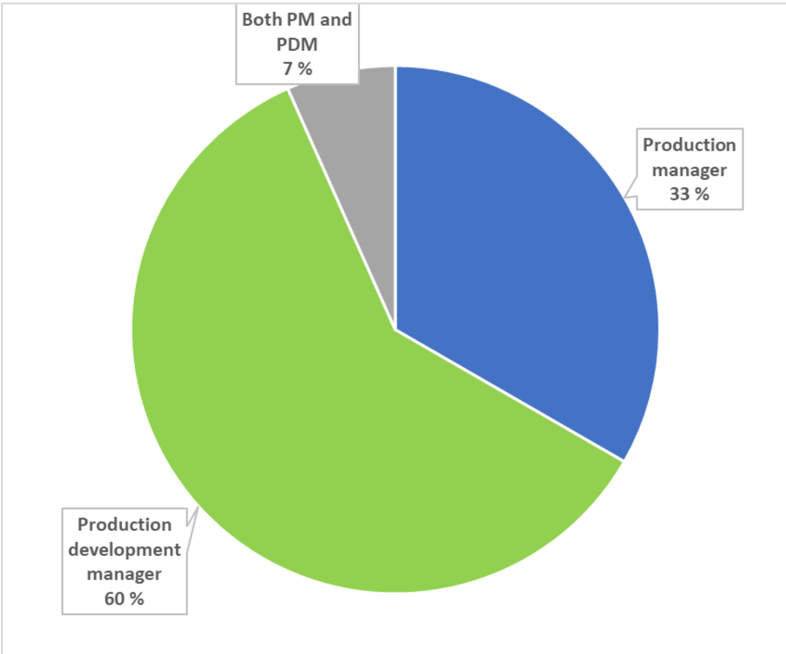

Figure 11: Current role of interviewees in empirical study

The interviews were conducted both in Finnish and English. 60 % of interviewees were Finnish and hence also the interviews. An additional interview guide in Finnish was also created. The remaining interviewees (40 %) were either Dutch, German or Spanish; hence, these interviews were in English.

Moreover, 60 % of participants had at least some experience with the VC production simulation software. The remaining 40 % of participants had no experience with production simulation software. In Table 4 below, the background of the interviewee participants is given along with their anonymous names.

Table 4: Background of interview study participants

Interviewee	Role	Simulation experience	Industry	Production portfolio	Annual production volume	Customer preferences	Production type
MachineryCo	PM	No	Forest machinery	Harvesters and forwarders	Not stated (confidential)	Quality (operational reliability), delivery speed, diverse product range	One-piece production
MillingCo	PDM	VC	Automotive	Milling and drilling machines	Not stated (confidential)	Flexibility, production volume, quality, and availability	Repetitive production
PumpCo1	PDM and PD expert	VC	Industrial pumps	Process pumps, turbo compressors, special pumps, and mixers	Thousands	Mainly customisability however others include flexiblity, speed, quality, and cost.	Batch production
FirearmCo	PDM	No	Firearms industry	Firearms (product 1) and ammunition (product 2)	Product 1: 100'000+ Product 2: Millions	Mainly quality (reliability, functionality) and customisability	Batch production
DecorCo	PM and PDM	VC	Kitchen, bathroom, and home décor	Kitchen equipment and chipboard products	Hundreds of thousands	Product customisability and quality	One-piece-production
ElectronicsCo	PDM	VC	Electronics for industrial use	Industrial standard electronic boards	5'000 to 20 million depending on product	Quality, delivery reliability, Flexibility	Batch production
TelecommunicationsCo	PDM	No	Telecommunications	Antennas, signal splitters, PLCs, components for public, PCBs	Millions	Cost and quality	Mass production
CabCo	PM	No	Agricultural and industrial vehicles	Safety cockpits for agricultural and industrial vehicles	Thousands	Customisability, delivery reliability and quality	Job shop
PumpCo2	PM	VC	Industrial pumps	Process pumps, turbo compressors, special pumps, and mixers	Thousands	Flexibility and quality	One-piece-production
MarineCo	PM	VC	Maritime	Large propulsion engines for large industrial or carrier ships	Less than a hundred	Quality and customisability	Job shop
ConsumerCo	PDM	VC	Hygiene consumer products	Shavers, baby bottles, soothers, groomer parts, toothbrush parts	Millions	Customisability, quality, cost, and flexibility	Mass production
RoboticsCo	PM, PDM and PD expert	VC	Automation	Robots	Thousands	All factors but especially delivery reliability	Between batch and one-piece flow.

3.1.2 Conducting interviews

The interview and analysis process can be seen in Figure 12 below. The semi-structured interviews, interview summary (2a) and interview validation (2b) will be detailed in this section 3.1.2.

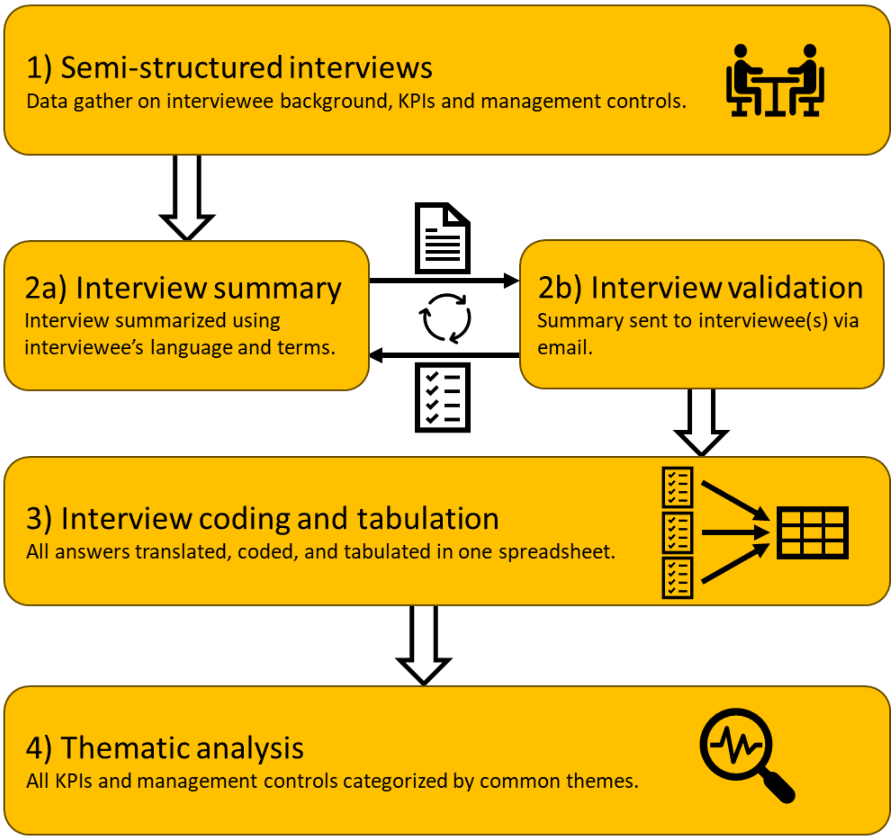

Figure 12: Interview analysis process

Justification for semi-structured interviews

The interviews were conducted as semi-structured interviews. The interview guide guided the discussions, which can be found in Appendix A. The semi-structured interview style was selected for several reasons. Firstly, it was found that semi-structured interviews provide a suitable balance between rigidity and freedom in the research. Many of the questions and topics in this study are interrelated and ambiguous; hence, a survey or structured interview would have allowed the study participant to elaborate on their answer.

For instance, many participants reported a specific KPI (e.g., OEE) as a metric they currently employ. However, with the freedom provided by the semi-structured interview, some participants could also elaborate on the usefulness of this metric. Some commented that the metric was too complicated for their production system. Similarly, some participants also mentioned how certain KPIs are measured in various ways within an organisation. A survey or structured interview would not have been as effective at capturing these tacit insights.

Moreover, the semi-structured interview was chosen due to the diverse backgrounds of the interviewees. It was clear that some participants could give more insight into some research areas. For example, some interviewees had used production simulation software whereas others had not, which provided different discussions on the practicality of KPIs and new functionality in the simulation software. Hence, the chosen interview method allowed flexibility for the participant to offer knowledge within their area of expertise.

The final reason for using semi-structured interviews was that it allowed for comparison between interviews due to its structure. This interview method ensured that the information provided by the interviewees could be coded within common categories and simplified the interview analysis task.

Location of interviews

Additionally, the interviews were organised in person whenever possible to facilitate more effective communication. One in-person interview also facilitated a tour of the production facility to elaborate on the ideas discussed in the interview. However, many interviewees were located overseas or far away from the capital area of Finland; hence, 70 % of interviews were organised via teams. All the team's interviews were video recorded, and the in-person meetings were audio recorded.

Interview structure

Most interviews took one to two hours. The interview structure was as follows:

1. **Study introduction.** The interviewer presents a short introduction, the purpose and aim of the study, and a brief explanation of the VC software. This provided the participant with the context of the study. Additionally, consent to recording the interviewee was agreed upon.
2. **Background of interviewee and company.** The interviewee describes their current responsibilities, experience in production, company production portfolio, customer segments, and the production process.
3. **Output KPIs.** This section is aimed at answering research question one. In this section, the interviewee is asked about the performance metrics they use in the factory, their KPIs, differences between cell and factory KPIs, KPI reporting and review, any trends affecting future KPIs, etc.

4. **Management controls.** This section is aimed at answering research question two. This section aimed to find actions taken to improve the current state of production, actions taken in malfunction situations, ensuring the operation of critical production processes and theoretical ‘what-if’ scenarios the managers would like to test if they could.
5. **Production philosophy.** This section aimed at gathering background information on the production philosophy in place within the manufacturing organisation. This section was deemed additional and undertaken if there was extra time at the end of the interview.

The interview guide was drafted and then reviewed by the advisor and Simulation Expert team within VC. This review and redesign facilitated an interview guide aimed at answering research questions one and two thoroughly. The complete interview guide can be found in Appendix A.

Reliability and validity of the interview study

The questions were first provided without specific examples to improve the reliability of the study. This interview technique was used as giving specific examples of KPIs would also affect the interviewees' answers, harming the investigation's impartiality. However, a careful example was provided if the interviewee did not understand the question or needed an example. For instance, when discussing ‘future trends affecting the measured KPIs’, energy consumption and CO_2 metrics were provided as examples. When interviewees confirmed their answers through an example provided by the interview, it was noted that the answer was given through the interviewer’s example. The results described in section 4 also indicate answers provided via an example.

Moreover, after each interview, a discussion summary was made using the interviewee's language and terms. This interview summary was emailed to the interviewee to allow the study participants to make any changes or additions to the notes. The purpose of this was to improve the interview process's validity by reducing any interviewer misinterpretations. Out of the 12 interviews, seven interview notes (58 %) were amended after sending this validation email. Additions and corrections included correcting company production volume, adding new KPIs, specifying ambiguous KPIs, specifying customer preferences, specifying product variants, and sending other material related to the study.

3.1.3 Analysing interviews

This section details the ‘interview coding and tabulation’ and ‘thematic analysis’ shown in Figure 12.

Interview coding and tabulation

The interviews were coded by forming common codes that arose from the interview questions. As the interview questions followed the interview guide, the answers in the interviews could also be documented using the same codes. The codes and specifications were formed by extracting information from the interview summaries one by one. All information that was deemed to be relevant in answering the research questions was included. Initial codes were formed from the first interview summary; however, more codes had to be added as it was realised that other interview summaries introduced new codes. As new codes were formed, previous interview entries were checked to evaluate their applicability to the new code. In the end, a total of 22 codes were created. The 22 codes were grouped into four main segments of the interview guide. The codes developed are displayed in Table 5 below.

Table 5: Interview codes by interview segment

Interview segment	Code
Part 1: Background of interviewee and company	❖ **Interviewee name** ❖ **Company name** ❖ **Role and experience:** description of current role and experience relevant to study. ❖ **Experience with production simulation software:** does the interviewee have experience with production simulation? ❖ **Industry:** within which industry does the interviewee's company operate in? ❖ **Production portfolio:** what products does the company produces? ❖ **Annual production volume:** how many units are produced per year and how is this measured? ❖ **Product variants:** how many product variants exist in the interviewee's production domain within the company? ❖ **Customer preferences:** what does the customer value from production (e.g., speed, quality, dependability, flexibility, or cost)? ❖ **Production type:** how is the production characterized (e.g., job shop, one-piece, batch, or mass production)? ❖ **Push or pull production:** does the interviewee characterize their production system as pull, push or mixture of both?
Part 2: PM and PDM Output KPIs	❖ **Primary KPIs**: the most important metrics used, which the interviewee views being most important. ❖ **Secondary metrics:** metric that are also followed but they are not KPIs. ❖ **Frequency of KPI review and updates:** how often the KPI data is updated and how often they are reviewed? ❖ **Cell vs. factory level KPIs:** are there any differences between KPIs tracked at the cell and factory level?
Part 3: PM and PDM Management Controls	❖ **Approach to production improvement:** how does the interviewee describe their approach to a production malfunction or issue (e.g., production volume below target)? How does the interview approach production improvement? ❖ **Example improvement/corrective actions:** what past examples of corrective or improvement actions does the interviewee mention?

	❖ **What-if scenarios:** what theoretical changes would the interviewee make to production if this did not affect the current system and it was risk free? ❖ **Challenges currently:** what challenges is the interviewee currently facing in production? What additional tools and resources would they need to solve the issue?
Part 4: Production Philosophies	❖ **Production philosophy:** does the interviewee believe that a certain production philosophy is in place in the factory? If so, does the interviewee believe this affects the metrics used?
Other comments	❖ **Other comments:** other insightful comments, which may be valuable to the study but did not fit under any other code (e.g., direct software development ideas).

Part 1 and Part 2 codes shown in Table 5 above rose directly from the interview questions. However, codes found in in Table 5, part 3 above (PM and PDM management controls) arose from interaction with the interviewees. It was realised that questions directly related to 'management controls' were too broad; hence, this management controls discussion developed into three parts: approach to production improvement, example improvement/corrective actions, and what-if scenarios.

This 'approach to production improvement' became a natural way to discuss management controls. It allowed the interviewee to start from the bigger picture and start thinking about production improvement. Here, the interviewee was allowed to freely discuss their general approach to identifying and correcting production problems.

The following code in Table 5 and part 3 is the 'example improvement/corrective actions'. This code is about concrete examples the interviewee has taken to improve or correct production. It brought more practicality and substance to the answer than the description of the general production improvement approach.

Lastly, 'what-if scenarios' were scenarios that the interviewee would like to test if they could do so in a hypothetical situation. It was assumed that PMs and PDMs are unwilling to test all scenarios, as this would halt production and changes could, for example, damage production equipment. Answers within this code tried to identify new functionality that could be added to production simulation software, as new production configurations can be tested in simulation without compromising the actual system.

Thematic analysis

Thematic analysis was selected as the analysis method for processing the interview study KPIs and management controls. The thematic analysis method was chosen due to its simplicity and flexibility. As the KPIs and management controls had commonalities, but there were a considerable number of them (a total of 46 KPIs), a simple method of grouping them by category was necessary. Similarly, the 'example improvement/corrective actions' and 'what-if scenarios' (total of 21 actions) needed a simple method of categorising them to make the data more understandable.

The codes from the interviews were taken, and the most relevant data on each research question was focused on. The answers under the 'Primary KPIs' code were all listed to construct data for research question one. Similarly, all 'Approach to production improvement', 'Example improvement/corrective actions', and 'What-if scenarios' were listed in a single spreadsheet to construct data for research question one.

Firstly, themes for the KPIs were investigated. This was done by examining all the KPIs and looking for common patterns. The data was grouped using two different sets of themes. Moreover, ChatGPT was also used to generate a third grouping along with applicable themes. After this process, all groupings and themes were re-evaluated, and the one most suitable in the study context was selected. A similar procedure was also taken for the 'Approach to production improvement', 'Example improvement/corrective actions', and 'What-if scenarios'.

Due to a lack of data and enough commonality between the data for code, the 'Approach to production improvement' thematic analysis for this code was disregarded. Hence, thematic analysis was only undertaken for 'Example improvement/corrective actions' and 'What'-if scenarios'. There were 14 categories for KPIs and four categories for the 'Example improvement/corrective actions' and 'What'-if scenarios' codes.

3.1.4 Conducting workshop

This section will discuss the methodology used to plan and design the VC simulation expert workshop with the aim of evaluating the applicability of the findings in simulation software. The workshop aims to assess the usefulness and practicality of the findings from the interview study with PMs and PDMs.

Overall workshop structure and design

The workshop was structured into four main parts, and its total duration was two hours. The first part consisted of an introduction to this empirical study. This part included an explanation of the framework shown in Figure 1, the workshop's purpose (to evaluate interview findings' usefulness and applicability simulation), and the workshop structure demonstrated in Figure 13 below. The three remaining parts consisted of case assignment 1, case assignment 2, and case assignment 3.

During each case assignment, the groups were split into three small discussion groups (3-4 participants per group). Each small group had to complete the case assignment by brainstorming individually in allocated Microsoft Teams breakout rooms. The breakout rooms were formed so that the group's answers would not be affected by each other, and it allowed for reliability analysis of the result. Each group was given a copy of the 'Group Workshop Document.xlsx' in which the case assignment instructions and answer fields were provided. This group Excel document was then sent to the researcher at the end of the workshop.

After the brainstorming, the groups were called back to the main room, and one representative from each group presented their answer in a couple of minutes. Sharing answers in the main room was undertaken so that groups could compare answers to facilitate a more open and fruitful discussion of the questions at hand.

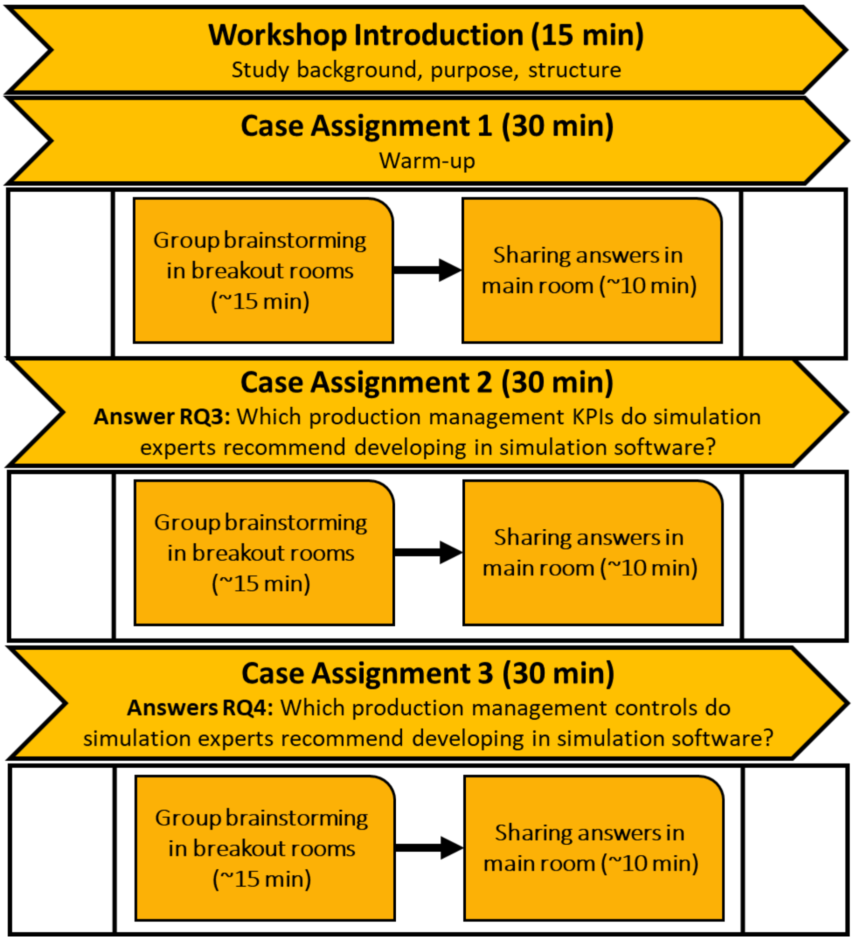

Figure 13: Simulation Expert Workshop Structure

Workshop participants

The workshop participants consisted of employees within VC. A total of nine participants took part in the workshop.

The participants were primarily from the simulation expert team within VC. Other members included in the workshop had extensive experience with production simulation, although they were not currently in the simulation expert team. This team is the interface between the software developers and sales at the company. The participants have extensive knowledge of the simulation software's technical capabilities, its use cases, and customer needs. The experience with simulation software varied largely between the participants. Participant's experience with production simulation software development and application ranged between two and 20 years.

This group of experts was selected for the workshop as they were deemed to have the best knowledge of production simulation software capabilities. As these experts also generate specifications for the development team, they understand the practical aspects of new functionality implementation and its limitations. Moreover, the members of this team are most accustomed to the framework presented in Figure 2.

Case assignment's design

Case assignment one was a warm-up task. This case assignment briefly described the theoretical case within which the PM is operating. This task was to list the KPIs that the study participants believe a PM would like to measure. Although these answers were not included as part of the study, they were included to warm the participants to the proceeding tasks. This also allowed to gauge the participants' understanding of the role of PMs and PDMs.

Case assignment two aimed at answering research question three: "*Which production management KPIs do simulation experts recommend developing in simulation software?*". In this task, the groups were provided with all the KPIs of the PM and PDMs listed in the interview study phase (46 KPIs). The groups were asked to choose at least 10 KPIs which would be useful in VC and at least 5 KPIs which were not useful. In addition, the groups could leave free comments next to their KPI selection rating. The groups could select one of three options for each KPI, which were the following:

- 'Yes – would be useful in Visual Components',
- 'No- would not be useful in Visual Components' and
- 'Unsure'.

In this case, assignment two, groups presented KPIs as outlined in the thematic analysis process described in section 3.1.3. In addition, the workshop participants were provided with the data on how often the interviewees reported a specific KPI theme (e.g., production output) to understand its relative prevalence.

Case assignment three aimed at answering research question four: *"Which production management controls do simulation experts recommend developing in simulation software?"*. Similarly to case assignment two, all found management controls (a total of 15 management controls) were listed and presented by themes found in the thematic analysis process, which is described in section 3.1.3. Due to the smaller quantity of management controls relative to KPIs (15 vs. 46) and their larger individual scope, the participants were asked to answer three questions for each management control. The three questions, alongside possible answers, are presented in Table 6 below.

Table 6: Case assignment three questions and possible answers (regarding management controls)

	Question	Possible answers
1	**Is VC missing this management control or does the management control require improvement?**	❖ Yes, this management control is missing from Visual Components, or it could be developed further. ❖ No, this management control is not missing from Visual Components, and it does not require further development. ❖ Unsure
2	**Could this management control be applied in the simulation environment? ***	❖ Yes, it could be simulated. ❖ No, it is not possible to be simulated. ❖ Unsure
3	**Is this management control valuable to the development of Visual Components?**	❖ Yes, this would be valuable to the development of VC. ❖ No, this would not be valuable to the development of VC.
4	**Free comment (if you wish)**	❖ Any comment pertaining to the management control.

*Note that question 2 is only applicable to management controls that are not already in Visual Components (it is not possible for an management control to exist in Visual Components and simultaneously not be possible to simulate).

3.1.5 Analysing workshop results

As mentioned in the previous section, three groups answered the questions regarding the KPIs and input sections. Each KPI and management control was classified by the mode of the groups' answers. These mode classifications included:

- All agree: All three groups agree with the statement.
- Majority agree: Two out of three groups agree with the statement.
- Undecided: There was no majority agreeing or disagreeing with the statement.

- Majority disagree: Two out of three groups disagreed with the statement.

Moreover, it is worth noting that not all groups had time to evaluate all the KPIs. The KPIs for which all groups answered are presented in the results section 4.3 and Table 10. The complete list of KPIs that also include incompletely answered ones is included in Appendix B. All groups answered the questions regarding the management controls.

Inter-rater reliability

Moreover, inter-rater reliability (IRR) was undertaken to assess the consistency and agreement between the different simulation Expert groups. This inter-rater reliability analysis allows to gauge the credibility of the workshop questions and whether different raters come to the same conclusion. Moreover, this analysis will gauge whether the study's questions were ambiguous. A high inter-rater reliability would indicate strong consensus amongst the simulation experts and that the workshop study was unambiguous.

The inter-rate reliability analysis was undertaken with two different methods. The first method included a simple percentage agreement calculation between multiple raters. This method is documented in the article by Shabankhani (Shabankhani, 2020). This method was chosen because it is the simplest one and provides easy interpretability regarding the inter-rater reliability for multiple raters.

Moreover, Fleiss' Kappa was also used to calculate IRR. Fleiss' Kappa measures the agreement when the study includes three or more rates. Although Cohen's Kappa is another simpler and widely used measure for IRR, it only applies in the case of two raters. The calculation of Fleiss' Kappa is also presented in (Shabankhani, 2020). Fleiss' Kappa was chosen alongside the percentage agreement measure as a secondary metric to provide better interpretability of the IRR. Moreover, it was selected as it applies to three or more raters.

The study by Milnowski was used to interpret the value of the percentage agreement analysis. This study provided boundary values for which the percentage agreement is sufficient for the consequential use of the results (Milanowski, 2014). Similarly, the study by Landis and Koch was used to interpret the Fleiss' Kappa IRR results (Landis and Koch, 1977).

4 Results

In this section, the results of each of the research questions are presented. The following four sections, sections 4.1 to 4.4, each focus on one of the research questions. The first two sections present the results from the interview study. Section 4.1 presents the results concerning PM and PDM KPIs. Section 4.2 offers the PM and PDM management controls found from the interview study. These two research areas are shown in Figure 1, which displays the framework for this study.

The last two sections display the results of the simulation expert workshop. Section 4.3 presents results on the usefulness of the KPIs in VC manufacturing simulation software evaluated by the workshop participants. Similarly, section 4.4 shows the results of the recommended management controls based on the workshop findings. The inter-rater reliability of the workshop answers is also presented in these two sections.

4.1 Production manager and production development manager KPIs

The reported PM and PDM KPIs can be found in Table 7 below. In addition, key quotes from the interviews are shown in Table 8 below. Moreover, the full description of KPIs can be found in Appendix B.

The results presented in this section focus on research question one: "*What output KPIs do production managers and production development managers track to monitor production performance?*". These KPIs were derived from the interview study. The KPIs are presented by category, and the percentages shown in Table 7 indicate the prevalence of this KPI category in the interview study (100 % would suggest that all interviewees reported using at least one item within this KPI category). In addition, Appendix B provides descriptions of all the KPIs listed in Table 7.

A total of 14 KPI categories were formed via the thematic analysis method. The PMs and PDMs reported a total of 49 unique KPIs. The most reported KPI categories in the interview study were found to be production output (92 % prevalence), overall equipment effectiveness (67 % prevalence), machine availability (58 % prevalence), quality (50 % prevalence), and personnel productivity (50 % prevalence). Other KPI categories included production lead time (33 % prevalence), work-in-progress (25 % prevalence), cost (25 % prevalence), personnel availability (25 % prevalence), schedule adherence (17 % prevalence), safety (17 % prevalence), logistics (8 % prevalence), environmental factors (8 % prevalence) and other (8 % prevalence).

The key quotes from interviews shown in Table 8 have been chosen, as they reveal other relevant research insights, which the KPI list in Table 7 does not showcase. The key quotes focus on three KPI categories, namely production output, overall equipment effectiveness (OEE) and environmental factors. Each of these quotes reveal characteristics of these KPI categories, which are commented in section 4.1.1.

4.1.1 Commentary on KPIs by category (RQ1)

This section comments on the characteristics of the identified PM and PDM KPIs, potential issues using certain KPIs, and other findings relevant to RQ1 and production simulation software development. Five KPI categories are focused on: production output, OEE, personnel productivity, cost, and environmental factors.

Generally, different production companies each had a unique set of KPIs to measure production. Also, within a category, e.g., quality, there were several different methods of measuring. Furthermore, the PumpCo2 PM even noted that they make temporary metrics to track a particular problem, but these metrics are then scrapped at some point and replaced by new ones. Hence, there was no standard set of metrics or standardised ways of measuring particular areas of production performance.

Production output

Production output is the most prevalent KPI category, and all PMs and PDMs measure some form of factory production output, except for one interviewee. TelecommunicationsCo did not mention any form of production output measurement. Most interviewees (67 %) measure factory production volume as the quantity of finished units in a certain period. It is worth noting that MarineCo measured production output as ‘job-shop value added hours’, as this was a more suitable metric in a job-shop style production environment.

The quotes PO1, PO2 and PO3 in Table 8 reveal the criticality and the cause for urgency of this KPI category. From the perspective of the PM, production output was highlighted as a relatively critical production KPI, and it was reviewed at a high frequency. For instance, when asked about KPIs in the factory, the quote PO1 by the PM at PumpCo2 stated, “Daily output. First [in the morning], I put on a macro from the ERP to check the output numbers. This is the most essential.” Similarly, when discussing the most critical KPIs on the shop floor, the quote PO2 by MachineryCo PM stated, “If we go to the operational level, the most important goal is to ensure that the daily production output target is achieved…”.

Moreover, falling behind in production output calls for urgent action. For example, the quote PO3 by the PM at RoboticsCo stated, "I would say really the output is the number I said first because we check it every day, we check it every morning… Whenever this KPI is not green, then there is an immediate escalation in the problem". Hence, production output is an essential PM metric which is monitored closely.

Overall equipment effectiveness (OEE)

The second most prevalent KPI in the interview study was OEE, which 67 % of the interviewees reported. Many interviewees found OEE to be an essential metric for them and that it provides crucial guidance in production improvement decision-making. Although the prevalence would indicate that it is a standard metric in the industry, several considerations arose during the interviews, which complicate its use.

The quotes OEE1, OEE2 and OEE3 in Table 8 reveal the shortfalls and ambiguity of the OEE metric. Firstly, the metric can be defined in various ways due to the interpretability of the metric's input variables. The quote OEE1 given by ConsumerCo demonstrates this:

> "It gives a little insight into what is causing production issues: is it performance, quality or availability related? Some people in the organisation believe that it is a magic number that tells us the full status of performance... Inside our factory, we use 30 different ways, or even more ways to calculate OEE. So, if you compare one [OEE] with another, it is not the same. Still, there are people inside the organisation that believe that it clarifies. We have to at least have an OEE of 80 or 85 % because then we belong to world class, and that is what we would like to achieve towards the future. I think it is like bookkeeping, and you can play around with these numbers." – ConsumerCo PDM, 26.06.2023

Furthermore, PumpCo2 reported using OEE, although he stated that the metric exists mainly due to the requirements given by the company management. Furthermore, as shown in quote OEE2, the PM believed that the metric does not provide him actionable insight:

> "Why is it not useful [for us]? Because we do not know how to utilise it. We are missing the culture, reactiveness, energy, and resources to utilise the OEE metric... What should we do if the value is low? Somebody needs to do continuous analysis on the OEE and make an analysis based on this; hence, it is not useful for us. That is why I don't follow the OEE metric." – PumpCo2 PM, 27.06.2023

Other companies, such as CabinCo, mentioned that they do not use the OEE metric because other metrics are already "reasonably reliable" manufacturing performance indicators. Conversely, MachineryCo also did not utilise OEE in their production, as they did not deem it suitable. This was namely due to the large number of product variants.

RoboticsCo, on the other hand, stated that OEE is a valuable metric for them, but they have a custom application for it. As shown in quote OEE3 in which their PDM states:

> “It is useful, and it would be the very best. We don’t use it in the robot assembly, but we use it in the machining department, where we have 15 machines… The ones [metrics] we really use are performance and availability – these are the main things. And we have an opportunity to put in the quality, but it is not as consistent to get a real benefit from the whole OEE. We use mostly two-thirds of the OEE data to analyse our production.“ – RoboticsCo PDM, 1.08.2023

Although OEE was used widely by the interviewees in the study, these findings also indicate its potential complications. For instance, the OEE metric can be interpreted in various ways, PMs need help to generate actionable insight from it, and there is no industry standard usage of OEE. This agrees with the discussion by Andersson and Bellgran on the complexity of using OEE as a performance metric found in the study (Andersson and Bellgran, 2015).

Personnel productivity

Although not unexpected, it is worth noting that a significant number of the interviewees (50 %) reported measuring personnel productivity in one way or another. This KPI category is nearly as prevalent as the machine availability category, measured by 58 % of the interviewees. Based on these results, personnel management is vital for PMs and PDMs concerning factory performance measurement. Although this may be expected, it may also have implications for simulation software development, which section 5.1 discusses more closely.

Cost

Although cost was stated in the literature as one of the five critical KPI categories in a manufacturing organisation (White, 1996), out of all the interviews, only 25 % reported using some direct cost measures. In particular, there were very few financial measures and most PMs and PDMs reported using non-financial measures to track production performance.

Other non-financial metrics indirectly represent cost considerations. For instance, OEE or productivity measures could be used to track the utilisation of a production facility, with a minimum target value calculated during the investment phase. Nevertheless, PMs and PDMs use fewer direct cost metrics to track production than expected.

Environmental factors

Environmental-related KPIs were only mentioned directly by one interviewee, which was MillingCo. This was also surprising and indicates that fewer PMs and PDMs consider including environmental factors as KPIs. For instance, the quote EF1 in Table 8 shows that the FirearmCo PDM believes little can be done about power usage and carbon emissions once the production line has been commissioned.

Although only one interviewee mentioned environmental KPIs, several believed that future industry developments would make them more prevalent. For instance, the quotes EF2 and EF3 in Table 8 demonstrate the believe that environmental factors are believed to become 'increasingly important' and more prevalent in the 'near future'.

Table 7: Reported production and production development managers Key Performance Indicators (KPIs)

Production output (92 %) ❖ Factory production volume [quantity/time period] ❖ Good quality parts [quantity] ❖ Job-shop value added hours [percent] ❖ Planned production output vs. realized production output [percent]	**Overall equipment effectiveness (67 %)** ❖ Overall equipment effectiveness [percent]
Machine Availability (58 %) ❖ Availability [percent per machine state] ❖ MTTR: mean-time-to-repair [time] ❖ Usage, disruption and waiting times [percent]. ❖ Number of encountered machine problems [quantity] ❖ Productive hours [quantity] ❖ Number of maintenance visits [quantity]	**Quality (50 %)** ❖ First pass yield rate [percent] ❖ Number of product defects per month [quantity] ❖ Number of reworks [quantity] ❖ Pass/fail rate of test drive [percent] ❖ Quality as annual income vs. value of defects [percent]. ❖ Production error free rate [percent] ❖ Defects per finished product [quantity/product] ❖ NCRs (nonconformances) [euros]
Personnel productivity (50 %) ❖ Personnel production output [quantity per person] ❖ Good individual performance [percent] ❖ Employee productivity [produced unit/worker hour] ❖ Personnel productivity ❖ FTE (full-time equivalent) [hours]	**Production lead time (33 %)** ❖ Cycle time [time] ❖ On-time delivery [percent] ❖ Planned throughput time vs. realized throughput time [percent]
Work-in-progress (25 %) ❖ Number of unfinished products [quantity] ❖ Quantity of WIP in various production stages [quantity] ❖ Value of WIP in various production stages [euros]	**Cost (25 %)** ❖ Cost to produce one part [euros/unit] ❖ Coverage of the different cost centers [euros vs. euros] ❖ Real hourly production rate per month [euros/hour] ❖ Cost of ownership [euros]
Personnel availability (25 %) ❖ Personnel headcount [quantity] ❖ Personnel absences [quantity]	**Schedule adherence (17 %)** ❖ Schedule keeping/master production scheduling adherence [unit undefined]
Safety (17 %) ❖ Number of near misses [quantity/time period] ❖ Number of safety related shopfloor meetings [quantity/time period]	**Logistics (8 %)** ❖ Response time from request to transfer [time]: how long it took to transfer a certain item starting from its request. ❖ Collected items per hour [items/hour]: ❖ Items collected per person [quantity/time] ❖ Number of transfers from the reception area to intermediate storage [quantity]. ❖ Transfers per hour [quantity/hour] ❖ Stock fill rate [percent or quantity] ❖ Quantity of time a worker must lift a product [quantity]
Environmental factors (8 %) ❖ Power/energy consumption [kW or kWh] ❖ CO_2 emissions [kg]	**Other (8 %)** ❖ Demand prediction accuracy [percent]

Table 8: Key quotes on production and production development manager KPIs

Quote	Production output	
PO1	PumpCo2	“Daily output. First [in the morning], I put on a macro from the ERP to check the output numbers. This is the most essential.”
PO2	MachineryCo	“If we go to the operational level, the most important goal is to ensure that the daily production output target is achieved…”.
PO3	RoboticsCo	"I would say really the output is the number I said first because we check it every day, we check it every morning… Whenever this KPI is not green, then there is an immediate escalation in the problem”.
	Overall equipment effectiveness (OEE)	
OEE1	ConsumerCo	“It gives a little insight into what is causing production issues: is it performance, quality or availability related? Some people in the organisation believe that it is a magic number that tells us the full status of performance… Inside our factory, we use 30 different ways, or even more ways to calculate OEE. So, if you compare one [OEE] with another, it is not the same. Still, there are people inside the organisation that believe that it clarifies. We have to at least have an OEE of 80 or 85 % because then we belong to world class, and that is what we would like to achieve towards the future. I think it is like bookkeeping, and you can play around with these numbers.”
OEE2	PumpCo2	“Why is it not useful [for us]? Because we do not know how to utilise it. We are missing the culture, reactiveness, energy, and resources to utilise the OEE metric… What should we do if the value is low? Somebody needs to do continuous analysis on the OEE and make an analysis based on this; hence, it is not useful for us. That is why I don’t follow the OEE metric.”
OEE3	RoboticsCo	“It is useful, and it would be the very best. We don’t use it in the robot assembly, but we use it in the machining department, where we have 15 machines… The ones [metrics] we really use are performance and availability – these are the main things. And we have an opportunity to put in the quality, but it is not as consistent to get a real benefit from the whole OEE. We use mostly two-thirds of the OEE data to analyse our production.“
	Environmental factors	
EF1	FirearmCo	"I'm not quite sure, it doesn't come directly into the production and the production cell. We can no longer influence energy consumption in production. It may be more at the point of investment. The machine requires a certain amount of power and the machine takes that energy from the grid."
EF2	RoboticsCo	“Whole topic of sustainability and ESG (Environment, Societal and Governance) are becoming increasingly important”.
EF3	PumpCo1	"I was thinking that probably these ESH indicators, or environment, safety and health indicators. They have certainly come and will come in the near future. So exactly this environmental aspect of the system applicability perspective. I would see that, yes, they probably will become more prevalent. We will be using much more of these in the future and put more emphasis on these indicators."

4.2 Production and production development manager management controls

The management controls were derived from the interview study; the results are presented in Table 9 below. Moreover, the full description of management controls can be found in Appendix C.

The results presented in this section focus on research question two: "*What management controls do PM and PDMs have at their disposal to control and improve the production system?*". The results present four management control categories: capacity and process optimisation, personnel management, buffer management, and supplier management. A total of 22 unique management controls were mentioned in the study by the interviewees.

In Table 9, the prevalence of each management control and management control category is also presented. The category prevalence percent indicates that the interviewee has mentioned at least one management control within the management control category. Table 9 below is first sorted by the most prevalent input categories and second by the prevalence of the individual management control within that input category.

Table 9 shows the most prevalent management control category, 'capacity and process optimisation'. The second most prevalent category, 'personnel management', indicates the importance of managing the personnel inside the factory. As identified in section 4.1 by the personnel productivity KPIs, the daily operational work of PMs is primarily governed by managing people. Specifically, 50 % of interviewees mentioned undertaking some form of cross-training of employees. As the quote below demonstrates, the PM at MarineCo said that the first action they can take if production falls behind schedule is to negotiate and increase worker overtime hours:

> "Of course, in this kind of operational environment, when you notice that you have fallen behind schedule, [the action] is to increase overtime hours of the workforce." MarineCo PM, 4.07.2023

Other management controls included changing the length of work shifts and moving personnel between different cells and functions.

Although the management control list presented in Table 9 shows 22 distinct management controls, it is likely that this list only captures a snapshot of management controls used by PMs and PDMs. Several more managers and experts must be interviewed to provide generalisable data. Despite this, the management control categories, particularly personnel management, are themes that may be likely to arise in further interviews as well. The implication of this to production simulation software is discussed in section 5.1.

Table 9: Production and production development management controls and countermeasures

	Prevalence
Capacity and process optimization	**83 %**
❖ Opening bottleneck by increasing its machine capacity	17 %
❖ Adding quality assurance camera to critical process	17 %
❖ Splitting a single-phased task into a two-phased task	8 %
❖ Balancing workload between machines	8 %
❖ Moving an urgent product to available capacity	8 %
❖ Changing to a more balanced tool in a machine	8 %
❖ Replacing faulty transport equipment	8 %
❖ Providing production planner with better demand data	8 %
❖ Trying out larger batch size manufacturing	8 %
❖ Increasing frequency of equipment cleaning	8 %
Personnel management	**67 (42) %***
❖ Increasing cross training of employees	50 (17) %*
❖ Changing the length of work shifts	17 %
❖ Moving personnel between different cells and functions	8 %
❖ Moving additional personnel physically closer to critical production process	8 %
❖ Specifying and improving work instructions	8 %
❖ Balancing worker variability by pairing a slow and fast worker together	8 %
❖ Providing workers with preliminary information on incoming products to reduce set-up times	8 %
❖ Negotiating and increasing worker overtime hours	8 %
Buffer management	**33 %**
❖ Changing the quantity and the size of buffers	25 %
❖ Moving the location of a buffer	8 %
❖ Upholding sufficient inventory levels around processes that are critical and prone to disturbances	8 %
Supplier Management	**8 %**
❖ Asking for raw material more firmly from a supplier	8 %

*Values in brackets indicate the prevalence of the study discounting interview answers for which an example was provided. Hence, the value in brackets indicate the prevalence of the management control only for answers where the interviewee provided this management control without an example from the interviewer.

4.3 Recommended KPIs in simulation software

The results for this section are presented in Table 10 below, for which the raters were asked to evaluate the usefulness of each KPI in the VC manufacturing simulation software. In addition, key quotes from workshop participants are displayed in Table 11.

The results of this section focus on research question three: "*Which production management KPIs do simulation experts recommend developing in simulation software?”*. Note that all the study participants have experience in the technical development of the software and frequent conversations with industrial customers. Hence, the term usefulness embodied both what the study participants believed to be technically feasible and what was thought to be in the customer’s interest. The KPIs are divided into three categories established by the mode of the answers, which include *‘majority of raters agree’*, *‘raters had no consensus’*, and *‘majority of raters disagree’*.

Out of the KPIs that the workshop participants evaluated, 57 % of KPIs were found useful in VC manufacturing simulation software by most raters. No rater consensus was established for 20 % of the KPIs (i.e., undecided). For the remaining 23 % of KPIs, most raters found that the KPIs would not be useful in VC manufacturing simulation software. Note that KPIs with an asterisk in Table 10 below only had two out of three ratings (i.e., one rater group could not provide an answer).

Note that not all KPIs found in the interview study (part 4.1 and Table 7) were included in the workshop and, hence, in the results presented in Table 10. There were two reasons for the omission of some KPIs. Firstly, results that had only one rating were removed, as it was deemed that the single rating was not sufficient to group the KPIs in Table 10. Similarly, three KPIs found in the interview phase, namely ‘productive hours’, ‘coverage of the different cost centres’, and ‘real hourly production rate per month’, were not included. These were impossible to include as the interview in which these KPIs were identified occurred after the simulation expert workshop.

The KPIs found in Table 10, which most raters have agreed to be useful in VC manufacturing simulation software, are an initial proposal of KPIs that could be added to the VC simulation software. For instance, basic KPIs such as factory production volume have strong indications that they should be included, as most interviewees use them, and the simulation experts also agreed on their usefulness. Several basic KPIs on this agreed list also have strong signals for integration into production simulation software (e.g., production error-free rate and availability).

Although a majority vote deemed 17 metrics useful in VC simulation software, concerns about their applicability were raised during the workshop. For instance, some concerns included a lack of data to simulate the value of a KPI (e.g., the number of encountered machine problems). As quote WS1 in Table 11 shows, one participant noted that such KPIs would require historical data to provide data for such values. On the other hand, most simulation experts agreed that the OEE metric was useful; however, the workshop discussion highlighted some issues with its implementation. For instance, one participant with extensive customer experience in simulation projects highlighted this in quote WS2: “Sometimes OEE is an input, and sometimes it is given [by the customer] as an output. They’ll [the customer] say what it is for a particular machine or cell. It is vaguely there. They [the customer] expect to see it, but the trouble is when you can’t define it.”

Hence, regarding OEE, the same issues were highlighted in the interview study and literature discussed in the article by (Andersson and Bellgran, 2015). Thus, the lack of a standard industry-wide definition of the KPIs and the lack of necessary input data in simulation further complicate the implementation of these KPIs into production simulation software. Potential solutions to some of these problems are discussed in section 5.1.

The list of KPIs that the majority found not useful included only seven items compared to the agreed items (included 17). The first surprising finding is that the workshop participants did not deem the ‘first pass yield rate’ a useful metric. This decision was justified by one participant group by not having KPIs that overlap, as shown in the quote WS3 in Table 11. This vision may, however, contradict empirical evidence from the interview study, as various PMs had unique ways of measuring production performance (e.g., for quality). Hence, including only one way of measuring a subset of production performance (e.g., quality) would not suit all simulation users.

Other KPIs, such as ‘near misses’, were not deemed useful due to their practicality in simulation software, as demonstrated by quote WS4. One reason for this view could be that the simulation software does not provide detailed behaviour of human behaviour. Moreover, simulating accidents is beyond the current capability of the software. Similarly, KPIs such as ‘planned throughput time vs. realised throughput time’ were not deemed useful due to the expected lack of input data in simulation.

4.3.1 Commentary on inter-rater reliability

The inter-rater reliability analysis for the simulation expert workshop is shown in Table 13 below. For the KPI evaluation, the percentage agreement was 46 %, which falls below the threshold for the consequential use of the ratings according to the threshold values by Milanowski (Milanowski, 2014). Similarly, the free-marginal Kappa value for the workshop KPI evaluation is 0,20, which indicates only slight agreement in terms of the usefulness of the KPIs (Landis and Koch, 1977).

These low IRR results may have two underlying causes. Firstly, the descriptions of the KPIs given to the workshop participants (shown in Appendix B) may have been ambiguous, causing the raters to interpret the KPI differently. Another reason may be the lack of product development vision in this team. Hence, this may indicate that within the team, there is no clear vision of what the VC software should be able to measure.

Table 10: KPI simulation expert's evaluation: Would this KPI be useful in Visual Components manufacturing simulation software?

Majority of raters agree

- Factory production volume [quantity/time period]
- Good quality parts [quantity]
- Availability [percent per machine state]
- MTTR: mean-time-to-repair [time]
- FTE (full-time equivalent) [hours]
- Production error free rate [percent]
- Overall Equipment Effectiveness [percent]
- Usage, disruption and waiting times [percent]
- Number of encountered machine problems [quantity]
- Number of maintenance visits [quantity]
- Number of product defects per month [quantity]
- Pass/fail rate of test drive [percent]
- Defects per finished product [quantity/product]
- *Cycle time [time]
- *Number of unfinished products [quantity]
- *Quantity of WIP in various production stages [quantity]
- *Response time from request to transfer [time]

Raters had no consensus (i.e., undecided)

- Personnel production output [quantity per person]
- Employee productivity [produced unit/worker hour]
- Number of reworks [quantity]
- Planned production output vs. realized production output [percent]
- Job-shop value added hours [percent]
- Personnel productivity

Majority of raters disagree

- First pass yield rate [percent]
- Quality as annual income vs. value of defects [percent]
- NCRs (nonconformances) [euros]
- Good individual performance [percent]
- *Planned throughput time vs. realized throughput time [percent]
- *Number of near misses [quantity/time period]
- *Number of safety related shopfloor meetings [quantity/time period]

*KPIs marked were only answered by two out of three groups.

Table 11: Key quotes from the simulation expert workshop

Quote	
WS1	"Can you measure in a simulation as opposed to on the floor? So if I'm running a factory its very clear I need these KPIs because it's a real-world situation. But in the simulation but can we even create them because we don't have that data. Or can they [industry simulation user] provide us the historical data. What's simulation KPIs vs. real-world KPIs?"
WS2	"Sometimes OEE is an input, and sometimes it is given [by the customer] as an output. They'll [the customer] say what it is for a particular machine or cell. It is vaguely there. They [the customer] expect to see it, but the trouble is when you can't define it."
WS3	"Most of these [KPIs] somewhat overlap. I would want to give one generic one from the software and just leave it to the engineer's discretion to figure out the data."
WS4	"It's [near misses] for the production line, it's a production item, it is not really for the simulation."

4.4 Recommended management controls in simulation software

The results for recommended management control development in VC manufacturing simulation software are shown in Table 12 below.

The results of this section focus on research question four: "*Which production management controls do simulation experts recommend developing in simulation software?"*. Table 12 includes ratings of three questions for each management control posed in the workshop.

Firstly, looking at the answers to question one, *"Is VC missing this management control or does the management control require improvement?",* there is agreement and disagreement to individual management controls. Looking at question two, *"Could this management control be applied in the simulation environment?",* all or most raters always agreed that the management control could be applied in a simulation environment. Finally, question three, *"Is this management control valuable to the development of VC?"*, only *'increasing cross training of employees'* had majority disagreement with the statement. In addition, three other management controls did not reach a consensus on this question.

Moreover, the first six management controls presented in Table 12 indicate majority agreement to all three questions.

Based on the results from the workshop, the suggested management controls to simulation software would include the first six items in Table 12. The first six items are recommended based on direct results, as the simulation experts all believe these management controls do not yet entirely exist in VC, the management control is possible to be simulated, and it would be valuable to the development of the software. The six management controls include:

- Moving an urgent product to available capacity.

- Upholding sufficient inventory levels around processes that are critical and prone to disturbances.
- Adding quality assurance cameras to critical process.
- Providing workers with preliminary information on incoming products to reduce set-up times.
- Splitting a single-phased task into a two-phased task
- Providing production planner with better demand data

Although these results indicate the development of these management controls, these management controls have not been given specifications for simulation software development. Brief descriptions of the management controls are provided in Appendix C; however, the management controls would need to be specified in detail before they can be feasibly implemented in production simulation software.

For instance, the management control 'moving an urgent product to available capacity' was described by a PM as 'moving a product with an urgent customer order or a delivery that is late on delivery to available capacity. This product can take priority over other products.' However, several open questions remain from the perspective of software development. How would this be implemented in simulation software? Does this indicate that simulation software should have data on the priorities of customer orders arriving at the factory? How would the urgent order be dealt with in simulation?

Another example of the recommended management control is 'providing workers with preliminary information on incoming products to reduce set-up times'. This management control was described as "the machine operator is given information in advance about the incoming product variants. This allows the worker to set up the machine correctly before the raw material comes to their station, increasing the process cycle time." Again, several open questions remain regarding the specifications and implementation of this management control into production simulation software. How can the effect of improved information flow and human information processing be modelled in simulation? Should this action be modelled simply as an operator process time improvement? How should the improved process time via additional information flow be estimated?

Hence, there are still unanswered questions regarding how these management controls should be implemented in simulation. Nevertheless, the list of recommended management controls shown in Table 12 can be used as a starting point to discuss simulation software development for production management. However, more investigation and analysis are necessary before these management controls should be taken for production simulation development.

4.4.1 Commentary on inter-rater reliability

Also, the inter-rater reliability of this management control analysis for questions one, two and three was also undertaken. Table 13 shows each question's percentage agreements and free-marginal multi-rater Kappa values. All percentage agreements fall below the 75 % threshold value, which would allow for the consequential use of the ratings according to (Milanowski, 2014). Regarding the Kappa value, questions two and three indicate fair agreement (Kappa 0,40 and 0,33), whereas question one only indicates slight agreement (Kappa 0,14).

It is suspected that this low IRR value for question one may arise from the ambiguity of the management controls. Another potential for low agreement may be due to varying production simulation experiences. In other words, more extensive simulation experience may change the view on the capability of the VC simulation software. Questions two and three had higher IRR values, indicating fair internal agreement concerning the capability to simulate the management control and its value to software development.

Table 12: Results on recommended PM and PDM management controls to manufacturing simulation software.

Management controls	Q1	Q2	Q3
❖ Moving an urgent product to available capacity	++	++	++
❖ Upholding sufficient inventory levels around processes that are critical and prone to disturbances	+	++	++
❖ Adding quality assurance cameras to critical process	++	+	+
❖ Providing workers with preliminary information on incoming products to reduce set-up times	++	+	+
❖ Splitting a single-phased task into a two-phased task	+	+	+
❖ Providing production planner with better demand data	+	+	+
❖ Changing to a more balanced tool in machine	+	+	?
❖ Specifying and improving work instructions	+	+	?
❖ Balancing worker variability by pairing a slow and fast worker together	?	+	?
❖ Balancing workload between machines	-	++	++
❖ Trying out larger batch size manufacturing	-	++	++
❖ Increasing cross training of employees	++	+	-
❖ Changing the length of work shifts	-	++	++
❖ Moving additional personnel physically closer to critical production process	-	+	+
❖ Moving personnel between different cells and functions	--	++	++

Q1	*Is VC missing this management control or does the management control require improvement?*
Q2	*Could this management control be applied in the simulation environment?*
Q3	*Is this management control valuable to the development of VC?*

++	*All raters agree*
+	*Majority of raters agree*
?	*Raters had no consensus (i.e., undecided)*
-	*Majority of raters disagree*
--	*All raters disagree*

Table 13: Inter-rater reliability of workshop answers

		Input action analysis		
	KPI evaluation	**Q1**	**Q2**	**Q3**
Percentage agreement	46 %	36 %	60 %	56 %
Free-Marginal Multirater Kappa	0,20	0,14	0,40	0,33
Interpretation of Kappa according to (Landis and Koch, 1977)	Slight agreement	Slight agreement	Fair agreement	Fair agreement

Q1	*Is VC missing this management control or does the management control require improvement?*
Q2	*Could this management control be applied in the simulation environment?*
Q3	*Is this management control valuable to the development of VC?*

5 Discussion

This section is divided into three parts. Part 5.1 discusses the implications of the findings, outlined in the results section 4, on software development. More specifically, novel features and functionality for the Visual Components (VC) simulation software development are proposed.

Part 5.2 discusses the contribution of these findings to current literature and its relevant to Industry 4.0. Moreover, future areas of research are proposed in this section. Finally, part 5.3 discusses the limitations of both the interview and workshop investigations.

5.1 Implications for production simulation software development

This section discusses how the findings of this empirical study affect VC simulation software development. More specifically, new software functionality and features are proposed to support production management decision-making. The recommended features include flexible simulation KPIs, improved data presentation, and simulating the workforce skill mix. In addition, visual mock-ups of these proposed concepts are shown. It is worth noting that these recommendations can be seen as preliminary suggestions; however, alternative solutions may be more suitable to address the findings from this study.

5.1.1 Flexible simulation KPIs

Although section 4.3 proposed built-in KPIs, which VC could measure, this recommendation does not fully address the diverse nature of metrics found in this study. Hence, the first software development proposal provides the simulation user with flexibility in defining simulation KPIs. The following reasons justify this. As Table 7 indicates, several ways of measuring specific production performance subsets exist. For instance, from the 15 interviewees, quality was measured with eight distinct KPIs. Secondly, the definition of KPIs varied largely from interviewee to interviewee. For example, it was found that companies like RoboticsCo had their unique way of measuring OEE, and ConsumerCo had around 30 ways of measuring this metric. This finding is also supported by literature (Andersson and Bellgran, 2015). Hence, only offering predefined built-in KPIs would not serve all customers due to their unique performance management metrics.

Supporting expressions

The software could support expressions in the user interface to implement flexibility with simulation metrics. Figure 14 provides a mock-up of this concept. Expressions could then be used to plot the data. The user could use a combination of variables to define their KPIs. Quality and OEE are given as examples in the left illustration in Figure 14. On the right-hand side of Figure 14, personnel productivity is defined. The metrics would, however, also require a method for retrieving the data. For instance, variables 'products_finished' and 'production_duration' would require a method for retrieving data from the simulation. This could be achieved via functions such as 'getFinishedProducts' or 'getSimulationRunTime', which read machines or simulation run time to construct these variables. Another alternative method for data retrieval may also be appropriate.

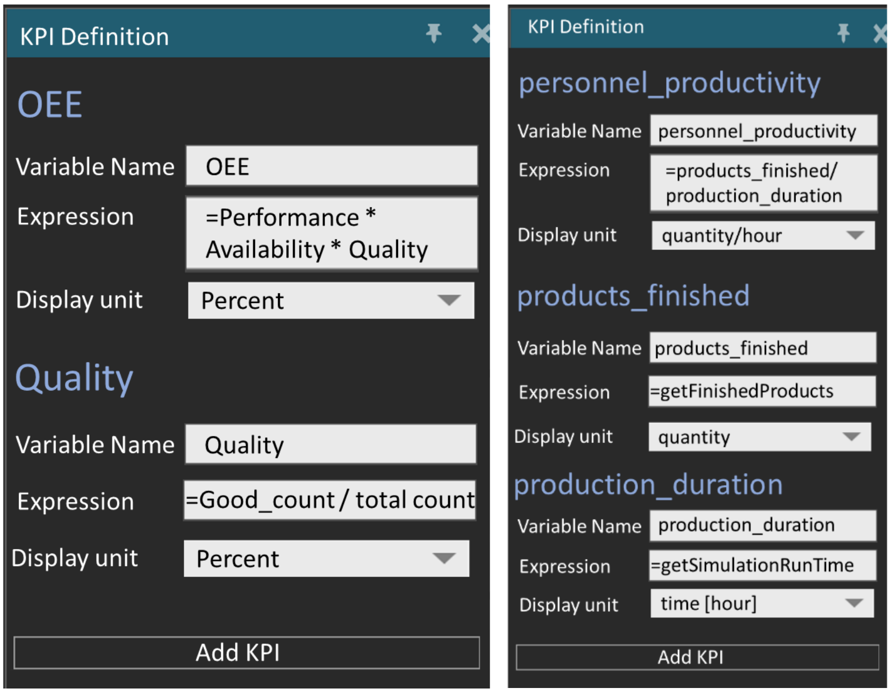

Figure 14: Mock-up of expressions in VC software

Standardised data retrieval from the simulation environment

Although expressions would provide flexibility to perform arithmetic calculations on the KPIs and combine them, retrieving the data for these KPIs from the simulation environment is equally essential.

Some standardised data retrieval could be implemented, for instance, by modifying the existing components found in VC software. The concept of data retrieval from simulation is illustrated in Figure 15 below. Currently VC has the 'Cycle Time' and 'Time Tracking Point', which can track a specified part of the simulation production line. For instance, the 'Cycle Time' component can be used to define input signals from the component, which trigger the cycle time calculation. Neither of these components, however, provides the functionality allowing for assigning data to variables, such as in Figure 14.

Hence, another software development recommendation is to provide an interface between data collection components and the statistics expressions. Allowing users to tailor their expressions and form comprehensive KPIs from a set of expressions would bring flexibility to the simulation KPIs.

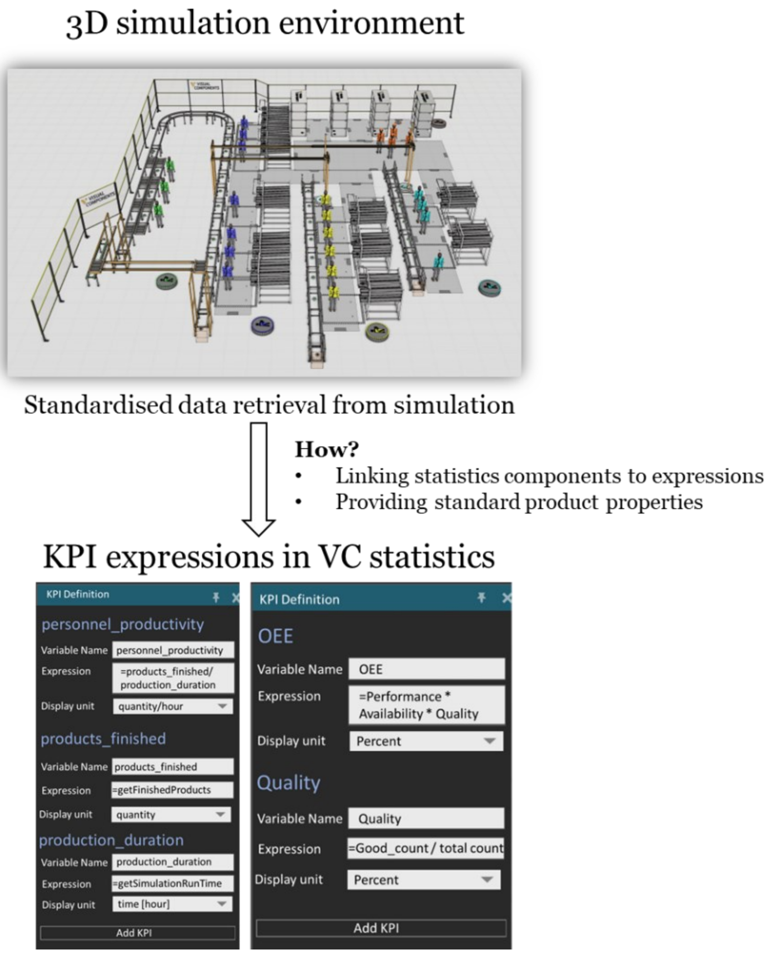

Figure 15: Retrieving data from the simulation environment to KPI expressions.

Other forms of data collection would also need to be standardised. For instance, quality KPIs such as ‘production error-free rate’ will also require standard data collection and retrieval functionality. Perhaps quality KPIs could be implemented by adding standard statistics properties to products in VC, which would label them as either ‘good apples’ or ‘bad apples’. A novel statistics component could then count the number of ‘good apples’ and ‘bad apples’ products, which could then be fed to the statistics expressions. This is one possibility; however, more investigation needs to be undertaken to decide on the best method for collecting and retrieving data from the simulation environment.

Ultimately, providing flexibility via expressions and standardised data retrieval from the simulation environment would also allow for analysing the production line from various perspectives. Defining and setting custom KPIs would cater to analysis at the line, cell, and factory levels. For instance, the 'production error-free rate' could be analysed for individual machines, but it could also be defined for an entire factory, given the flexibility of the expressions.

5.1.2 Improved data presentation

Section 5.1.1 presented ideas for flexible KPI definition and data retrieval. Another recommended feature is improved data presentation. Rather than showing data only from a single cell, the software could simultaneously represent data from various cells or processes. This would allow for analysis at a production or factory manager level. A mock-up of this concept is provided in Figure 16 below.

Figure 16 shows the cycle time for various cells in a factory. A PM or PDM can take this type of line-balancing analysis to decide where more resources should be allocated. Similarly, graphs such as this would indicate potential bottleneck areas. In this case, in Figure 16, the 'heat treatment' may be the bottleneck. The y-axis, however, could be, for instance, changed to the quantity of products in a queue at each cell, which may be a better way of identifying the bottleneck. Again, the flexibility of expressions and data presentation would allow the user to define their KPIs and method of data presentation uniquely.

Figure 16: Mock-up of flexible data presentation in VC software

The data presentation should flexibly support different forms of data visualisation. Hence, it also raises the question of whether this data presentation could be made compatible with external software specialising in data visualisation. Similarly, these external software packages would allow for simple arithmetic operations and combinations of KPIs. This solution would require connectivity between the data retrieved from VC's simulation environment and the data visualisation software. Software such as Datapine allow for user-friendly interfaces that are easy and quick for data visualisation.

5.1.3 Simulating workforce skill mix

The final proposed software feature is a personnel skill matrix. Essentially, this feature would allow the simulation of new and improved workforce skill mix. Both the RoboticsCo and MarineCo PMs reported that they have to make decisions on personnel training primarily based on gut feelings. Based on the interview study, it seemed that the PMs deal a lot with managing personnel, particularly managing the skills of the work force. Moreover, the results shown in Table 9 also support this feature, as 50 % of interviewees reported 'increasing cross-training of employees' to improve production. More specifically, interviewees justified this management control as it improves the robustness of the production system (e.g. if one employee falls ill). Hence, this feature aims to address this issue, as simulation software currently does not support PMs in this area.

Hence, integrating this feature into production simulation software would support PM decision-making regarding personnel training. Simulation could be used to test out the robustness of the workforce to unexpected events such as illnesses. Moreover, robustness against machine failures could be tested, as personnel capable of performing machine repairs must also be present when the breakdown occurs. Thus, the simulation may help to determine the production availability gains if specific employee cross-training is implemented.

The simulation user input of production personnel skills could be entered similarly to the mock-up in Figure 17 below. The PM using the simulation software could detail each employee's critical skills in a spreadsheet. The human transport controllers in VC would then read this spreadsheet and distribute tasks on the shop floor based on it. The simulation could then be rerun with an improved personnel skill set to analyse the improvement it would bring to production availability.

	Skill #1	Skill #2	Skill #3	....
Otto 1	Yes	No	No	
Otto 2	No	No	Yes	
Anna 1	Yes	Yes	No	
Anna 2	No	Yes	Yes	
.....				

Figure 17: Mock-up of simulating personnel skills

There are, however, remaining questions about simulating personnel skills. Firstly, the right granularity for skills would need to be defined. In other words, a single assembly step may entail several hundred separate activities. However, specifying all skills at this level would make simulation too complicated to develop. On the other hand, simplifying the skills more than necessary may not provide PMs with the insight required to support personnel training-related decisions. These concerns were highlighted by the PM at MarineCo.

Calendar system and work shifts

Moreover, the management controls given in Table 9 showed that 67 % of interviewees reported undertaking some form of personnel management. Hence, to cater the simulation software to PMs and PDMs, this would suggest that VC should also develop functionality supporting other personnel management decisions. This may indicate that VC should implement features such as a calendar system and work shifts, allowing for simulation from the personnel perspective. This would allow for testing out different shift lengths, which was also reported as a management control in the study, shown in Table 9.

5.2 Contribution to literature and Industry 4.0

This study addresses several gaps in the literature, which were outlined in the section 2.5 and adds confirmation to findings in other studies. For instance, previous literature identified a vast number of KPIs used in manufacturing (Contini and Peruzzini, 2022), (Cristea and Cristea, 2021), (International Organization for Standardization, 2014); however, it did not provide insight into which were the most prevalent KPIs on the shop floor. This study identified the topmost prevalent KPI categories that production managers use: production volume, OEE, machine availability, quality, and personnel productivity.

Moreover, this study added confirmation in production management literature to previous studies. For example, similar complexities of such metrics as OEE and productivity were identified, as reported by (Andersson and Bellgran, 2015). Furthermore, the findings of (Cristea and Cristea, 2021) were also confirmed regarding the variability of the selection of KPIs from company to company in the batch and assembly production industry.

In terms of management controls, only a few studies (De Meyer and Ferdows, 1990), (Lagacé and Bourgault, 2003), (Gelders *et al.*, 1994) have reported investigating this research area, and these studies are also not representative of modern production practices. Hence, these findings contribute to a relatively unexplored research area of management controls and reveal insight into the daily activities of production managers.

Furthermore, this study guides simulation software development, seen as an 'enabling technology' of the I4.0 revolution (de Paula Ferreira *et al.*, 2020). No previous study has explicitly investigated and researched KPIs in production simulation software. In addition, the suggested simulation software features align the requirements of shopfloor performance management with simulation software.

The suggested features in this thesis can be seen as an intermediate step to adopting more effective I4.0 tools in simulation software. Without relevant KPIs and data collection methods in simulation software, ML and AI tools lack the feedback data to optimise the production environment. In other words, if it is not possible to collect relevant metrics and data from the simulation environment, harnessing an ML algorithm will be highly challenging. Once the outlined proposals in the section 5.1 have been implemented, the KPI data can be used as optimisation objectives for these effective tools. For instance, the line balancing problem showed in Figure 16 could harness ML algorithms to find the optimal production capacity in each cell to minimise the throughput time of the whole factory.

The adoption of ML and AI algorithms can be seen as the next area of research in this domain. For instance, some potential research areas that would further integrate I4.0 capability into simulation software may include:

- Which ML algorithms are the most suitable for optimisation problems using the KPIs presented in this research?
- What input variables should be implemented into production simulation software? For instance, cell-specific production capacity may be a suitable input variable for the line balancing problem.
- What real-world optimisation problems would benefit from ML in production simulation?
- How should simulation software be designed to accommodate ML capability?
- How can simulation optimisation be achieved using these tools whilst adhering to computational constraints? In other words, having to iterate through thousands of production layout alternatives (in 3D simulation) may not be feasible due to computational constraints.

Although these research questions require extensive investigation, this research area could considerably boost the productivity of production simulation software. It would allow software such as VC to solve increasingly complicated optimisation problems with much quicker turnaround times. The power of ML and AI has been proven in many other applications, but the full benefit of it in VC production simulation is yet to be harnessed. This study lays out foundations for the development of these tools via the identification of relevant KPIs.

5.3 Limitations in the study

5.3.1 Interview study

There were some limitations in the interview study. For instance, only 15 interviewees were included, which affected the generalisability of the results. Notably, the list of management controls only seems to be a snapshot of all potential managerial actions that can be taken to improve or correct production. In terms of the KPIs, there was more commonality between the interviewees, but it is unlikely that all relevant KPIs were captured. Although 15 interviewees are a limited sample, it was deemed sufficient for this study, as the targeted participants were industry experts with extensive production knowledge.

Moreover, the interview study's participants were 60 % Finnish. Hence, Finnish performance management and production improvement culture may be overrepresented in the results. Including more participants outside of Finland would provide a better global perspective on the performance KPIs and management controls.

Another limitation of this study is the chosen qualitative research method. The chosen research method was a semi-structured interview. With this qualitative research method, it is possible that not all interviewees were able to list the correct KPIs and management controls on the spot. Although the interview questions were sent to the study participants beforehand, not all interviewees had prepared extensive answers. This may have omitted some critical items during the interviews, harming the study's validity. In contrast, a survey type of study would have allowed participants to take the time to, e.g., gather and list all the KPIs they use. Although the semi-structured interviews presented this potential downfall, it was deemed suitable as it allowed to discuss the topics more freely. This discussion was able to capture unanticipated insights about, e.g., the nature of the KPIs.

5.3.2 Workshop study

The workshop study included nine participants, a relatively small sample size. Similarly, there were only three groups, which provided for three ratings per item in the workshop. Essentially, the results from the workshop could be driven by the ratings of a couple of individuals. Although the sample size was small, it was deemed sufficient for this study, as the workshop participants had the best knowledge in production simulation.

Other factors, such as the dynamics of the workshop, may also have affected the reliability of the study. After the workshop, the study participants commented that individual group members or specific concerns took hold of the group discussion. Hence, these individuals may have driven the discussion, subsequently influencing the ratings the groups gave.

Finally, the KPIs and management controls provided to the workshop participants may have been ambiguous. Although descriptions of the KPIs and management controls were given, these descriptions could have been more extensive to enhance the reliability of the study.

6 Conclusion

This thesis investigated how production simulation software should be developed for production managers (PMs). Simultaneously, the study investigated how the statistics functionality in the VC software should be improved. The production management perspective was explored via interviewees with 15 industry experts. In addition, a separate workshop was organised for simulation experts to evaluate the industry findings. These findings can be considered significant, as they shed light on the work of PMs in factories and support I4.0 goals. Additionally, production simulation can be used as a tool to reduce resource and activity waste, thus making production more sustainable. This work specifically aims to develop simulation software for PMs, who have considerable influence on the daily operations of production facilities.

The first key finding from this study was how the selection of performance management metrics varies from one company to another in various discrete and assembly production industries. However, there were some commonalities, such as production output and OEE, which most interviewees reported. Another key finding was how the interviewee companies define and apply the production KPIs differently. For instance, OEE seemed to have various definitions and custom applications varying from company to company.

Regarding the management control findings, PMs have unique and numerous ways of dealing with production issues and improvements. Although this study captured various management controls, this is likely only a snapshot of the industry-applied actions managers can take. Nevertheless, many of the actions taken by the PMs had to do with managing personnel, which production simulation software does not perfectly support. The most reported personnel management action was personnel cross-training.

Moreover, this study proposed novel simulation software features. These features were proposed to address the findings from the empirical study. The software development proposal included supporting KPI expressions, standardised data retrieval from the simulation environment, improved data presentation and simulating the workforce skill mix. It became apparent that other features related to personnel management, such as a calendar system and work shifts, may be necessary to address the concerns of PMs.

Although these proposed features aim to address the findings from the study, more investigations need to be undertaken to implement these features. For instance, devising methods of standardised data retrieval from the simulation environment needs to be investigated to support simulation KPI expressions. Similarly, the implementation of the data visualisation in VC needs to be discussed further.

This thesis investigated simulation software development from the perspective of PMs. However, the question remains: for whom should production simulation software be developed? Introducing features to software that deal with personnel management effectively steers the simulation tool towards solving operational production issues. Alternatively, the simulation could focus on supporting the facility investment decision phase. Although this question was not directly addressed in this thesis, it would be an important discussion point before implementing any novel software capability.

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A. Sample interview questions

Part 1: Background of Interviewee and Company

- **Start of the interview**
  - Brief explanation of the purpose of the interview (what I am after), consent to interview, and general interview arrangements (duration, etc.)
- **Warm-up questions (to get interviewee more comfortable)**
  - What are your current responsibilities in company X?
  - What do you find most interesting in your job?
- **Company industry and production type?**
  - What is the company product portfolio (i.e., what do you produce)?
  - What customer segments do you serve and what are their demands (flexibility, speed, quality, cost, customizability)?
  - Which product's manufacture do you personally focus on (i.e., within the company)?
- **Production process**
  - How would you categorize the production process (i.e., job shop, batch, mass, process, etc.)?
    - How many units do you produce annually?
    - How many product variants are there?
  - Would you describe the production process as either pull or push? Or as a mixture?

Part 2: Output KPIs

- What performance indicators do you use to measure the performance of the factory?
  - Do you have categories for your performance metrics? If yes, what are they?
  - Can you elaborate on KPI x, y, or z?
  - How and who collects the data for these KPIs? (sales & delivery info, stock & warehouse data, weekly report from production)
- What are the most important metrics that you use to measure the performance of the factory (KPIs)?
- Do you measure specific cells/line KPIs in the factory as well (i.e., KPIs in factory modules)?
  - If so, how are the KPIs of the cell/line related to the whole factory KPIs?
- How frequently are these KPIs updated?
- How frequently is this KPI reported?
- In the organization, who decides and develops these KPIs?
  - How does the target process work?
  - How does the reporting in this respect work?
- Are these KPIs uniform throughout factories in the organization?
- Are there any trends in your industry which might affect future KPIs?

Part 3: Management Controls

- What are the methods that you use to improve factory production?
    - Which KPI does this also improve? What do you follow whether it improves or becomes worse?
- What decisions can you make to improve production in a factory (continuous improvement)?
    - Can you provide some examples of these?
- What actions do you take in faulty situations in production?
- What variables can you affect to 'tune' the production system?
- What do you do if KPI x is below target level? What actions do you take to improve it?
- Are there certain factors in production which you cannot influence? (e.g., supply chain issues)
    - Which KPIs are dependent on this?
- Are there certain decisions you make based on gut feeling rather than KPIs?
    - If yes, do you have any examples of these?
- Do you think there are certain focus points in your production facility that need to be monitored closely (e.g., a bottleneck or critical quality issue in the production process)?
    - How can you control this part of the production process?
- What further resources, tools or flexibility would you need to improve production even more?
- Would 3D manufacturing simulation facilitate your decision-making to improve production? If so, can you imagine how you might apply it?

Part 4: Production philosophy in production planning

- LEAN: Do you aim to follow Lean principles when planning production (i.e., minimizing waste in the form of waiting, defects, overproduction, inventory, transport, motion, etc.)?
- JIT: Do you aim to plan the production by the Just-in-Time principle in the production system (i.e., only delivering products exactly when they are needed)?
- TOC: Do you aim to maximize the utilization of the bottleneck in the production line?
    - Are you aware of what the bottleneck in the production line is?
- Agile: Do you aim to gain a competitive advantage through applying the agile manufacturing philosophy?
    - If there is a product change, how do you adapt to this? Is this a strength in your organization?
- Do you think you follow a certain production philosophy when planning production (e.g., Lean, JIT, TOC, Agile Manufacturing, Mass customization, etc.)?

B. PM and PDM KPIs with descriptions and prevalence

	Reported by
Production output	**92 %**
❖ **Factory production volume [quantity/time period]:** how many products, kilograms, etc. the factory produced in a certain time period.	67 %
❖ **Good quality parts [quantity]:** how many units did the factory produce which were also good in quality.	8 %
❖ **Planned production output vs. realized production output [percent]:** how many products did the factory plan to produce vs. how many were actually produced.	8 %
❖ **Job-shop value added hours [percent]:** scheduled vs. realized value-adding work in project production (e.g., ship building production). For example, if 1000 value-adding hours were scheduled and 800 value-adding hours were completed then the metric is 80 %.	8 %
Overall equipment effectiveness (OEE)	**67 %**
❖ **Overall equipment effectiveness [percent]: c**ombination of factory availability, performance, and quality.	67 %
Machine Availability	**58 %**
❖ **Availability** [percent per machine state]**:** states of the machines, production cells or factory (idle, stopped, working, etc.)	25 %
❖ **MTTR: mean-time-to-repair [time]:** what was the average time taken for the different machines on the shop floor to be repaired.	17 %
❖ **Usage, disruption and waiting times [percent]: e**ach state is reported separately and as %.	8 %
❖ **Number of encountered machine problems [quantity]:** how many machine breakdowns or other problems were reported in a certain time period.	8 %
❖ **Productive hours [quantity]:** how many productive production hours took place in a given time period.	8 %
❖ **Number of maintenance visits [quantity]:** how many maintenance visits took place in a certain time period.	8 %
Personnel productivity	**50 %**
❖ **Personnel production output [quantity per person]:** how many units did the individual produce and report.	17 %
❖ **Good individual performance [percent]:** number of process performances below target time. For example, machine operator ideal process time for welding is 10 min. He completes four welds in 11 min and six welds in 8 min. The good individual performance is 60 % (6 out of 10 processes are below ideal time).	8 %
❖ **Employee productivity [produced unit/worker hour]:** units manufactured per employee hours.	8 %
❖ **Personnel productivity:** Maynard Operation Sequence Technique (MOST) metric (this is detailed in (Jain et al., n.d.))	8 %
❖ **FTE (full-time equivalent) [hours]:** how many people are needed to run the production line per skillset (e.g., quality personnel, production managers, technical personnel, operators, etc.).	8 %
Quality	**50 %**
❖ **First pass yield rate [percent]:** what proportion of finished products passed the quality test on their first iteration.	17 %
❖ **Number of product defects per month [quantity]:** how many defects occurred in the calendar month in production.	8 %
❖ **Number of reworks [quantity]:** how many reworks had to be undertaken in given time period**.**	8 %
❖ **Pass/fail rate of test drive [percent]:** what proportion of finished products passed the quality test and how many failed.	8 %
❖ **Quality as annual income vs. value of defects [percent]:** the monetary value of the defects (euros) divided by the total annual income of the production company (euros). Reported in %.	8 %
❖ **Production error free rate [percent]:** what percent of production was error free.	8 %
❖ **Defects per finished product [quantity/product]:** how many defects occur on average per finished product.	8 %
❖ **NCRs (nonconformances) [euros]: w**hat is the monetary value of nonconformances in production from a certain time period.	8 %
Production lead time	**33 %**

❖ **Cycle time [time]:** the average time taken to manufacture one production unit.	17 %
❖ **On-time delivery [percent]:** what number of products were produced and shipped to the customer on time.	17 %
❖ **Planned throughput time vs. realized throughput time [percent]:** comparison of planned throughput time vs. actual throughput time. For example, if average product throughput is 4 min and planned throughput was 5 min then actual throughput exceeded the plan by 25 %.	8 %
Work-in-progress (WIP)	**25 %**
❖ **Number of unfinished products [quantity]:** how many unfinished products exists in the whole production line.	8 %
❖ **Quantity of WIP in various production stages [quantity]:** how many unfinished products exist per stage in the production process (e.g., packaging, welding, quality control, etc.)	8 %
❖ **Value of WIP in various production stages [euros]:** what is the monetary value of WIP in the production line, measured in euros.	8 %
Personnel availability	**25 %**
❖ **Personnel headcount [quantity]:** how many workers are available in a given time period (e.g., on the day, weekly, monthly, etc.).	17 %
❖ **Personnel absences [quantity]:** how many workers are absent due to holidays, illnesses, etc.	17 %
Cost	**25 %**
❖ **Cost to produce one part [euros/unit]:** what is the total cost of producing one product including both production line investment costs and variable costs.	8 %
❖ **Coverage of the different cost centers [euros vs. euros]:** The earnings and costs that a cost center brings in are compared. A cost center is defined as a set of processes in the production line.	8 %
❖ **Real hourly production rate per month [euros/hour]:** the realized production hours last month divided by the realized cost of production.	8 %
❖ **Cost of ownership [euros]:** the total cost of ownership of operating a line. This includes servicing costs, energy costs, maintenance costs, etc. This is comparable to the total costs of ownership of a car where you also must pay for its insurance, maintenance, repair, etc.	8 %
Schedule adherence	**17 %**
❖ **Schedule keeping/master production scheduling adherence [unit undefined]:** how on time is the production compared to the production plan.	17 %
Safety	**17 %**
❖ **Number of near misses [quantity/time period]:** how many near misses happened in a given time period. Near miss means something close to an accident (e.g., almost slipping on the factory floor or hand almost getting stuck in machine, etc.).	8(8) %
❖ **Number of safety related shopfloor meetings [quantity/time period]:** how many safety-related shopfloor meetings took place in a given time period.	8 %
Logistics	**8 %**
❖ **Response time from request to transfer [time]:** how long it took to transfer a certain item starting from its request.	8 %
❖ **Collected items per hour [items/hour]:** how many items were collected per hour.	8 %
❖ **Items collected per person [quantity/time]:** how many items were collected per person within a given time period.	8 %
❖ **Number of transfers from the reception area to intermediate storage [quantity]:** how many transfers were made from raw-material reception to the factory's intermediate storage.	8 %
❖ **Transfers per hour [quantity/hour]:** how many transfers were made per hour.	8 %
❖ **Stock fill rate [percent or quantity]:** what proportion of the stock level is full, given as % or quantity.	8 %
❖ **Quantity of time a worker must lift a product [quantity]:** number of times a worker must lift a product per given time period.	8 %
Environmental factors	**8 %**
❖ **Power/energy consumption [kW or kWh]:** kWh per machine, kW per product, and peak power demand per machine.	8(25) %
❖ **CO_2 emissions [kg]:** measured per machine and per produced unit.	8(8) %
Other	**8 %**
❖ **Demand prediction accuracy [percent]:** how close the demand prediction was relative to the actual input demand.	8 %

C. PM and PDM management controls with full description and full prevalence

Capacity and process optimization	83 %
❖ **Opening bottleneck by increasing its machine capacity:** increasing bottleneck production capacity by adding more machine capacity.	17 %
❖ **Adding quality assurance camera to critical process:** automating quality control process in a critical production phase by adding smart cameras inside machine.	17 %
❖ **Splitting a single-phased task into a two-phased task:** for instance, the assembly procedure is made two-phased. The work is divided from a single worker to two workers where worker 1 assembles first stage and worker 2 the second stage.	8 %
❖ **Balancing workload between machines:** allocating more work from a busy machine to a machine that has available capacity.	8 %
❖ **Moving an urgent product to available capacity:** moving a product with an urgent customer order or a delivery that is late on delivery to available capacity. This product can take priority over other products.	8 %
❖ **Changing to a more balanced tool in a machine:** changing the tool used in a machine. Old tool produces quality, which is beyond customer expectations at the expense of slower production speeds. A more suitable tool is integrated in the machine, which considerably improves the whole line's production cycle time.	8 %
❖ **Replacing faulty transport equipment**: realizing that scratches and other visual defects on a sub-assembly are caused by faulty transport equipment. Faulty transport equipment is replaced.	8 %
❖ **Providing production planner with better demand data:** the PDM representative develops or improves the data quality, which the production planner uses for demand forecasting.	8 %
❖ **Trying out larger batch size manufacturing:** PM would like to try out larger batch sizes to see whether this would improve their production performance.	8 %
❖ **Increasing frequency of equipment cleaning:** painting equipment would malfunction frequently, because of paint particle contaminating the equipment's joints. This was countered via increasing the cleaning frequency from a monthly to a weekly interval. Additionally, a deep clean was integrated annually via disassembly of paint equipment components.	8 %

Personnel management	42 (25) %
❖ **Increasing cross training of employees:** production personnel are cross-trained to ensure that the production personnel skill-mix is more robust and flexible. Allows the PM to reduce the effect of sick leaves and improve the mobility of his/her team and improve the ergonomics of the job. Training can be undertaken via formal training or simply rotation of workers to different stations.	17 (33) %
❖ **Changing the length of work shifts:** individual shift lengths can be tailored on a weekly basis (e.g., shifts on Monday and Tuesday are longer but Friday is shorter). This allows the PM to fit the work shifts with the current workload at hand.	17 %
❖ **Moving personnel between different cells and functions:** cross-trained production personnel is moved from one department (e.g., machining) to another department (e.g., assembly). Moving personnel allows PM to deal with production backlog and sick leaves in certain departments.	8 %
❖ **Moving additional personnel physically closer to critical production process:** the physical location of a critical worker's station is moved inside the factory. This worker is cross-trained, and they can substitute for another worker, who must undertake machine maintenance or respond to a production disruption elsewhere.	8 %
❖ **Specifying and improving work instructions:** updating and enhancing worker instructions to improve the instructions provided to the workers within the factory.	8 %
❖ **Balancing worker variability by pairing a slow and fast worker together:** the PM pairs a slower and faster working operator in the same shift alongside each other. This aims to motivate the slower worker, as they are alongside the faster worker. Similarly, pairing a slower and faster worker balances the production output from shift to shift.	8 %
❖ **Providing workers with preliminary information on incoming products to reduce set-up times:** the machine operator is given information in advance about the incoming product variants. This allows the worker to set up the machine correctly before the raw material comes to their station, increasing the process cycle time.	8 %

❖ **Negotiating and increasing worker overtime hours:** if production is behind schedule or the order quantity exceeds the production output achievable with normal working hours, the PM can negotiate overtime with the production personnel.	8 %
Buffer management	**33 %**
❖ **Changing the quantity and the size of buffers**: the size and quantity of the raw-material, WIP and finished production buffers can be changed to accommodate production variability. Similarly, this action can be used to reduce factory footprint, or the cash tied in unfinished or unsold products.	25 %
❖ **Moving the location of a buffer**: the physical location of the buffer is moved for various reasons (reducing transport or walking distances or to improve safety).	8 %
❖ **Upholding sufficient inventory levels around processes that are critical and prone to disturbances:** the inventory levels around critical production points (e.g., bottlenecks) are held at a sufficient level to ensure optimal utilization of bottleneck capacity.	8 %
Supplier Management	**8 %**
❖ **Asking for raw material more firmly from a supplier:** if raw material is missing from production the PM may use firmer negotiation strategy.	8 %