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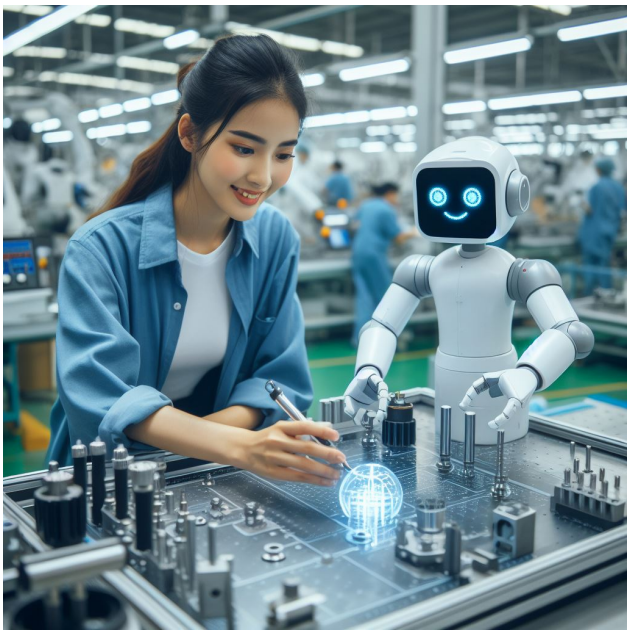

Accelerating Operational Excellence through Industry 4.0 Technologies

Developing and Evaluating an OpEx 4.0 Maturity Assessment Framework for the Nordic Manufacturing Industry

Master's thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Cover: A girl and a co-bot working together in an Industry 4.0 environment. Figure generated through Dall-E 3.

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Abstract

While Industry 4.0 (I4.0) primarily focuses on technological advancements, Operational Excellence (OpEx) harnesses human potential. However, a critical challenge arises from the lack of integration between the two, posing a barrier to realizing the full potential of I4.0. This thesis aims to explore how to integrate I4.0 with OpEx effectively—referred to as OpEx 4.0—and to create a framework capable of measuring the maturity level of OpEx 4.0 across various organizations. Utilizing an iterative process, the framework was developed in seven steps through a multi-method approach: a thematic analysis of three existing frameworks, a semi-structured literature review, and ten case studies using a Structured-case research cycle. The framework was evaluated through survey responses and maturity level analysis from six assessments across diverse organizations. Findings indicate the framework's user-friendliness, efficiency, and reliability in generating actionable insights applicable to organizations of varying sizes, industries, and maturity levels. It enables the creation of tailored road-maps and strategic positioning relative to industry benchmarks within a quick, three-hour format per company visit, showcasing its practical applicability. Subsequently, the results informed the identification of primary challenges, opportunities, and ambitions within the Nordic manufacturing industry. The findings indicate an average OpEx 4.0 maturity rating of 2.8 out of 5, highlighting areas for improvement. Analysis reveals that companies in this sector must focus on enhancing structured improvement processes, technology utilization, comprehensive understanding of all organizational dimensions, and active employee engagement in OpEx 4.0 principles. While most organizations acknowledge the potential for improvement, there appears to be a hesitancy to actively pursue the highest maturity level of OpEx 4.0 among the vast majority of organizations.

Keywords: Industry 4.0, Operational Excellence (OpEx), Operational Excellence 4.0 (OpEx 4.0), Assessment framework, Nordic Manufacturing Industry

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A special thank you goes to all the researchers who contributed their time and knowledge through interviews. Your willingness to share your experiences and insights was crucial in the iterative development of the OpEx 4.0 framework. Your contributions significantly enriched the quality and depth of this study.

We are profoundly grateful to all the companies that participated in our assessments. Your openness and cooperation in sharing data and providing access to your operations were essential for the practical evaluation of the framework. Your contributions have not only supported this research but also paved the way for future advancements in the integration of Industry 4.0 and Operational Excellence. We feel privileged to have worked with such exemplary companies, finding both inspiration and enjoyment in the process.

Lastly, we would like to thank our families and friends for their constant support and encouragement. Your constant belief in us has been a source of strength throughout this journey.

Thank you all for making this thesis possible.

Jonathan Malmqvist and Albin Mårdh, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
AGV	Automated Guided Vehicle
AR	Augmented Reality
CF	Conceptual Framework
CMM	Capability Maturity Model
CPS	Cyber-Physical systems
CPU	Central Processing Unit
CSFs	Critical Success Factors
DMAIC	Define-Measure-Analyze-Improve-Control, improvement method
DT	Digital Twin
IoT	Internet-of-Things
I4.0	Industry 4.0
JIT	Just-in-time logistics
LM	Lean Management/Lean Manufacturing
LSS	Lean Six Sigma
LSS 4.0	Lean Six Sigma 4.0
ML	Machine learning
MOM	Manufacturing Operations Management
OpEx	Operational Excellence
OpEx 4.0	Operational Excellence 4.0
PDCA	Plan-Do-Check-Act, continuous improvement cycle
PM	Predictive Maintenance
RQ	Research question
SM	Smart maintenance
SMEs	Small and medium-sized enterprises
TPS	Toyota Production Systems
TQM	Total Quality Management
VR	Virtual reality
WCM	World Class Manufacturing
WCOM	World Class Operations Management

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1
Introduction

In this chapter, the introduction to this master's thesis is presented, including the background, aim, research questions, scope, and delimitations. This master's thesis is conducted at the request of EFESO Consulting to investigate Operational Excellence in an Industry 4.0 environment, hereafter referred to as OpEx 4.0.

1.1 Background

Ever since industrialization began, paradigm shifts have been caused by technological leaps known as industrial revolutions (Lasi et al., 2014). Mechanization, intensive electricity use, and widespread digitization signify the first, second, and third industrial revolutions respectively, see Figure 1.1. "Industry 4.0" was coined in 2011 (Kagermann et al., 2011) at the Hanover Fair and officially announced in 2013 as a German government strategic initiative to play a pioneering role in its manufacturing industry, hereafter referred to as I4.0. This planned fourth industrial revolution is based on advanced digitization, internet technologies, and future-oriented technology in smart objects.

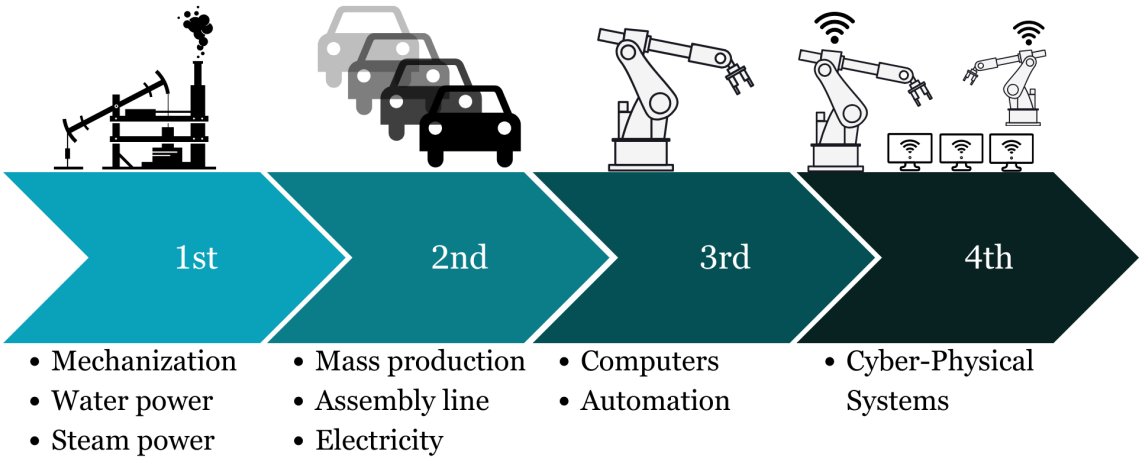

Figure 1.1: The four industrial revolutions. Adapted from Roser (2015).

The driving forces for the Fourth Industrial Revolution can be summarized as an application-pull (industrial demands) and a technology-push (technological advances) (Lasi et al., 2014). The increasing industrial demands are short development periods, individualization, flexibility, decentralization, resource efficiency, and more. The most prominent technological advances—increased mechanization and automation, digitization and networking, and miniaturization—are crucial for companies striving to remain competitive and prosper in the foreseeable future. Embracing and adapting to these driving forces, companies encounter not only technological but also complex organizational challenges (Lasi et al., 2014). Various operations management concepts and frameworks are deployed to address these multifaceted organizational implications and challenges. One such pivotal concept is Operational Excellence (OpEx). Despite its widespread application over several decades, the precise definition of OpEx remains somewhat ambiguous and continues to evolve (Tortorella et al., 2021). OpEx is implemented through enterprise-wide practices across four key dimensions: Culture, Continuous Process Improvement, Enterprise Alignment, and Results (Rusev & Salonitis, 2016). It transcends traditional tools and techniques, such as Six Sigma, Kaizen, and more, by integrating Lean principles with strategic organizational culture and management. OpEx may also be referred to as a continuous improvement philosophy to enhance customer value and optimize business resources. Regardless, companies employing OpEx gain advantages, ensuring sustainable growth even in competitive conditions (Muazu et al., 2021).

EFESO champions a principle known as the 10/30/60% rule, which posits that successful adaptation in I4.0 is driven by 10% technology, 30% processes, and 60% people and their skills. While I4.0 forums often emphasize new technologies, they frequently overlook the critical roles of processes and people. This oversight is precisely what EFESO aims to address through OpEx 4.0, advocating for a balanced focus that integrates technology with a human-centric approach. This paradigm shift moves beyond the traditional process-centric view of I4.0, proposing a more holistic model that intertwines technology with human factors. Despite existing frameworks for assessing traditional OpEx and I4.0, EFESO recognizes that these tools are becoming outdated and lack integration. Notably, there is a significant gap in both academia and industry regarding a unified concept of OpEx 4.0, which is critical for fully leveraging the potential of I4.0 technologies. This thesis, therefore, is not just an academic exercise but an endeavor to develop a comprehensive OpEx 4.0 assessment framework. Such a framework is essential to understand the current maturity, ambitions, and main challenges faced by companies in the Nordic manufacturing industry.

Current research on integrating OpEx methodologies—such as Lean, Six Sigma, and Lean Six Sigma—with I4.0 technologies often remains theoretical and conceptual (Anthony, 2024; Rossini et al., 2019). While these studies discuss the potential synergies between OpEx techniques and I4.0 technologies, they generally lack a focus on practical implementation strategies. In contrast, the industry is actively integrating emerging I4.0 technologies to enhance operational performance, striving for excellence in quality and reliability. Achieving a sustainable competitive

advantage necessitates not only the effective integration of these technologies with OpEx methodologies but also a deep understanding of how to implement these integrations within existing operational frameworks (Anthony, 2024). While numerous claims are made regarding the potential benefits associated with the technologies, a limited understanding exists of its optimal implementation within existing operations. Some studies suggest that the industry faces challenges in achieving the anticipated improvements, alongside an overall poor understanding of implementing I4.0 technology (Dillinger et al., 2022). This oversight highlights significant research gaps, including the absence of precise frameworks that provide clear road-maps and guidelines for an integrated OpEx and I4.0 model. Furthermore, there is a scarcity of comprehensive case studies to test and validate these frameworks (Skalli et al., 2023).

In an increasingly tough global market, with rapid technological advancements, supply chain disruptions, and geopolitical instability, Nordic companies must act swiftly if they want their domestic manufacturing industry to survive. However, integrating I4.0 technologies into existing operations has proven challenging. This thesis addresses this critical gap by developing a new framework that not only bridges the theoretical concepts with the practical application but also ensures that the potential of I4.0 is fully harnessed, helping companies thrive in a competitive environment. By providing actionable insights and tools, this thesis plays a pivotal role in guiding companies through the complexities of merging technology with traditional processes and workforce dynamics, ensuring that they not only survive but excel in the new industrial era.

1.2 Aim

This master's thesis aims to develop a robust OpEx 4.0 assessment framework. By moving beyond theoretical exploration and providing tangible, actionable strategies, the framework is designed to be a practical tool for assessing maturity, ambition, and main challenges faced by manufacturing companies. This thesis aims to yield useful insights based on cutting-edge research within OpEx 4.0, contributions from industry experts, and comprehensive case studies. This master thesis holds an overarching aim to achieve a comprehension of OpEx 4.0 in the Nordic manufacturing industry.

1.3 Research questions

The main questions to be answered in this master thesis are:

1. *How does OpEx 4.0 encompass and integrate the practices of Operational Excellence with Industry 4.0 technologies?*
2. *Which elements are critical for a successful and viable assessment of OpEx 4.0?*
3. *What are the challenges and opportunities for practitioners using the OpEx 4.0 maturity assessment framework?*

1.4 Scope and Delimitations

This master's thesis, conducted at Chalmers University of Technology, faces inherent constraints due to the format of a 20-week, full-time study, equivalent to 30 ECTS credits. These constraints limit the time and resources available for activities such as interviews and company visits, which may affect the depth and robustness of the research. Specifically for this master's thesis, the most notable delimitations are the following:

- **Use case**: The assessment is intended to be carried out by external auditors, who are experts (the authors included), at an early stage of an organization's journey towards OpEx 4.0.
- **Format of maturity assessment framework**: A "quick scan", that can be carried out during a 2-4 hour visit, including a factory tour and one or multiple sit-down interviews with knowledgeable people within the organization.
- **Nordic manufacturing industry**: The Nordic region refers to Sweden, Finland, Denmark, and Norway. The manufacturing industry includes all producers of goods (tangible assets), not companies producing solely services:
  - All discrete manufacturing
  - Industrial equipment, automotive, aerospace, and defense, etc
  - Food production, Pharmaceuticals, etc
  - Forest, Packaging, etc
- **Size of organizations**: The framework is designed for assessing SMEs or individual sites within multi-site or international organizations. While sites can leverage capabilities from the broader organization similar to SMEs using external resources, the assessment focuses solely on the maturity of the individual site. This approach is necessary due to the complexities and scale of larger organizations relative to the intended scope and format of the maturity assessment framework.
- **Sustainability**: This thesis primarily concentrates on social sustainability, ethical implications, and the role of environmental sustainability within manufacturing organizations. Given that economic sustainability is well-covered and inherently supported by OpEX (Anthony, 2024) and OpEx 4.0, this aspect will not be a central focus of the research.

2
Theory

In this chapter, a theoretical background is provided to offer the necessary knowledge about the subjects covered in this master's thesis. Including OpEx, I4.0, maturity models, and frameworks.

2.1 Operational Excellence

The concept of operational excellence (OpEx) evolved from a synthesis of various quality management and efficiency methodologies that developed throughout the 20th century. One of the early contributors was Dr. Joseph M. Juran, who in the early 1950s taught Japanese business leaders about quality improvements (Defeo, 2020). As more companies began to adopt the methods of Juran and others, Japanese companies' journey towards OpEx started. Arguably, the most strongly associated company with the Japanese quality movement is Toyota Motor Company, referred to only as Toyota from now on. However, Toyota's operational improvements, which later contributed to the OpEx movement, were primarily driven by their internal development of the Toyota Production System (TPS). Shigeo Shingo was among the first to bring these insights to the Western world, and the Shingo model was created. Today, the term OpEx is strongly related to the Shingo model, an approach to business that emphasizes quality at the source, value to the customer, a zero-inventory supply chain, and an understanding of the workplace at all levels. Utah State University annually awards the Shingo Prize to organizations that follow the 10 Shingo guiding principles, often referred to as the core principles of OpEx (Shingoinstitute, n.d.):

1. **Respect every individual**: This applies to customers, employees, partners, and suppliers. For example, involving all employees in improvement projects and coaching them on problem-solving will make them feel emotionally invested in their work.
2. **Lead with humility**: Employees should be empowered to contribute ideas and feedback without any fear of repercussions. Leaders should be willing to seek input, listen, and learn.
3. **Seek perfection**: Perfection is an aspirational goal that is not likely to be achieved, but the pursuit of it creates a mindset and culture of both continuous and radical improvement.
4. **Embrace scientific thinking**: Innovation and improvement are the consequence of repeated cycles of experimentation and learning.
5. **Focus on processes**: It can be easy to blame other people for failure, but

more often than not, the problem is the process. A process-led approach is key to OpEx.

6. **Assure Quality at the source**: Perfect quality can only be achieved when every element of work is performed perfectly every time. When and if errors occur, they must be detected and corrected at the point and time of their creation.
7. **Improve flow & Pull**: Value for customers is maximized when it is created in response to real demand and a continuous and uninterrupted flow. Anything that disrupts the continuous flow of value is waste.
8. **Think Systemically**: Understanding the relationship between all parts of a process will help you make better decisions and meaningful improvements. It's important to remove any barriers that prevent the flow of ideas through an organization.
9. **Create a Constancy of Purpose**: Everyone in an organization should be aware of its goals and mission statement from day one, so they can align their ideas, and actions decisions accordingly. This strategic alignment is key for OpEx.
10. **Create Value for the customer**: Value is defined as what a customer is willing to pay for. The best organizations continuously work to gain a deeper understanding of their customer's needs and expectations, so they can keep adding value.

The principles are categorized into four dimensions: cultural enablers, continuous process improvement, enterprise alignment, and results. See Figure 2.1 for a visual representation.

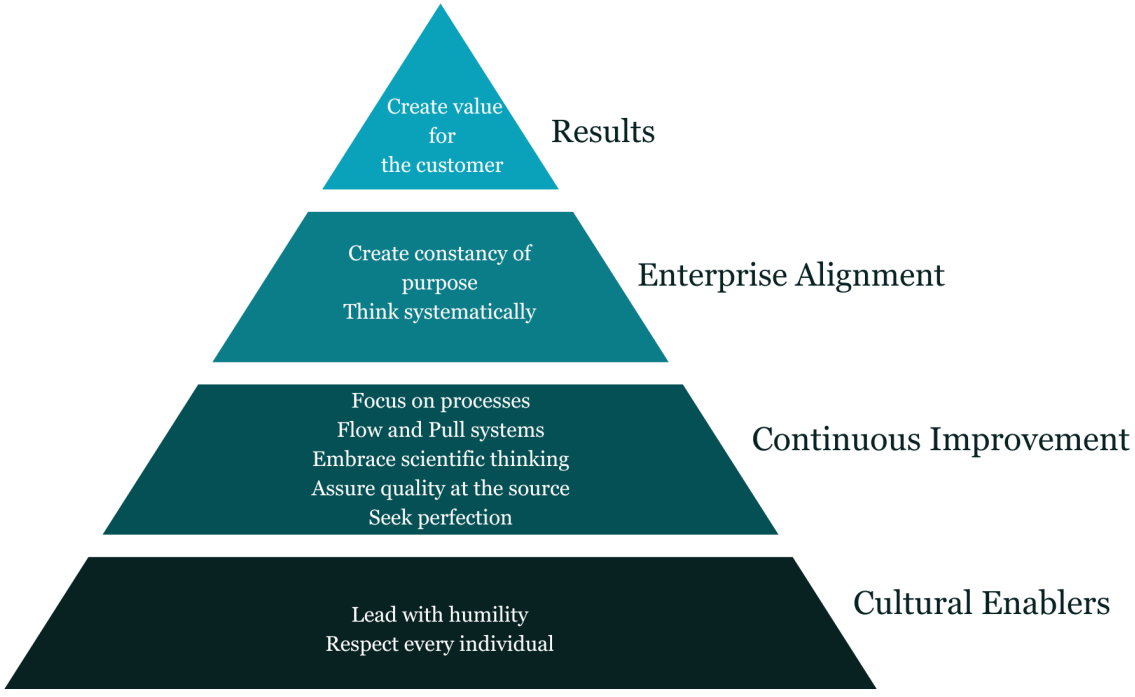

Figure 2.1: Guiding Principles of OpEx. Adapted from Shingoinstitute (n.d.).

Although the term OpEx has been widely applied over the past few decades, its meaning is still ill-defined (Tortorella et al., 2021). However, there is some level of agreement that excellence is not a state but a journey (Sampaio, 2019). Some suggest that OpEx is any plan that aims to develop or improve requirements, for excellence in operations, whether based on Total Quality Management (TQM), Toyota Production System (TPS), World Class Manufacturing (WCM), or any other (Terra et al., 2023). OpEx uses lean principles to achieve its goals by removing waste and integrating continuous improvements to achieve the best results (Tripathi et al., 2022). OpEx goes beyond the use of individual tools and techniques, it incorporates Lean principles with organizational culture and management at a strategic level.

Lean manufacturing often refers to a company's ongoing and systematic effort to eliminate sources of waste in a production process. Toyota is considered by many to have pioneered modern lean manufacturing by implementing JIT (just-in-time) inventory systems on a full scale in 1938 (Connaughton, 2023), amongst other things. But Toyota truly caught the world's attention in the 1970s when it became clear that there was something special about Japanese quality and efficiency (Liker, 2021). Waste in lean manufacturing refers to eight different kinds of activities that do not contribute value to the customer (Connaughton, 2023):

1. **Overproduction**: The practice of producing something without a customer.
2. **Waiting**: When workers or processes are idle due to waiting for parts, equipment, information, or machine setup.
3. **Conveyance**: Unnecessary moving of material, parts, or information, etc.
4. **Processing**: Sometimes called over-processing, and refers to when more work is executed than is required by the customers. It can also refer to when the same data must be entered multiple times.
5. **Inventory**: This occurs when assets are used to stock parts/products that an end-consumer has not ordered.
6. **Unnecessary motion**: Includes time spent performing extra movements by workers specifically. For example, walking to collect parts for assembly.
7. **Processing failures**: Time or effort spent on reworking defects.
8. **Space**: Refers to using more real estate than what is required, including the extra utilities and overhead to manage the space.

Any action, whether it is a technique or tool, that reduces any of these eight types of waste can be considered a part of a lean manufacturing strategy. Still, there are five tools for reducing waste that is strongly associated with lean manufacturing (Connaughton, 2023): Cellular manufacturing, JIT, Kaizen, Kanban, and Poka-yoke. These tools, and others such as 5S (cleaning and organizing), often get all the attention from organizations, but Lean is an entire system that must permeate an organization's culture (Liker, 2021). A downside of lean is that it is unsuited to strong market deviations. Lean requires a lot of time to improve processes, which is unsuited to products with short life cycles, and future production characteristics are complex, requiring high and rapid innovation (Uriarte et al., 2018). Today, customer needs and requirements are rapidly changing, and two-thirds of consumers feel that

companies are not responding fast enough (Droga & Shah, 2022).

Rusev and Salonitis (2016) declare OpEx as a consequence of enterprise-wide practices based on correct principles that can be classified under four dimensions: culture, continuous process improvements, enterprise alignment, and results. To achieve OpEx, organizations need to be mature across all four dimensions. It is also important to highlight that organizations aiming to pursue a level of excellence need to ensure that their principles are consistently followed across the entire organization (A. M. Carvalho et al., 2021). The adoption of I4.0 methods has become a strategic policy, raising debate over the possible societal consequences (Terra et al., 2023). The move to I4.0 has resulted in the creation of new OpEx plans, organizations seek more efficient manufacturing processes that emphasize improving production methods and using quality tools. These programs attempt to accomplish continuous improvement in processes, goods, and services, driving organizations toward greater efficiency and productivity. The key to effective implementation of improvement tools lies in prioritizing the underlying principles rather than just their application (Rusev & Salonitis, 2016).

Implementing OpEx initiatives can contribute to organizational improvement; however, they do not alone ensure long-term success (A. Carvalho et al., 2017). There are instances where even successful organizations have lost market share and profit margins because they failed to adapt to new strategic and cultural market demands over time. Consequently, the focus of OpEx has evolved from merely achieving superior business performance to also managing change while maintaining high performance levels. For the successful implementation of organizational excellence programs, it is essential to ensure a cultural fit. These programs can foster organizational learning and help align the organizational culture with standards of excellence. Nonetheless, there is little evidence that excellence programs can sustain OpEx in organizations over the long term (A. Carvalho et al., 2017).

2.1.1 Improvement Methods

In this section, some of the most notable improvement methods of OpEx will be described, including Kaizen, Six Sigma, and Lean Six Sigma.

Kaizen
Kaizen is the Japanese term for the organizational philosophy and methodology of continuous improvement (Mercadal, 2023). Kaizen promotes constant and sustainable improvement, most often through small incremental steps. Kaizen must involve the entire workforce to be effective (Connaughton, 2023) and is thus inherently participatory. If accurately established within the organization, any member can and should identify and propose improvements, which in turn can be implemented effectively. This is why Kaizen also can be useful in maintaining a sense of participation and ownership among the workers, who in turn will contribute to raising the standards to reach the organization's goal (Mercadal, 2023). In practice, the philosophy of Kaizen is often expressed through designated teams or groups, but can also be

adopted individually. These constellations follow the PDCA cycle, sometimes referred to as the Deming cycle/wheel or the incremental process improvement wheel, of Plan, Do, Check, and Act, see Figure 2.2.

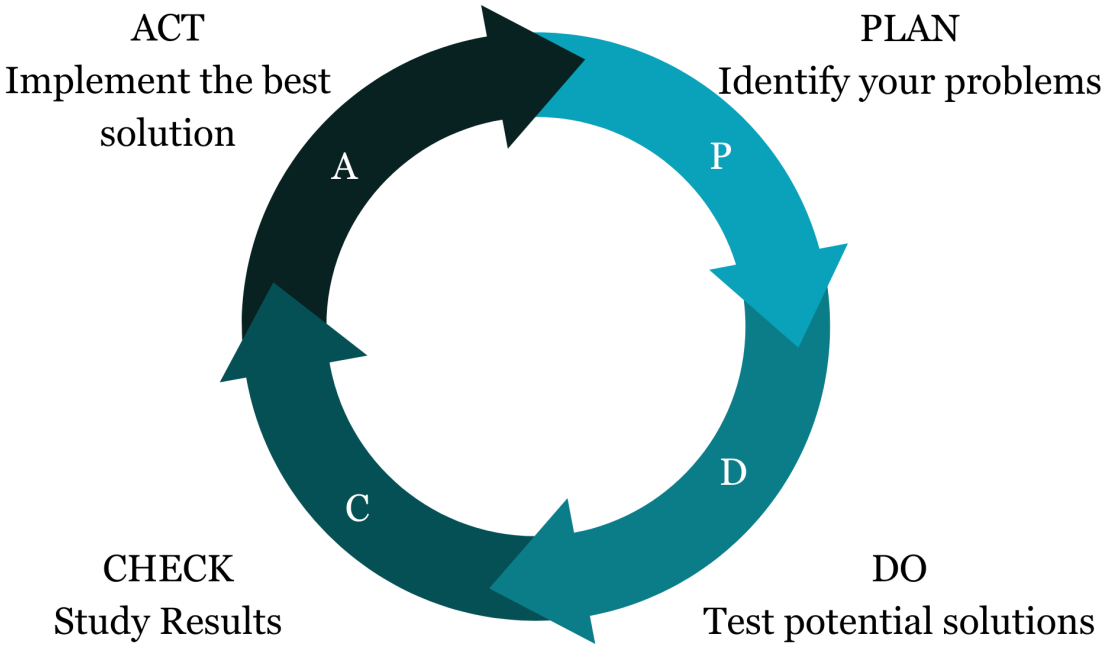

Figure 2.2: The PDCA cycle. Adapted from Mindtools (n.d.).

In the *Plan* phase objectives are identified, goals are set, the problem is analyzed, and an action plan is created to solve the problem and achieve the goals. In the *Do* phase, the action plan is carried out. In the *Check* phase, the obtained results are analyzed. Once the results have been obtained and verified, the Kaizen team must *Act* and identify whether or not a change/modification is required to improve the process or the quality of the product. These changes are in best-case scenarios consolidated through new standards and integrated into the work procedures and culture of the organization. The cycle is then repeated, improving the process each time with small incremental changes, that are both easier and less costly to implement than a few large changes (Mercadal, 2023).

Six sigma

Six Sigma is an effective implementation of proven quality principles and techniques, incorporating elements from many quality pioneers and their work (Pryzdek & Keller, 2023). The name comes from the Greek letter Sigma, σ, which is used by statisticians to measure variability in a given process and represents standard deviation. In the context of Six Sigma, the goal is to operate at a performance level six standard deviations away from the mean of a normal distribution. This implies an extremely low defect rate, at only 3.4 defects per million opportunities. In comparison, traditionally, companies accepted three- or four-sigma performance as a norm, which creates between 6,200 and 67,000 defects per million opportunities (Pryzdek & Keller, 2023).

Six Sigma takes a handful of tried-and-true, proven methods and trains in-house technical leaders, famously known as Six Sigma Black Belts, to a high level of proficiency in using these methods. Some methods have been used for decades and some are based on the latest computer technology. Regardless, these methods are applied together with a simple performance improvement model known as DMAIC (Pryzdek & Keller, 2023):
D - Define the goals of the improvement activity
M - Measure the existing system
A - Analyze the system to identify ways to eliminate the gap between the current performance of the system or process and the desired goal
I - Improve the system
C - Control the system

The philosophy of Six Sigma is the application of the scientific method to the design and operation of management systems and business processes that enable employees to deliver the greatest value to customers and owners (Pryzdek & Keller, 2023). The scientific method is the following:

1. Observe some important aspects, either of the organization itself or the market it operates in.
2. Develop a hypothesis consistent with these observations.
3. Make predictions based on your hypothesis.
4. Test predictions by conducting experiments or making further careful observations.
5. Record results, modify hypotheses based on new facts, and use statistical tools to eliminate or distinguish noise.
6. Repeat steps 3 and 4 until the hypothesis and results from a given experiment/observation are the same.

In Six Sigma, waste can be regarded as the difference between potential and actual quality. Six Sigma focuses on reducing waste, as in improving actual quality, by helping organizations produce products/services better, faster, and cheaper.

Lean Six Sigma
Lean Six Sigma (LSS) is a hybrid methodology designed to accommodate global challenges and constraints by capitalizing on Lean thinking and Six Sigma (Stern, 2018). In the late 1990s, companies started to recognize that Lean and Six Sigma do not conflict with each other but complement each other perfectly. Many of the early adopters saw the benefits of combining the toolboxes and attacking both defects and waste. LSS supports the idea of continuous improvement and uses both the PDCA cycle and the DMAIC model, along with many other famous tools from the respective methodologies. In LSS, organizations continuously ask themselves: *Who are the customers? What will it take to satisfy them?*

2.2 Industry 4.0

Industry 4.0, illustrated in Figure 1.1, represents a significant shift driven by the rapid evolution of digital technologies (Suleiman et al., 2022). It is characterized by the integration of cyber-physical systems, merging virtual and physical processes, as visualized in Figure 2.3. This revolution is fueled by both an application pull from industrial demands and a technology push due to technological advancements (Lasi et al., 2014). In I4.0, machines and equipment are interconnected, communicating directly via cloud networks, enabling decentralized and autonomous decision-making in real-time. The full potential of I4.0 is realized not through isolated technology applications but through their comprehensive integration, transforming traditional manufacturing systems (Issa et al., 2018).

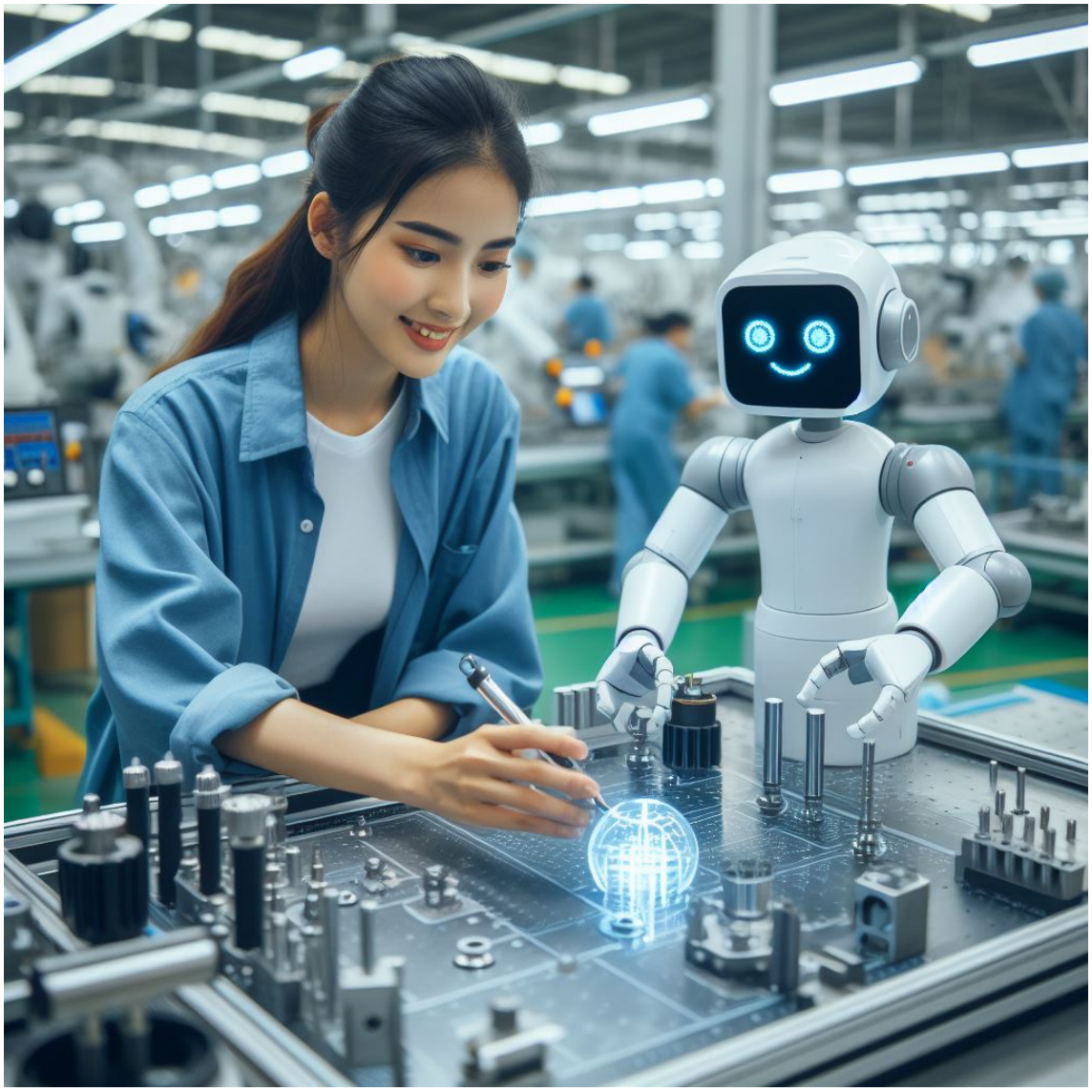

Figure 2.3: A girl and a co-bot working together in an Industry 4.0 environment. Generated through Dall-E 3.

Research and development have led to evolving interpretations of I4.0 since its inception in 2011, with no universal standard. Each country adapts its approach, influenced by its dominant industries and market needs (Yang & Gu, 2021). This diversity in approaches reflects the varied industrial landscapes and market demands across different regions.

2.2.1 Main Concepts of Industry 4.0

There were nine concepts of Industry 4.0 when it was first announced (Yang & Gu, 2021), all shortly described below.

Cyber-Physical Systems
Cyber-physical systems (CPS) is a system that effectively integrates cyber and physical components using modern sensors, computing, and network technologies (Alguliyev et al., 2018). Widespread adoption of CPS forms the process of combining technologies and knowledge, providing autonomy, reliability, systematicity, and control without human participation. CPS can be regarded as the basis for the development of everything smart, mobile systems, defense systems, and more.

Internet of Things
Internet of Things (IoT), refers to a state, or a paradigm, where many of the objects that surround us will be on the network in one form or the other communicating, where sensors and actuators blend seamlessly with the environment around us (Gubbi et al., 2013). The idea is to enable data exchange and communication between these devices, creating a network that enhances automation, efficiency, and functionality. In I4.0, IoT is believed to play a pivotal role in enabling a smart factory where machines, sensors, and systems communicate seamlessly to create a highly efficient and interconnected industrial ecosystem.

Big Data
Big Data is a complex process of gathering, compiling, cleaning, and analyzing large sets of data to transform raw data into information that can be used for decision-making (Tao et al., 2019).

3D Printing
3D printing, also known as additive manufacturing, is a manufacturing process that involves generating a structure by "printing" material layer-by-layer based on three-dimensional model data. The term 3D printing includes various, vastly different, manufacturing methods that all follow the same principle of applying material. These methods have been developed to meet the demand for printing complex structures at fine resolutions and the main benefits are freedom of design, mass customization, and minimum waste (Ngo et al., 2018).

Robotics
Robotics involves the design, creation, and operation of intelligent machines capable of performing tasks autonomously or semi-autonomously. In modern industry,

robots can complete their tasks intelligently, focusing on safety, flexibility, and collaboration (Goel & Gupta, 2020). In the future, together with the help of AI and ML, robots will continue to evolve the manufacturing industry and enhance the global economy.

Simulation
Simulation involves the imitation, or replication, of processes, systems, or situations from the real world using models or computer-based models. It's a technology for developing planning and exploratory models to optimize decision-making (de Paula Ferreira et al., 2020). Simulations can be applied to optimize the design and operations of complex and smart production systems, as well as aid in risk evaluation, cost calculations, predict implementation barriers and impacts on operational performance, etc.

Augmented Reality
An enhanced replica of the physical world using graphics, sound, and other sensory information (Ghobakhloo, 2018). Many definitions suggest that AR is a technology that overlays digital computer-generated information on objects or places in the real world to enhance the user experience (Kardong-Edgren et al., 2019).

Cloud Computing
Is a technology that comprises the leasing of the IT resources such as CPU (Central Processing Unit) or storage on a pay-per-use basis over the Internet (Alcácer & Cruz-Machado, 2019).

Cybersecurity
Cybersecurity is the practice of protecting computer systems, networks, and data from unauthorized access, attacks, and damage. With the increased connectivity and online capabilities that follow in I4.0, cybersecurity plays a leading role in preventing the loss of companies' competitiveness (Lezzi et al., 2018). This is why cybersecurity is expected to become an integral part of the strategy, design, and operations of companies embracing I4.0 technology.

Other Concepts
As we continue to build on the foundational work of the past decade, it is crucial to embrace current trends such as industrial AI, edge computing, 5G deployment in factories, collaborative robotics, autonomous intralogistics systems, and reliable data infrastructures (Kagermann & Wahlster, 2022). These technologies are instrumental in enhancing resilience, sovereignty, semantic interoperability, and sustainability within the sector as well as fostering digital innovation ecosystems vital for maintaining adaptability in an increasingly volatile economic and geopolitical climate.

Multiple other technologies and concepts have been associated with I4.0 and Smart manufacturing. One of which is Digital Twins (DT). The foundational concept of a DT involves three key components: a physical product, its virtual representation, and the bi-directional data connections that facilitate real-time data exchange (Jones

et al., 2020). Although research on DT has evolved, the basic premise remains unchanged. The complexity of a DT system can vary from a Digital Model with manual data transfer, a Digital Shadow with one-way automatic data flow, to a fully-fledged Digital Twin featuring bi-directional automatic data transfer. Additionally, 5G technology is recognized as a crucial facilitator for future factories and I4.0 environments, enabling faster, more reliable wireless communication essential for advanced manufacturing operations (Rao & Prasad, 2018). AR and Virtual Reality (VR) are also pivotal, often used interchangeably but incorrectly so. VR offers a fully virtual experience, while AR enhances real-world environments with virtual elements. Despite overlaps, the distinction is significant, leading scholars to advocate for precise and contemporary definitions of each technology (Kardong-Edgren et al., 2019).

2.3 Frameworks for Maturity Assessments

This section presents the theory of maturity models and frameworks for maturity assessments. Focusing on their application in measuring and improving organizational processes within manufacturing.

2.3.1 Maturity assessments

A maturity model can be described as a proven and valuable technique in measuring different aspects of a process or organization (Proenca, 2016). Maturity assessments are used to determine the current maturity level of a certain aspect of an organization and to enable stakeholders to identify strengths as well as improvement points, auditing, and benchmarking. Based on the results, a prioritization can be done to conclude what's needed to reach a higher maturity level. A maturity assessment model often consists of five levels and is often named according to an increasing degree of maturity: Initial, Managed, Defined, Quantitatively managed, and Optimized. However, the number of levels and their respective names may differ.

Capability Maturity Models (CMMs) are central to many assessment frameworks and are increasingly utilized to gauge how comprehensively an organization implements processes across its various business functions (Kerrigan, 2013). Initially designed for software development, CMMs have been successfully adapted to other areas, evolving into a versatile framework for process improvement. As the manufacturing industry is going through a digital transformation, the gap might decrease from its initial use case. CMMs provide a structured approach for organizations to define and progressively enhance their business processes (Kerrigan, 2013).

One significant adaptation of CMMs in manufacturing is the Manufacturing Operations Management/Capability Maturity Model (MOM/CMM) developed by the Manufacturing Enterprise Systems Association. This model serves as a tool to assess an organization's proficiency in process improvement (Brandl, 2016), using a familiar five-level progression to evaluate performance. Higher scores in this assessment correlate with greater efficiency, fewer errors, and reduced systemic problems in manufacturing operations. However, implementing MOM/CMM is both time and resource-intensive, largely due to its reliance on extensive questionnaires and a lack of strategies for leveraging evaluation results for improvement (Li et al., 2017).

Assessments play a crucial role in OpEx, acting as a 'reality check' for organizations embarking on their OpEx journey (Rusev & Salonitis, 2016). To successfully achieve OpEx, it is essential that organizations not only implement the correct principles but also integrate these deeply within their organizational culture (Rusev & Salonitis, 2016). This integration underscores the importance of a holistic assessment framework. A five-level maturity scale has proved effective for assessing OpEx maturity, providing a clear pathway for organizations to gauge their progress and areas of improvement (Isoherranen et al., 2016).

2.3.2 OpEx 4.0 frameworks

Over the years, multiple assessment tools have emerged for measuring Industry 4.0 maturity, each focusing on different aspects and yielding varied results. There are many depictions of I4.0 maturity levels, often in the shape of a staircase going from digitization (computerization and connectivity) to I4.0, see Figure 2.4, with incremental steps such as *Visibility* ("Seeing" - What is happening?), *Transparency* ("Understanding" - Why is it happening?), *Predictive capacity* ("Being prepared" - What will happen?), to finally *Adaptability* ("Self-optimizing" - How can an autonomous reaction take place?).

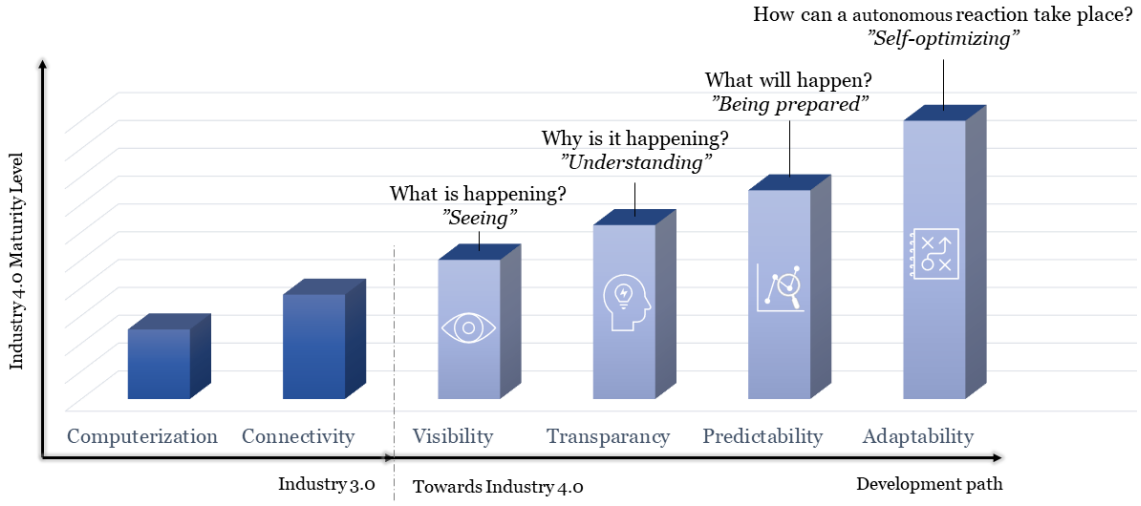

Figure 2.4: Industry 4.0 Maturity Levels. Adapted from Ravi Kumar and Enose (2018).

A comprehensive review of these I4.0 maturity models (Nick et al., 2021) revealed that:

- Maturity models are mainly technology-focused, they neglect managerial aspects and organizational dimensions
- Companies' size is not considered
- Type of production (e.g., process industry) is not dealt with
- Type of the company (service, production, etc.) is not examined
- Complexity and type of the product are not investigated

This is central to this master thesis, to bridge the gap between organizational factors and technology through a more holistic framework. This endeavor aligns with ongoing research efforts to enhance current I4.0 maturity models, such as the CCMS 2.0 (Nick et al., 2021), or to develop new ones tailored to organizations adopting Smart manufacturing strategies, such as the Smart Manufacturing System Readiness Assessment (SMSRA) framework (Li et al., 2017). As Li et al. (2017) suggests, manufacturing enterprises cannot fully benefit from I4.0 technologies without reaching a certain maturity level in their operations. Li et al. (2017) provides an example:

"If there is no procedure established for production tracking, manufacturers are not able to select and locate necessary sensors in their manufacturing systems".

Furthermore, the MESA MOM/CMM is generally considered a precursor to the SMSRA framework, despite some existing overlaps. The creators of the SMSRA framework argue that a factory should ideally be at level 4 or 5 on the MOM/CMM before employing the SMSRA framework (Li et al., 2017). This reflects the paradigm shift facing the manufacturing industry and it may suggest that certain aspects of OpEx may not be directly relevant for an OpEx 4.0 assessment. Instead, these elements should be considered prerequisites that must be in place before initiating the maturity assessment process.

3
Methods

In this chapter, the methodology of this master's thesis is described. This master's thesis aims to create a framework for assessing OpEx 4.0 in manufacturing companies and the research strategy is centered around answering these research questions:

1. *How does OpEx 4.0 encompass and integrate the practices of Operational Excellence with Industry 4.0 technologies?*
2. *Which elements are critical for a successful and viable assessment of OpEx 4.0?*
3. *What are the challenges and opportunities for practitioners using the OpEx 4.0 maturity assessment framework?*

Firstly, a literature review was conducted to understand the concept of OpEx 4.0, answer the first research question, and work as a basis and input into answering the second research question. Secondly, the main method to answer the second research question was an iterative design process where the framework gets increasingly close to a complete framework for OpEx 4.0. Lastly, several caste studies at manufacturing companies are conducted to test, evaluate, and analyze the framework.

3.1 Literature Overview

A semi-systematic literature review inspired by the PRISMA guidelines ("Preferred Reporting Items for Systematic Reviews and Meta-Analysis", 2024) was conducted to understand how OpEx 4.0 relates to traditional Operational Excellence and Industry 4.0, the synergies between the OpEx methodologies and emerging technologies within I4.0. The objective was to achieve a theoretical baseline on the relevant topics to build upon further in the thesis, critically evaluate data, and offer positive and valuable results (Knopf, 2006). It was an iterative process that improved and changed course as more knowledge was acquired.

The databases used were mainly *Scopus* and *Google Scholar*, but also databases through *Chalmers Library* and the internet for industry sources. The search strategy was the following:

- **Search terms and Keywords**: 'Industry 4.0'; 'Operational Excellence'; 'Operational Excellence 4.0'; 'OpEx'; 'OpEx 4.0'; 'Lean'; 'Six Sigma'; 'LSS 4.0'; 'Maturity models'; 'Assessment'; 'Frameworks'; etc.
- **Combinations**, for example: 'Operational Excellence' AND 'Industry 4.0'

AND 'Framework'
- **Filters and Criteria**:
  - Years: 2012 - 2024 (Industry 4.0 was first coined in 2011)
  - Language: English
  - Document type: Article; Conference paper; Book; Book chapter; Review (s);

Since the topics and the research on both OpEx and I4.0 are vast but scarce for OpEx 4.0, since it is a relatively new concept, it was important to have robust selection criteria to ensure quality, and relevance, as well as to save time in the process. The selection criteria were therefore the following:

- **Relevance**: Sources must explicitly discuss both concepts in some sense, not just one of the two.
- **Quality and Credibility**: Preference for peer-reviewed articles and the impact factor or reputation of journals/conferences/publishers.
- **Geographical Considerations**: The literature review focuses on the Nordic region, supplemented by studies from regions with similar cultural, socio-economic, and technological profiles to ensure relevance and applicability. In striving for relevance to the Nordic context, studies from regions with significantly differing socio-economic or industrial conditions were selectively considered and sometimes disregarded, ensuring the applicability and validity of the findings for the Nordic Manufacturing Industry.
- **Industry-Specific Focus**: Manufacturing industry, discrete manufacturing, and similarly, since OpEx can vary drastically across various industries.
- **Recency and Relevance**: More recent publications are favored.
- **Citation Count**: Higher citation counts are seen as preferable.

Sources were later screened for relevance through reading abstracts or summaries and kept if determined it could be useful to answer our research questions. In the next step, the sources were read in their entirety, if necessary, and later used in the thesis if they stated something unique, interesting, and relevant for OpEx 4.0.

3.2 Framework Development

To answer Research Question 2, a framework was developed for assessing OpEx 4.0 using a methodology similar to the structured-case research cycle, originally presented by Carroll and Swatman (2000), see Figure 3.1 below for a conceptualized framework development process. This methodology has three main elements: the conceptual framework, the research cycle, and literature-based scrutiny of the theory built. "Structured" refers to three structural components of the method, and "case" refers to what is being studied. A case can thus be a person, group of people, organization, process, etc. This type of field research enables the development of a deep understanding of the complex interactions of people, processes, and technology within organizations (Carroll & Swatman, 2000).

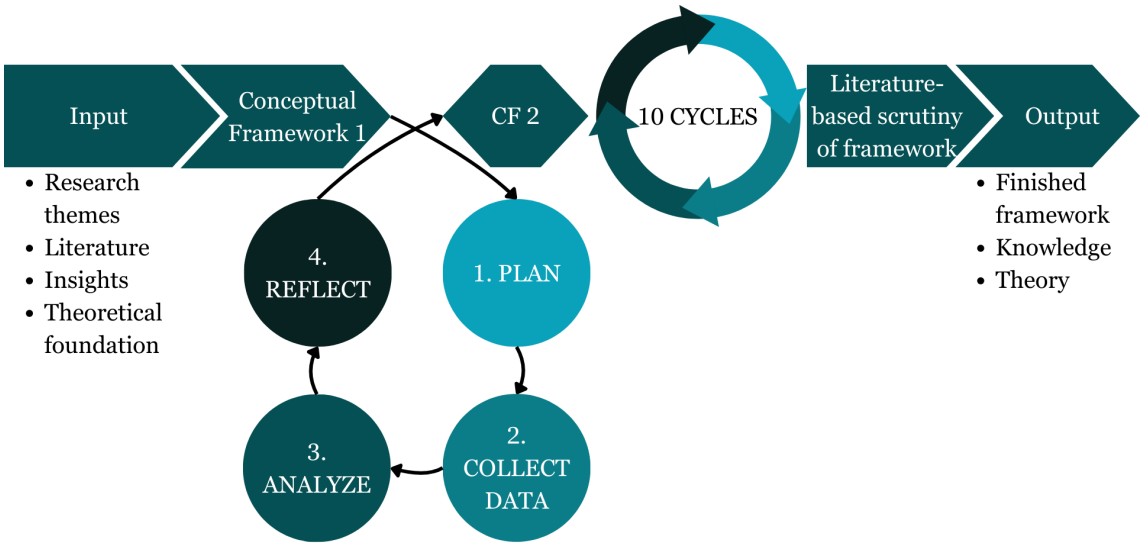

Figure 3.1: A spiral towards understanding, a visual representation of the structured-case methodology. Adapted from Carroll and Swatman (2000).

3.2.1 Conceptual Framework

The conceptual framework represents the researcher's aims, understanding, and theoretical foundations, and is a key element of the structured-case methodology, not only in the initial stages but throughout the whole development of the framework, as it explains the main things studied (key factors, constructs, or variables) and the relationships between them. The conceptual framework is formed from the research themes, existing knowledge from both literature and insights and is filtered by the researcher's theoretical foundations (Carroll & Swatman, 2000):

- The research theme is OpEx 4.0.
- Insights provided by EFESO (existing OpEx- and I4.0-assessment frameworks).
- The literature overview.
- Our theoretical foundations can be considered an academic background in Mechanical Engineering (B.Sc) and Production Engineering (M.Sc).

3.2.1.1 Thematic analysis

To develop the initial conceptual framework, a thematic analysis was performed to distill insights from three OpEx scans (see Appendix A.1). OpEx frameworks are categorized into *Dimensions*, *Themes*, *Questions*, and *Maturity levels*. Dimensions represent broad areas within OpEx, linked to organizational structures, functions, and Shingo principles. Each dimension encompasses several overarching themes that collectively define the dimension. Under each theme, specific questions help assess the organization's maturity level. There are five maturity levels, ranging from non-existent or poor execution to best-in-class execution, which permeates the entire organization. The intended result is one maturity assessment framework, in a quick-scan format, suitable for further development towards OpEx 4.0.

Thematic analysis is a qualitative analytic method that is versatile and widely used within psychology and other disciplines and can be applied across various theoretical frameworks, offering flexibility in analyzing qualitative data (Braun & Clarke, 2006). Thematic analysis facilitates the identification, analysis, and reporting of patterns (themes) within data. Thematic analysis offers several advantages, including its accessibility for researchers with little experience in qualitative analysis and its ability to produce rich and detailed data. It allows for a broad summary of key features across a large data set and an in-depth exploration of specific aspects, providing valuable insights into the research topic. Thematic analysis as a step-by-step process (Braun & Clarke, 2006) is described below in Table 3.1.

Table 3.1: Phases of Thematic Analysis. Adapted from Braun and Clarke (2006).

	Description
1	**Familiarizing Yourself with Your Data:** Engage deeply with the data, possibly including transcribing, reading, and re-reading the data, noting initial ideas.
2	**Generating Initial Codes:** Systematically code interesting features across the data set, organizing data relevant to each code.
3	**Searching for Themes:** Sort different codes into potential themes, collating all relevant coded data extracts within these themes.
4	**Reviewing Themes:** Review and refine themes, ensuring they form a coherent pattern and accurately reflect the data set.
5	**Defining and Naming Themes:** Define and further refine themes, capturing the essence of what each theme is about and ensuring internal consistency.
6	**Producing the Report:** Integrate vivid and illustrative data extracts into an analytic narrative that tells a coherent story about the data.

The thematic analysis proceeded from top to bottom (*Dimensions* down to *Maturity Levels*), examining each level in sequence, keeping the succeeding lower levels until appropriate. As shown in Appendix A.1, the three frameworks were developed for different purposes, resulting in significant variations in scope and execution.

3.2.1.2 Merging with Industry 4.0

The subsequent step involved integrating I4.0 technologies and capabilities. Given that the initial framework was preliminary and not fully developed, the implementation of I4.0 aimed to sketch a basic outline of a combined "OpEx and I4.0"-framework. Consequently, minimal adjustments were made to refine the framework, which included minor revisions and clarifications of questions and maturity levels. Utilizing the foundational theories and initial findings surrounding I4.0, OpEx, and OpEx 4.0, we integrated specific maturity levels with corresponding I4.0 technologies and capabilities. The selection of questions for this integration focused on those that naturally aligned with I4.0 technologies, showcased clear, textbook examples of use cases, and could be reliably replicated across the framework.

3.2.2 Research cycle

The research cycle consists of four stages, drawing on practice-based models like the action research problem-solving cycle and the incremental process improvement wheel (Carroll & Swatman, 2000), see Figure 2.2. Although these stages are described as distinct, they are fluid and ill-defined, with frequent iteration occurring between adjacent stages.

Plan
The first stage of the research cycle is planning (Carroll & Swatman, 2000). Here, the research themes and design are selected, and later the case to be investigated. The themes guide the areas of interest, and the methods for collecting, recording, processing, and analyzing data are planned.

Collect data
Next, the data are collected and recorded based on the initial plan (Carroll & Swatman, 2000). Field notes record the researcher's interpretations, which may open up new areas for exploration. It is important to be able to respond to opportunities in this stage, to be able to respond to unexpected outcomes and emerging themes. For instance, adding additional questions during an interview protocol to incorporate new emerging themes. The data collection may therefore overlap with the analysis stage. However, the analysis continues after the data collection has ended.

Analyze
Next, raw data is organized and reduced to meaningful data (Carroll & Swatman, 2000). This is done by structuring the data into a structural order that corresponds to the research themes and is linked to the aims of the research project. This is an ongoing, iterative process, that guides further reading of the data.

Reflect
The final step, reflection, goes beyond merely confirming evidence (Carroll & Swatman, 2000). It involves reviewing research methods, evaluating analysis outcomes, assessing emergent themes, and challenging current interpretations. The conceptual framework is then updated to incorporate new knowledge and theory, fostering an

iterative relationship between data, initial findings, and the framework itself. This reflection stage concludes once the framework is validated, solidified, or adjusted to include new insights. This refined framework sets the stage for the next research cycle.

3.2.2.1 Cases

The purpose, plan, and methodology for all 10 cases are presented below. These refer to the interviewees during the framework development, and not the company visits.

Case 1 - Industrial supervisor
The plan for Case 1 was to investigate the overall structure of an OpEx 4.0 maturity assessment framework. Something unique that was presented compared to the provided frameworks from EFESO are the theme-specific questions. One per theme and without maturity levels. These can be asked instead of all traditional specific questions. Some broad themes have two questions and some smaller themes have none. The first conceptual framework, the instructions, and the necessary information were sent to the industrial supervisor. Questions to be explored:

- How does the structure compare to other maturity assessment frameworks?
- What is a suitable format for a "quick scan" for OpEx 4.0?
- Are the top-level *Dimensions* and the lower-level *Themes* still suitable in OpEx 4.0, and how does the framework perform and compare to traditional OpEx?

Case 2 to 4 - OpEx-, OpEx 4.0-, Industry 4.0 Expert
The plan for Cases 2, 3, and 4 was to explore the optimal integration of traditional OpEx practices with I4.0 technologies. Although the interviews will concentrate on similar aspects of OpEx 4.0 framework development, they yield diverse perspectives contributing to the same objective.
The main questions explored during the three interviews include:

- How do you optimally integrate Industry 4.0 with Operational excellence?
- Can all technologies be integrated into OpEx, and to what extent?
- How should the Maturity levels be structured?
- How to develop the best possible framework for assessing OpEx 4.0 maturity?

Case 5 to Case 10 - Researchers/Experts within specific areas
The plan for Case 5-10 was to investigate and improve each of the 10 dimensions of OpEx 4.0. For each area, one designated researcher/expert will be consulted, some experts were consulted about several areas simultaneously. All cases followed the same structure, where the main questions were:

- What are the most important aspects of XX for companies that reach a high maturity in OpEx 4.0?
- How can we capture that within 5 themes?
- How effectively does our framework capture these key aspects and themes?
- Does our framework capture the capabilities and needs of the future for Nordic manufacturing companies that want to remain competitive?
- What are we missing and can be improved?

  - Which questions need to be changed to improve our framework?
  - Is the structure optimal?

The research design employed a semi-structured interview conducted in a workshop format, emphasizing constructive dialogue between participants and researchers.

3.2.3 Literature-based scrutiny of the theory built

Each research cycle leads to a more profound and nuanced understanding and the potential for gaining additional insights always exists. However, a stage of theoretical saturation is eventually reached, characterized by repetitive observations that offer minimal new knowledge. At this juncture, a comprehensive understanding of the assessment framework was achieved and critically contrasted with the literature (Carroll & Swatman, 2000). The scrutiny of related literature was conducted as part of the reflection phase of this thesis and is discussed in the discussion chapter, rather than being presented in the results section. Two aspects are considered:

- **Agreement between the findings and the literature** - Is the final assessment framework replicating, consolidating, or extending existing theory?
- **Conflict between the findings and the literature** - Any area or nature of any conflict needs to be examined and persuasively explained by the researchers

3.3 Determine the challenges and opportunities of the framework

Once the framework was developed using the structured-case methodology and considered finished, it was tested to determine the challenges and opportunities. The testing involved conducting case studies where the authors undertook guided site tours followed by targeted, semi-structured interviews with informed employees, such as production managers. The case studies encompassed six diverse manufacturing companies from the Nordic region. These companies were selected to represent a range of industries, sizes, and technological complexities, ensuring a broad analysis of the framework's applicability and effectiveness across different operational contexts. See Table 3.2 for a short description of the organization's characteristics and the titles of the interviewees.

Table 3.2: Characteristics of case companies and job titles of interviewees.

Case #	Main Product	Job title of interviewee
Company 1	Electronics	Production manager
Company 2	Renewable energy innovation	Production manager
Company 3	Automotive components	Plant manager
Company 4	Packaging	Quality and Lean Manager
Company 5	Laser technologies	Head of production
Company 6	Truck and trailer components	Supply chain Manager

Organizations involved in the case studies received an OpEx 4.0 maturity score that includes individual scores for each area and an average, overall score. The template for sending the results to the organization can be seen in Figure 3.2.

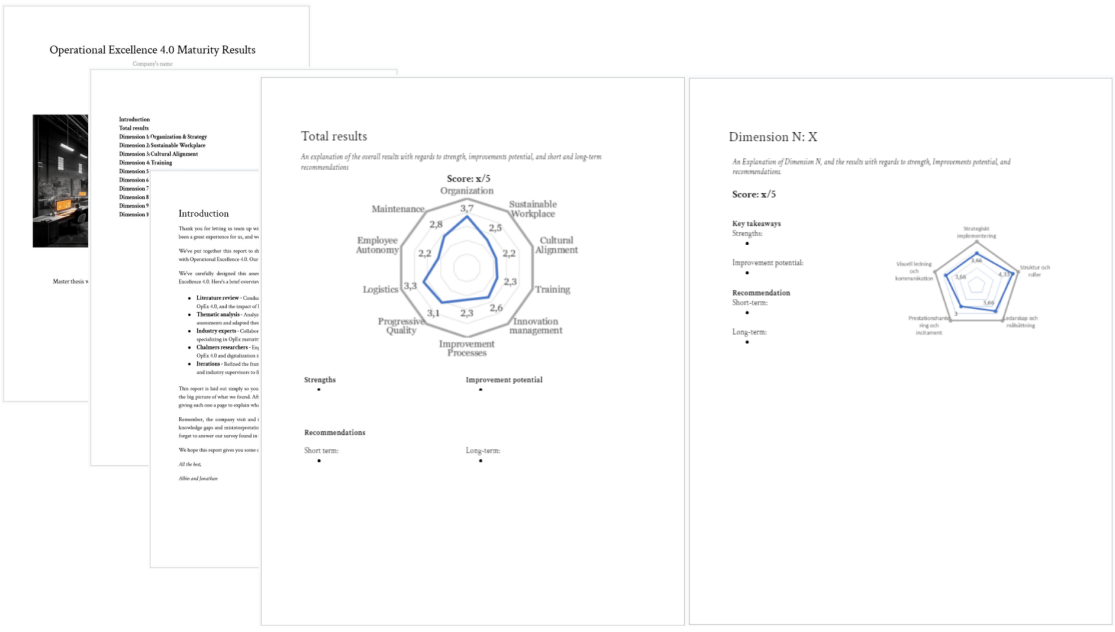

Figure 3.2: Template for the results.

3.3.1 Gathering Insights from Case Studies

Initially, insights from each case study were reviewed in collaboration with the corresponding company. Following each case study, participants received a survey alongside the results. The responses to these surveys were then utilized to evaluate user-friendliness, perceived value, and the future application of the framework. The survey included questions such as:

User-friendliness

1. *"To what extent do you agree with this statement: As an interviewee, I find the framework intuitive, clear, easy to understand, and user-friendly."*
   The participants could answer the questions in five different ways from "Completely disagree" to "Completely agree".

2. *"Were there any parts of the assessment that were confusing? You can choose multiple options and write more specific things under "Other...".*
   possible answers included: "None that I can think of", "Overall structure of the framework", "How the questions were phrased", "The names of the dimensions and themes", "despite the descriptions provided beforehand"

3. *"Were there any parts of the framework that were particularly challenging to answer properly? You can choose multiple options."*
   Possible answers included: "None that I could think of", and all dimensions.

4. *"How could the framework or questions be improved for better clarity and ease of use?"*
   Here, the participants could write freely.

Perceived value

5. *"To what extent do you agree with this statement: The insights provided by the framework are highly valuable, beneficial, helpful, and relevant for our organization."*
   The participants could answer the questions in five different ways from "Completely disagree" to "Completely agree".

6. *"To what extent do you agree with this statement: The insights provided by the framework are highly actionable and I can directly apply these insights to make significant improvements or changes."*
   The participants could answer the questions in five different ways from "Completely disagree" to "Completely agree".

7. *"If you answered that the insights were **not** valuable (etc) **nor** actionable (etc); What is missing or lacking in the insights we provided?"*
   Here, the participants could write freely.

8. *"Did the assessment highlight any new insights or areas for improvement that were previously overlooked?"* Here, the participants could write freely.

9. *"Do you think the results from the assessment are true for your organization? Why/Why not?"*
   Here, the participants could write freely.

10. *"Would you consider using this framework again in the future?"*
    With the following answer alternatives: "Yes, I believe OpEx 4.0 can benefit my organization and can help with creating road maps, action plans, etc." "Yes, I want to follow up on our progress in a couple of months/year." "No, I am happy with the results and insights through this master's thesis." "No, I think there are other concepts than OpEx 4.0 that are more important to stay competitive in the future."

11. *"Do you think your organization should continue working towards Operational Excellence 4.0?"*
    With the following answer alternatives: "No, we are happy with our current traditional concepts/philosophies." "Yes, and we have the capabilities to do so." "Yes, but we need to develop our internal capabilities to succeed." "Yes, but we need and want external help to transform our organization and develop our capabilities"

12. *"How likely are you to recommend this framework to other people in your organization or other partner companies in your value chain?".*
    Where the participants could rank their perceived value from 1-5.

Additional info

13. "Is there anything else you want to add or something we should know?"
    Here, the participants could answer freely.

3.3.2 Analysis of the Framework

After each case study, observations and findings pertinent to Research Question 3 (RQ3) were documented by the authors. This methodical recording ensured that unique insights or anomalies were systematically captured, thus facilitating a thorough analysis aligned with the broader research objectives. Subsequently, scores from all companies were analyzed to discern overarching trends. This step was integral to understanding the broader implications of the findings and assessing the framework's effectiveness in real-world settings. The qualitative data from interviews and open-ended survey responses were then thematically analyzed to identify common patterns and unique insights across different organizations. Additionally, observations from site tours provided deeper contextual insights into the day-to-day operations and implementation challenges faced by the companies, enriching the analysis. Guided by the following general research questions, the study aimed to delve deeply into the specific challenges and opportunities presented by the framework, focusing on its usability, flexibility, and reliability:

- What are the challenges when using the framework?

- How can the framework be improved?
- Can you conduct market-wide analyses?
- Can the results be used to create road maps for specific companies?
- What can the data be used for?
- Can we trust the results and what is the relative value of the results?

This structured approach allowed for a comprehensive understanding of the framework's application across varied organizational contexts and highlighted areas for further refinement. Simultaneously, an initial market analysis of the Nordic Manufacturing industry was conducted.

3.4 Research Quality

Research reliability is categorized into external and internal reliability (Bell et al., 2019). External reliability evaluates the study's replicability, assessing if similar results can be obtained when the research is replicated. Internal reliability examines the consistency of the results within the study itself.

To improve external reliability, this Master's thesis employs standardized data collection procedures and maintains transparent research methods. The development of the final framework through seven iterations from an initial conceptual framework is meticulously documented and detailed to ensure replicability. A potential limitation is the use of thematic analysis from EFESO's unpublished material, which serves as the structural basis for the initial framework. This reliance on non-public information may affect the replicability of the findings.

Internal reliability faces challenges from several sources. The identification of general trends from a small sample of companies may exaggerate statistical significance, particularly if one company disproportionately influences the results. Furthermore, the assumption of "no issue found" or similarly may not indicate the absence of issues but rather a limited scope of case studies. Nonetheless, these findings can still provide sufficiently reliable answers, under certain conditions. However, internal reliability may be compromised when analyzing various organizations. This issue arises because different representatives might have differing opinions on where their companies fit within the specified maturity levels of the framework. This variation can lead to discrepancies in how maturity levels are assigned across different evaluators.

Furthermore, the use of semi-structured interviews, which include tailored follow-up questions based on participant responses, introduces another variable. Although initial questions are standardized, the nature of follow-up questions can significantly influence the study's outcomes, potentially leading to variability in key takeaways across different research implementations. This goes for both the use of semi-structured interviews in the structured-case methodology for the framework development and during the company visits.

Despite these concerns, the methodologies applied are deemed robust, providing a strong foundation for obtaining reliable insights. This approach underlines the thesis's commitment to achieving insightful and dependable conclusions.

4
Results

In this chapter, the results of this master's thesis are presented. The sections are divided according to the three research questions.

4.1 How does OpEx 4.0 encompass and integrate the practices of Operational Excellence with Industry 4.0 technologies?

In this section, how OpEx 4.0 encompasses and integrates the practices of traditional OpEx and I4.0 is presented. While the exact definitions for both OpEx and I4.0 are somewhat ill-defined (Tortorella et al., 2021), there are multiple descriptions of the individual concepts and practical use cases. Even though there might be some coexistence between OpEx and I4.0 practices, the existing literature falls short in providing a comprehensive understanding of how to successfully integrate these two (Buer et al., 2018), and the concept of "OpEx 4.0" might not be equal to just combining I4.0 with OpEx, partly because there is a vast difference between the conceptual and operational definitions of both OpEx and I4.0 (Culot et al., 2020; Razavi Hajiagha et al., 2024). There is currently no clear definition of OpEx 4.0 either. When the exact phrases 'Operational excellence 4.0' and/or 'OpEx 4.0' are employed on platforms like Scopus, zero results are returned as of the beginning of 2024. Instead, sources typically explore OpEx within an I4.0 environment, there are multiple definitions of similar concepts to that of OpEx 4.0 (such as LM4.0, SS4.0, and LSS4.0).

EFESO describes OpEx 4.0 as a fusion of continuous improvement methods with emerging technologies like AI, ML, IoT, and data analytics, aiming to streamline processes and eliminate non-value-adding activities (Nystèn, 2023). This integration not only enhances productivity and sustainability but also strongly emphasizes a human-centric approach, aligning people, processes, and technology. McKinsey & Co. echoes this sentiment, noting that a few leading heavy-industry companies have effectively merged lean methodologies with technology to create augmented production systems (Gregorio et al., 2023). These systems not only leverage technology but also adapt core principles of lean production to optimize operational management and process design in a tech-enhanced environment. TÜVSÜD (TÜVSÜD, n.d.) highlights that OpEx 4.0 aims to improve productivity, reduce costs, and enhance product quality through data-driven optimization of plant processes. It is presented

as a gateway to continuous operational learning and improvement, emphasizing safety, integrity, and economic efficiency. Hitachi frames OpEx 4.0 as a collaboration between technology and people to achieve optimal outcomes, promoting a holistic approach to business strategy that integrates technological advancements with organizational culture and workforce needs (Dalal, 2018).

One literature review on Lean management, Six Sigma, and Industry 4.0 yielded an integrated framework of "LSS4.0" (Skalli et al., 2023). The framework consists of an iterative development process approach that transforms organizations from pre to post-digitalization. The framework contains inputs and requirements, outputs and benefits, as well as outlines drivers, barriers, synergies, challenges, and critical success factors(CSFs). This results section follows the same structure to answer how OpEx 4.0 encompasses and integrates the practices of OpEx with I4.0 technologies by presenting synergies between OpEx methodologies and I4.0 technologies, implementation challenges, CSFs for implementation, and the drivers for OpEx 4.0.

4.1.1 Synergies of OpEx and I4.0

OpEx and I4.0 are considered complementary and behave synergistically with each other in many ways (Razavi Hajiagha et al., 2024). OpEx addresses and significantly impacts both the challenges and benefits of I4.0. OpEx, with its focus on extended concepts of quality, affects various dimensions of I4.0 and supports its implementation. Lack of proper infrastructure, a common OpEx challenge, influences both the benefits and challenges of I4.0 as well, requiring intelligent equipment and high monetary investment. Moreover, OpEx challenges such as "lack of expertise" and "lack of financial resources" are influenced by I4.0 challenges and benefits, indicating a reciprocal relationship. Furthermore, while OpEx supports I4.0 to compensate for resource shortages, the two concepts are interdependent and complementary in their implementation (Razavi Hajiagha et al., 2024). This mutual influence highlights the need for a coordinated approach to leverage the strengths of both OpEx and I4.0 for organizational improvements. Some of the key similarities are the following:

- **Continuous improvement is pivotal in both Lean Manufacturing and I4.0** - While Lean Manufacturing centers around waste reduction and process enhancement, I4.0 emphasizes leveraging advanced technologies to enhance efficiency and production capabilities (Bueno et al., 2023). Chiarini and Kumar (2021) propose that integrating LSS and I4.0 seeks to reduce waste within machines, cells, and lines whilst achieving autonomous quality control systems.
- **Process optimization** - Lean manufacturing strives to create efficient, process-oriented systems by eliminating unnecessary operations, simplifying processes, and establishing standardized procedures. Similarly, I4.0 technologies facilitate the optimization of manufacturing processes through automation, data analytics, and enhanced communication capabilities (Bueno et al., 2023). An important aspect is that they both aim to create a smooth flow of processes (Wankhede et al., 2024).
- **Customer focus is a shared objective between Lean and I4.0** - Lean is

striving to effectively meet customer demands and I4.0 is a means to achieve it. In Lean manufacturing, the emphasis lies on delivering high-quality products, Reducing waste, and concentrating on value for customers. Conversely, I4.0 technologies enhance this customer focus by enabling customization and responsiveness to customer needs through advanced digital capabilities (Bueno et al., 2023).

- **Adaptation to Change** - Both OpEx and I4.0 require organizations to adapt to changes in technology, processes, and customer demands. They both emphasize the need for organizations to be agile and responsive to changes in the business environment (Bueno et al., 2023). This also emphasizes understanding how the work happens, as well as improving the reliability of the processes (Wankhede et al., 2024)

Multiple authors have created matrices to showcase which I4.0 technologies are compatible and suitable for various manufacturing concepts. In Table 4.1 some examples are represented. Pereira et al. (2019) created one for digital technologies that can be used for each lean practice and D Orazio et al. (2020) developed a matrix linking the principal dimensions of WCM (which significantly overlaps with traditional OpEx) to the major technological categories of I4.0. Dubbed the WCM-I4.0 Matrix, it encompasses 100 I4.0 technologies ideally matched to the WCM pillars. The matrix reveals that each of the 100 technologies is utilized at least once, but they have distinct applications and vary in usage frequency. Skalli et al. (2023) supports this, asserting that smart manufacturing or operations do not require the adoption of all I4.0 technologies.

Table 4.1: Lean/WCM practices and the supporting I4.0 technologies.

Lean tools supported by I4.0 technologies (Pereira et al., 2019)				
Lean	**I4.0 Technologies**			
VSM	Data/Analytics	VR/AR	Simulation	...
JIT	CPS	IoT	3D printing	Simulation
KPI	CPS	Data/Analytics	Simulation	3D-models
Empowerment	Data/Analytics	...	...	...
Six Sigma	CPS	IoT	Data/Analytics	
Etc...				
WCM-I4.0 Matrix (D Orazio et al., 2020)				
WCM	**I4.0 Technologies**			
SMED	IoT	AR	Simulation	AM
SOP	IoT	Mobile tech	AR	Simulation
PM	Cloud	Cog. Comp.	Mobile tech	AR
Defects mon.	Cloud	IoT	Cog. Comp.	AR etc...
JIT	Cloud	IoT	M2M	Simulation
Etc...				

Predictive maintenance (PM) mentioned above can be considered related to the concept of Smart Maintenance (SM), an organizational design for managing the

maintenance of manufacturing plants in environments with pervasive digital technologies (Bokrantz et al., 2020). This design encompasses four, measurable, core dimensions (Bokrantz & Skoogh, 2022): Data-driven decision-making, Human capital resources, Internal integration, and External integration.

4.1.2 Implementation challenges

Common challenges associated with integrating I4.0 different OpEx methodologies include:

- **Overemphasis on Technical Use Cases**: Companies often focus narrowly on technical use cases without addressing broader OpEx strategies, which can result in unfulfilled promises from new technologies (Gregorio et al., 2023).
- **Internal Capability Deficits**: Many organizations lack internal capabilities to develop, deploy, and sustain new technologies, leading to digitization efforts that often fail to deliver lasting results (Bughin et al., 2018; Colotla et al., 2024).
- **Lack of Standardization and Vision**: A lack of standardization, vision, and trained support hinders effective adoption of new technologies (Joshi et al., 2024).
- **Leadership Engagement and Training Restructuring**: Leadership engagement and organizational alignment with digital strategies are crucial, along with restructuring traditional training programs to fit the digital context (Lameijer et al., 2021).
- **High Integration Costs**: The high costs associated with integrating I4.0 technologies and developing new skills pose significant barriers to implementation (Terra et al., 2023).
- **Resistance to Change**: Resistance to change within organizational cultures makes it difficult to adopt new processes (Bueno et al., 2023; Wankhede et al., 2024).
- **Knowledge and Resource Limitations**: Enhanced employee education, improved knowledge about I4.0, and better knowledge management systems are needed to address knowledge and resource limitations (Wankhede et al., 2024).
- **Lack of Adoption Road-maps and Support**: Challenges include unclear adoption road-maps, insufficient government support, and a scarcity of proven success cases (Bueno et al., 2023).
- **Absence of Clear Business Models**: A lack of a clear business model strategy and difficulty in gaining stakeholder and supply chain partner support are additional significant challenges.

Research identifies *Cultural Resistance to Change* and *Sustaining Changes and Achieving Long-Term Success* as key challenges in integrating OpEx and I4.0. Cultural resistance directly affects technology adoption and effectiveness (Terra et al., 2023; Wankhede et al., 2024), while maintaining long-term improvements remains challenging (Bughin et al., 2018; Colotla et al., 2024). In *Culture Change That Sticks* (Katzenbach et al., 2012), it is argued that most companies try to implement change

while overhauling the culture, only to see the change initiative fizzle, fail, or backfire. Moreover, viewing resistance to change as a barrier rather than a resource can inadvertently foster a culture that opposes transformation (Ford & Ford, 2010), promoting competitive, defensive behaviors that impede successful implementation. Ignoring potential improvement ideas also obstructs progress. Introducing new technology in manufacturing demands sustained motivation among employees.

4.1.3 Critical success factors for implementation

Critical success factors for the implementation of integrated OpEx principles and I4.0 technologies:

- **Top Management Commitment**: Strong commitment from top management is essential, supported by a transformational leadership style to drive technology integration and continuous improvement (A. Kumar et al., 2022; Wankhede et al., 2024).
- **Lean Management Implementation**: Implementing Lean Management (LM) is crucial before adopting I4.0 technologies to understand and optimize business processes (Bueno et al., 2023).
- **Aligned Business Strategies**: Establish clear business strategies that align with digital transformation objectives (Wankhede et al., 2024).
- **Well-Defined Processes**: Ensure business processes are well-defined before automation begins (Bueno et al., 2023).
- **Balanced Technology Adoption**: Balance technology adoption with simplicity by avoiding over-automation and ensuring interoperability and real-time capabilities (Bueno et al., 2023; Buer et al., 2021).
- **Appropriate IT Infrastructure**: Develop an appropriate IT infrastructure for data storage, collection, and analysis (Wankhede et al., 2024).
- **Culture of Continuous Improvement**: Foster a culture of continuous improvement with management commitment, particularly in educating and engaging employees (Bueno et al., 2023).
- **Personnel Training**: Educate and train personnel to align OpEx methodologies with I4.0, especially in manufacturing industries (Ozbiltekin-Pala et al., 2024; Wankhede et al., 2024).
- **Smart Manufacturing Strategies**: Continuously adopt new strategies and embrace recent trends in smart manufacturing to maintain competitiveness (Ozbiltekin-Pala et al., 2024).
- **Deep Process Understanding**: Implementing LM leads to a deeper understanding of processes, which is vital for smart manufacturing systems (Bueno et al., 2023).
- **Strategic Investment Planning**: Plan investments effectively to achieve the highest results at the lowest cost for strategic alignment in manufacturing industries (Ozbiltekin-Pala et al., 2024).
- **Horizontal and Vertical Integration**: Ensure horizontal and vertical integration for effective implementation, with vertical integration focused on updating ERP modules to manage performance indicators in real-time, dynamically adjust KPIs, and integrate new technologies (Chiarini & Kumar,

2021).

While all these factors and challenges are vital, research indicates that some are particularly critical for success. *Top Management Commitment and Support* is the most crucial, as it shapes strategic direction, allocates resources, and drives momentum for integration efforts (A. Kumar et al., 2022; Wankhede et al., 2024). Similarly, *Strategic Alignment and Business Process* are essential for ensuring that I4.0 technologies complement and improve existing operational frameworks instead of conflicting with them or causing redundancies (Bueno et al., 2023; Ozbiltekin-Pala et al., 2024). Based on factors like cost, quality, delivery, flexibility, performance, and energy, the most crucial technologies for integrating Lean Six Sigma and I4.0 have been identified (Ibrahim & Kumar, 2024):

- **Modeling and simulation**: Essential for cost optimization and predictive manufacturing strategies.
- **AI & ML**: Improves quality through data-driven insights.
- **Big data Analytics**: Enhances production flexibility.
- **Automation and Industrial Robots**: Boosts production flexibility.
- **Smart sensors**: Promotes energy efficiency and sustainability.

Above that, effective change management and employee engagement are critical for successfully leveraging the workforce potential during digital transformations (Nystèn, 2023). Even though companies taking on OpEx 4.0 face new challenges, the change management fundamentals remain the same. One of the fundamental theories on change is Kotters' *Leading Change: Why Transformation Efforts Fail* (2007) In the article, Kotter presents the eight steps to transform an organization successfully, see Table 4.2 below.

Table 4.2: Kotters' eight steps to transforming your organization. Adapted from Kotter (2007).

	Steps to successfully transform your organization
1	Establishing a sense of urgency
2	Forming a powerful guiding coalition
3	Creating a vision
4	Communicating the vision
5	Empowering others to act on the vision
6	Planning for and creating short-term wins
7	Consolidating improvements and producing still more change
8	Institutionalizing new approaches

To overcome the implementation challenges associated with culture, organizations should leverage the existing cultural strengths of an organization (Katzenbach et al., 2012). By aligning change strategies with these cultural elements, and honoring the intrinsic strengths of the culture, change initiatives can achieve both strategic

and practical coherence, enhancing the likelihood of success. Success is also influenced significantly by change agents' position within personal relationship networks (Battilana & Casciro, 2013). Proximity to those who are ambivalent about change, known as fence-sitters, is advantageous, whereas closeness to outright resistors is less effective. Similarly, Greenhalgh et al. (2004) emphasizes the importance of social influence and network dynamics in the adoption of innovation. Power dynamics between the project steering group and the main project worker have a critical role in ensuring successful implementation. This underscores how power relations within an organization can significantly impact the effectiveness of change initiatives. Change initiatives can only be implemented and sustained through a highly engaged and supportive management (Savolainen et al., 2020), but a true commitment to change requires a participative approach across all organizational levels (Macchi et al., 2017).

In the evolving manufacturing landscape, traditionally rigid hierarchical structures are giving way to supervisor-less, self-directed teams that embody higher autonomy and decision-making capabilities (N. Kumar, 2023). Smart Manufacturing technologies now empower these teams with real-time planning and self-optimization capabilities, significantly altering plant operations and job characteristics by reducing low-skilled work and increasing high-skilled opportunities (Bortolotti et al., 2023). This shift not only allows for the automation of routine tasks, freeing employees to engage in more diverse work and learning opportunities but also keeps workers crucial for managing unexpected issues and spearheading continuous improvement.

Teams that operate with higher autonomy generally exhibit better performance, as autonomy enhances Lean commitment and improves overall corporate performance (Fausing et al., 2013). The challenge for managers within Lean/OpEx organizations lies in balancing standardized work with team proactivity. Encouraging team participation in decision-making about work design and fostering inter-team collaboration can help navigate this balance (Lantz et al., 2015). Such involvement improves communication, clarifies goals, and fosters a proactive culture that can lead to the establishment and enhancement of continuous improvement processes. Proactive teams are more likely to engage in identifying areas for improvement and taking the initiative to start continuous improvement projects.

To further boost motivation amid the paradigm shifts involving I4.0 and OpEx 4.0, *Self-Determination Theory* (Deci & Ryan, 1985) suggests focusing on tasks that promote intrinsic motivation factors such as autonomy. Autonomy, the degree of freedom and choice employees have in their work, is crucial for a motivated workforce. Higher autonomy correlates with greater Lean commitment and improved corporate performance (Bortolotti et al., 2023) since continuous improvement on the shop floor cannot occur without the involvement of employees. Clear, challenging goals with feedback significantly impact team motivation and performance (Locke & Latham, 1990). As technological changes demand new skills, emphasizing high learning goals can encourage individuals to excel. Specifically, setting ambitious learning targets enhances knowledge and results in superior performance (Seijts & Latham, 2012).

When employees lack confidence or skills for high-performance tasks, prioritizing learning goals can improve motivation and outcomes. Involving teams in setting specific and high goals, as opposed to vague or low ones, also proves to be a successful strategy for maintaining engagement and fostering an adaptive, continuously improving workforce.

4.1.4 Drivers

Industry stakeholders emphasize that OpEx 4.0 provides unique advantages beyond traditional OpEx and I4.0 technologies, offering comprehensive improvements across multiple facets of business. These benefits include:

- **Culture of Continuous Improvement**: Foster a culture of continuous improvement, innovation, and adaptability to ensure long-term success in a dynamic business environment (Nystèn, 2023)
- **Enhanced Business Results**: Achieve better ROI, quick payback times, and significant cost savings (Nystèn, 2023) (Dalal, 2018) (Hitachi, n.d.)
- **Increased Efficiency and Productivity**: Boost efficiency and productivity through data-driven insights and streamlined processes (Nystèn, 2023) (TÜVSÜD, n.d.) (Gregorio et al., 2023) (Dalal, 2018) (Hitachi, n.d.)
- **Improved Customer Satisfaction**: Elevate customer satisfaction through methods like mass customization (Nystèn, 2023) (Dalal, 2018) (Gregorio et al., 2023) (Hitachi, n.d.)
- **Shorter Lead Times**: Reduce lead times to enhance responsiveness to market demands (Nystèn, 2023)
- **Increased Safety**: Improve workplace safety (Nystèn, 2023) (TÜVSÜD, n.d.) (Gregorio et al., 2023)
- **Reduced Environmental Impact**: Minimize environmental impact and work towards net-zero emissions (Nystèn, 2023) (Gregorio et al., 2023) (McKinsey & Company, 2023)
- **Talent Attraction**: Strengthen the ability to attract top talent in recruitment processes (Hitachi, n.d.) (Dalal, 2018)
- **Employee Engagement**: Boost employee engagement, motivation, and excitement (Gregorio et al., 2023) (McKinsey & Company, 2023)
- **Managing Disruption**: Equip businesses to t thrive amidst the disruptions brought by I4.0, focusing on preparing for and managing these changes effectively (Hitachi, n.d.).

4.2 Which Elements are Critical for a Successful and Viable Assessment of OpEx 4.0?

In this section, the critical elements for a successful and viable assessment of OpEx 4.0 will be presented. Firstly, the results from the research cycles within the structured case methodology will be presented as the critical elements to make a successful and viable assessment of OpEx 4.0. Since the results of the various case studies conducted throughout this thesis have been the building blocks of the framework, nurturing the development and critically testing the framework's content. Secondly, the framework iterations will be presented. Lastly, the final framework is showcased.

4.2.1 Critical Elements

This subsection showcases the cases, who was interviewed, what aspect was investigated, and the key takeaways that influenced the development of the OpEx 4.0 maturity assessment framework. In multiple cases, some of the insights were repetitive, did not directly impact the development, and sometimes positively impacted other dimensions that were not originally intended. These details are not presented. The critical elements below are unique and have been directly implemented in the framework. The texts in *italic* are a mix of quotes, reflections, and summaries that stood out from each case.

Case 1: Industrial supervisor - Structure & OpEx
The framework should be restructured and standardized, for example, into 10 dimensions, 5 themes, and 3 questions per theme.

- Smart approach with one theme-specific question overarching the existing questions to create flexibility and adaptability.

Case 2: OpEx Scan Expert - Approach for OpEx 4.0
The framework should integrate OpEx and I4.0 into a unified model with combined maturity levels, reflecting both high-level OpEx practices and advanced I4.0 technologies, with the highest maturity level representing an optimal fusion of both elements.

- OpEx 4.0 aims to enhance traditional OpEx through the integration of I4.0 technologies like data analytics, AI, and real-time data usage on the shop floor.

Case 3: OpEx 4.0 Expert - OpEx 4.0 Expert
A critical aspect that needs to be assessed in OpEx 4.0, is the ability to effectively integrate digital solutions into existing operational frameworks. Conductors need expertise in operations and digital technologies. The use of the digital/I4.0 maturity model (connectivity, seeing, understanding, predicting, automating) is recommended to categorize maturity levels, where OpEx is the base and the I4.0 technology enables new capabilities and accelerates traditional OpEx.

- *A good tool needs to be applicable and flexible.*

Case 4: Industry 4.0 Expert - The impact of I4.0 on Operational Excellence
The framework should be based on OpEx as the foundation, selectively integrating I4.0 technologies that provide clear business benefits and enhance data management practices. Therefore, all I4.0 technologies do not need to be assessed or implemented. Data, data quality, Machine2Machine communication, and other data-sharing aspects need to be integrated throughout the framework.

- *A common pitfall in integrating I4.0 technologies is the reliance on poor-quality data.*

Case 5: Future of Work Expert - Training
The framework should emphasize the need for individualized learning approaches, integration of training into daily tasks, collaboration with educational institutions, collaboration within the organization, and the use of I4.0 technologies to enhance learning. The current framework is mostly adequate but may benefit from greater emphasis on specific skills and real-time problem-solving capabilities.

- *I4.0 technologies such as AI and micro-learning tools can enhance traditional training methods, providing tailored educational content and supporting diverse learning needs, including on-demand and job-specific training.*

Case 6: Quality Expert - Improvement Processes & Progressive Quality
The framework must ensure that quality is deeply embedded across all operations, not merely complying with standards like ISO 9000. Documentations should not be paper-based or stored in some random database: QMS, ISO, and Matrices should become more widely available and easier to understand, this includes accessible tools for quality improvement at all levels. The quality dimensions should reflect traditional Quality fundamentals. Ensure the framework explicitly addresses integrating digital tools and data analytics to support proactive quality improvements. Increase emphasis on teamwork and cross-collaboration.

- *I4.0 facilitates a proactive approach to quality management through enhanced data availability, allowing for better monitoring of processes, customer interactions, and overall quality. However, merely digitizing analog processes without enhancing them is a common pitfall.*

Case 7: Social Sustainability and Human Factors Expert - Employee Autonomy & Sustainable Workplace
The framework should be tailored and focused, directly relating to the core aspects of autonomy and sustainability. Viewing workers as long-term investments is essential. Consider the scope for sustainability, and avoid overly broad or ambiguous questions. Focus on the local community and the specific site's environmental impact. Minimize the risk of interference between employee autonomy and standard

work processes. The framework should explicitly address how technologies and process improvements enhance the safety, ergonomic, and cognitive aspects of workplace design.

- Autonomy should be exercised with caution to prevent disruption to established work processes. Improvements should be implemented in a structured manner, preferably when necessary.

Case 8: Smart Maintenance Expert - Maintenance
A highly mature maintenance operation achieves its goals in a highly cost-efficient manner. The framework for assessing maintenance should include critical themes such as Maintenance Strategy, Data-driven Decisions, Collective Knowledge, Internal Integration, and External Integration, to adequately cover the essential aspects of maintenance. Note, that it may not fully convey the day-to-day operational realities of maintenance on the shop floor.

- I4.0 brings both demands and opportunities. In an I4.0 factory, there's no standing still. This environment constantly pushes our personnel to develop new capabilities. At the same time, it provides us with advanced digital tools that are transforming the way we handle maintenance operations.

Case 9: Supply Chain Management Expert - Logistics
Use the term Logistics to not confuse someone with the scope. The framework should capture end-to-end logistics. Switch focus from separate lean aspects to a more "Lean flow". Try to balance Lean with adaptability/flexibility. Maturity levels should better correspond to the most important needs of traditional logistics since I4.0 implementation is limited by how mature their logistics operations are.

- Having automated systems isn't beneficial if people aren't actually using them. What's crucial is achieving effective efficiency. Maturity should be measured by the levels of competence and knowledge. Essentially, we should focus on automating processes that genuinely benefit from automation.

Case 10: Change & Innovation Management Expert - Cultural Alignment & Innovation management
The framework should capture and value an organizational structure that is adaptable to specific industry needs, seamlessly integrating knowledge and roles from leadership to the shop floor to enhance adaptability to new technologies and processes. Organizations need to proactively manage the cultural and organizational changes brought by digital transformation, addressing resistance and ensuring the organization evolves with technological advancements. Emphasize a unified culture that aligns with strategic goals while remaining agile enough to encourage innovation. Refine strategy understanding and differentiate between targets and actual performance. Leadership should act as guides, fostering a proactive approach to training and empowering employees to support cultural change through structured transformation plans.

- *The process does not necessarily stop after the product has been produced—it changes how you think about your offerings, challenging traditional views. It significantly impacts those working within older paradigms, introducing new jobs and roles that are not yet defined. This leads to a lot of uncertainty and resistance, underscoring the importance of effective change management.*

4.2.2 Conceptual Frameworks

In this part, the most prominent conceptual frameworks in terms of importance and relative change, compared to previous iterations, will be presented to contextualize the critical elements.

Conceptual Framework 1
The first conceptual framework, CF1, was unfinished in many ways. Firstly, the structure was irregular in terms of size and level of detail. As can be seen in Figure 4.1 below, CF1 is characterized by having vast differences throughout the framework, with a span of two to five themes per dimension, zero to two theme-specific questions, and one to eight sub-questions.

Dimension 1					D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Theme														
Theme-specific question														
Theme-specific question														
Q1	M1	M2	M3		M4									
Q2	M1		M3		M5									
Q3	M1	M2	M3	M4	M5									
Q4	M1	M2	M3	M4	M5									
Q5		M2	M3	M4	M5									
Theme														
Theme-specific question														
Q1		M2	M3	M4	M5									
Q2	M1	M2	M3	M4	M5									
Q3	M1	M2	M3	M4	M5									
Theme														
Theme-specific question														
Q1	M1		M3		M5									
Q2	M1		M3		M5									
Q3	M1	M2	M3	M4	M5									

11 Dimensions
2 - 5 Themes per Dimension
0 - 2 Theme-specific questions
1 - 8 Sub-questions
Irregular combinations of Maturity Levels

Figure 4.1: Structure of the first conceptual framework.

Secondly, the framework was not complete in terms of Maturity levels. This can be

seen in Figure 4.1 just below the "Theme-specific questions", where there are many different combinations of Maturity levels one through five (Marked as "M1", "M2", etc). Which is a natural consequence of the thematic analysis of the various frameworks, see Appendix A.1. Furthermore, I4.0 is not completely integrated yet, for example, only two maturity levels are marked as red in this dimension, symbolizing I4.0 integration. Thirdly, there is no thought behind the order of either dimension, theme, or questions.

Conceptual Framework 3

In the third Conceptual Framework, a more refined version started taking place. As can be seen in Figure 4.2, a new standardized structure was implemented throughout the framework.

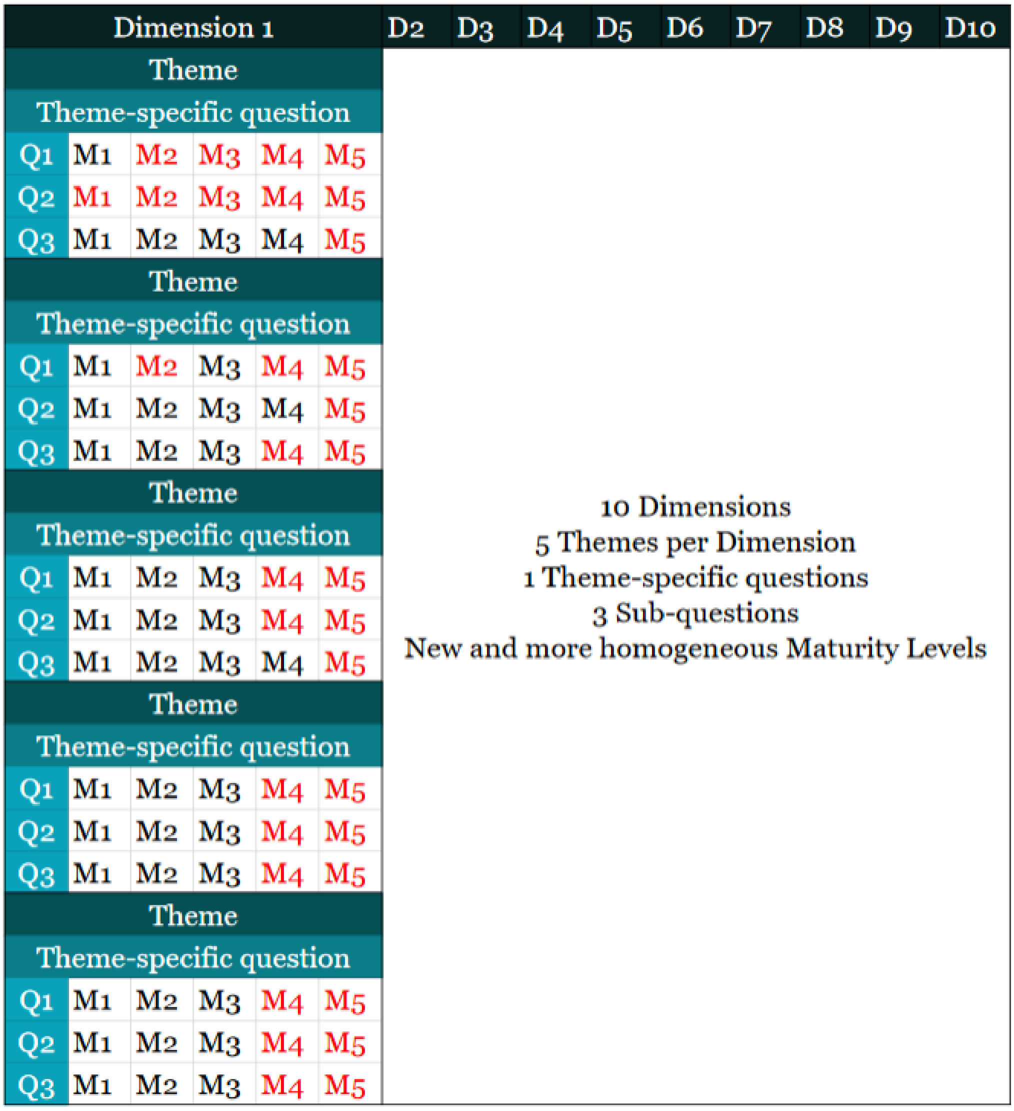

Figure 4.2: Structure of the third conceptual framework.

A by-product of trying to follow the new structure is the presence of dimensions and themes that include two aspects of OpEx 4.0. For example, "Education and

Training" and "Safe and Sustainable Workplace". Something that permeated the whole framework, all the way down to sub-questions that asked for different things simultaneously. In many cases, the framework tried to measure and assess multiple aspects at the same time that, despite being correlated, often were contradictory. In this iteration, new Maturity Levels were specified for a more homogeneous assessment and partly implemented throughout the framework. CF3 is still unfinished with unresolved issues such as questions and maturity levels that need to weave in new insights, be rephrased, etc, and some that are still missing completely.

Conceptual Framework 6
CF6 represents the final iteration before the ultimate version, offering a comprehensive and coherent structure compared to earlier frameworks. It integrates all dimensions with corresponding themes, theme-specific questions, sub-questions, and maturity levels, all adhering to a uniform logic. CF6 enhances clarity with well-defined dimensions and themes, ensuring that each question targets a single, non-contradictory aspect. The arrangement of dimensions and themes logically progresses from overarching organizational concerns down to specific functional details.

4.2.3 Final Framework of OpEx 4.0

The final maturity assessment framework of OpEx 4.0 consists of 10 dimensions, 50 themes, and 200 questions with corresponding maturity levels. The finished framework can be seen in Appendix A.2. However, since the framework is considered intellectual property owned by EFESO large parts of the framework are hidden.

The dimensions are the following:

- **Organization**: The structure and procedures within the organization that govern strategic approach, target setting, operational management, and communication.
- **Sustainable workplace**: An integrated approach focusing on employee safety, environmental sustainability, and societal well-being, guided by the Triple Bottom Line which emphasizes social and environmental considerations alongside the economic sustainability inherent in OpEx 4.0.
- **Cultural alignment**: The integration and embodiment of the organization's core values within its culture, managing and encouraging specific behaviors throughout the company.
- **Training**: The methods and practices for training management and employees to excel in modern, high-performance production environments.
- **Innovation management**: The adoption and integration of sustainable design, lean principles, operational foresight, and continuous learning to drive efficient and responsible innovation within the organization.
- **Improvement processes**: The systematic identification and addressing of bottlenecks and weaknesses to ensure continuous and effective organizational improvements.
- **Progressive quality**: The processes ensuring product quality, addressing quality issues, and enhancing process efficiency through rigorous testing and

analysis.

- **Logistics**: The organization's understanding of customer value and demand, application of lean flow principles, flexibility in handling disruptions, inventory management, and end-to-end logistics efficiency.
- **Employee Autonomy**: Support and empowerment of employees and teams for autonomous, supervisor-less, and self-directed work, evaluating how workplace conditions impact daily tasks and decision-making.
- **Maintenance**: The implemented maintenance strategy and its performance in terms of data-driven decisions, human capital resources, and internal and external integration.

The theme-specific questions are crafted to allow interviewees the freedom to answer openly while maintaining specificity within the theme's scope. The objective is to prompt interviewees to address the three sub-questions naturally, minimizing the need for additional questions from the conductor. Subsequently, the sub-questions delve into specific aspects of the theme, leaving little room for extensive elaboration. These follow-up questions are employed when interviewees overlook or misinterpret the theme-specific inquiry. This approach not only ensures a nuanced assessment but also serves as a fail-safe to facilitate a smooth interview process. Each of the five themes within every dimension correlates with the overarching concept while offering distinct perspectives, enhancing the comprehensiveness of the examination.

The maturity levels of OpEx 4.0 can be seen in Figure 4.3 below. It's a combination that measures how far along the development path an organization has gotten in its OpEx journey and which capabilities they have through emerging I4.0 technology. In essence, this implies that you can only score a specific maturity if you achieve both the demands on fundamental OpEx principles and processes as well as the associated capabilities (through the use of I4.0 concepts and technology). The description of the maturity levels is the following:

- **Maturity Level 1**: No active implementation of OpEx principles and processes. Basic infrastructure in place enabling connectivity.
- **Maturity Level 2**: Sporadic, non-systematic application of OpEx principles and processes. Initial data collection and storage, beginning to harness digital and seeing capabilities.
- **Maturity Level 3**: Systematic and structured OpEx processes are established. Advanced data utilization with analysis and contextualization, enhancing organizational understanding.
- **Maturity Level 4**: OpEx principles and processes are widely and successfully implemented. Integration of advanced analytics and systems for predictive insights.
- **Maturity Level 5**: Full and seamless integration of OpEx principles, exhibiting minimal deviations. Leveraging digital technologies for automating and optimizing processes. The organization utilizes emerging technology to accelerate its efforts toward OpEx.

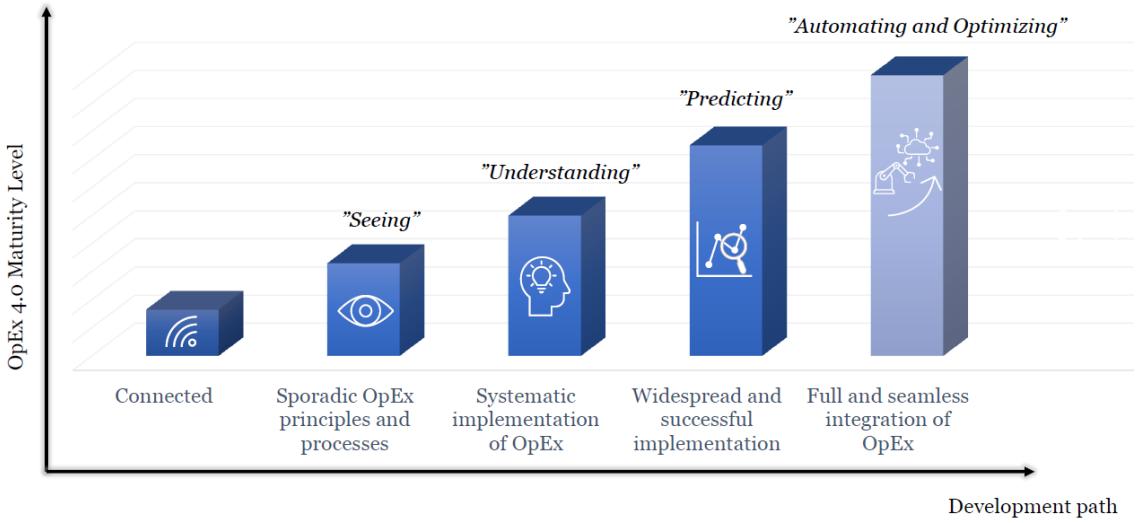

Figure 4.3: OpEx 4.0 Maturity Levels.

4.2.4 Guide for Using the Framework

Conducting a maturity assessment is an integral part of implementing the OpEx 4.0 framework. This process not only evaluates the current operational capabilities of an organization but also identifies areas for potential enhancement. The following steps outline a structured approach to applying the OpEx 4.0 maturity assessment, ensuring that the assessors can effectively utilize the framework to provide insightful, actionable data. This sequence is designed to maintain clarity and consistency throughout the assessment, promoting an accurate and comprehensive understanding of each organization's maturity levels. The process for conducting the OpEx 4.0 maturity assessment follows these steps:

1. Before visiting the company, written information regarding the definition of OpEx 4.0, the maturity assessment framework, and instructions about how the organization should prepare.
2. An introduction is given, outlining the format and maturity levels used for measurement while addressing any uncertainties.
3. Representatives from the organization conduct a site tour, focusing on understanding the operations. Sporadic questions may be asked during this phase for assessment purposes.
4. One or more knowledgeable individuals from the organization are interviewed using the framework to explore the specified dimensions. These interviews are recorded, transcribed, and later analyzed to determine the organization's maturity level.

Figure 4.4 illustrates an example of the framework components viewed by the assessor during the interview and subsequent analysis. Subsequently, the scores for each sub-question are averaged within each theme, contributing to the overall dimension score, which in turn determines the organization's overall maturity level.

Dimension: Maintenance					
Theme: Data-Driven Decision Making					
Theme-specific question: To which degree are your maintenance decisions based on data?					
Sub-question 1: How do you collect and analyse maintenance data?	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Sub-question 2: How are the machines in the factory prioritized for maintenance activities?	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Sub-question 3: Are main areas of breakdowns detected and reduced systematically?	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

Figure 4.4: Example of Framework Components: Dimensions, Themes, Questions, and Maturity Levels.

4.3 What are the challenges and opportunities for practitioners using the OpEx 4.0 maturity assessment tool?

This section explores the challenges and opportunities of using the OpEx 4.0 maturity assessment tool. It assesses the tool's usability, perceived value, and reliability to understand its potential applications and limitations better. Additionally, this section will discuss the results from case studies, which help determine the OpEx 4.0 maturity level, and the primary challenges, opportunities, and ambitions within the Nordic manufacturing industry. The organizations that were analyzed during the case studies varied in size and segment, from around 30 to a couple of hundred (depending on if you include other sites):

- **Company 1**: Electronics
- **Company 2**: Renewable energy innovation
- **Company 3**: Automotive components
- **Company 4**: Packaging solutions
- **Company 5**: Laser technologies
- **Company 6**: Truck and Trailer components

The varied survey responses reflect the different needs and perspectives of the participating companies, highlighting the diverse challenges and opportunities the OpEx 4.0 maturity assessment tool offers across organizations. The initial five companies approached the assessment with optimism regarding the potential insights that the OpEx 4.0 framework could offer, despite varying levels of familiarity with the concepts involved, and were amenable to arranging the assessment visits.

Conversely, the engagement with Company 6 presented unique challenges. The representative from this company required additional persuasion to participate and initially expressed skepticism about the value of the maturity assessment, questioning both the underlying concept and the expertise of the assessors. During the visit, after expounding on traditional Lean principles and citing the organization's robust financial performance, the representative was forthright in his belief that the framework was unlikely to offer any novel insights or valuable information to their operations.

4.3.1 Survey responses

This section presents the OpEx 4.0 maturity assessment framework survey results, distributed to all interviewees and organizations involved in the case studies. The responses are categorized into three main areas: User-Friendliness, Perceived Value, and Future Application.

4.3.1.1 User-friendliness

From the participants' survey responses, it is evident that the final framework is user-friendly. None of the participants found any part of the framework confusing (including overall structure, phrasing, and names of dimensions/themes) nor had suggestions for improvement. However, two participants did encounter challenges when responding to specific dimensions. These challenges varied between the two participants, suggesting that the issues were not inherent to the framework but rather dependent on the individual respondents, which was confirmed by the same respondents later in the survey. As displayed in Figure 4.5, all participants agreed or completely agreed with the statement:

"As an interviewee, I find the framework intuitive, clear, easy to understand, and user-friendly."

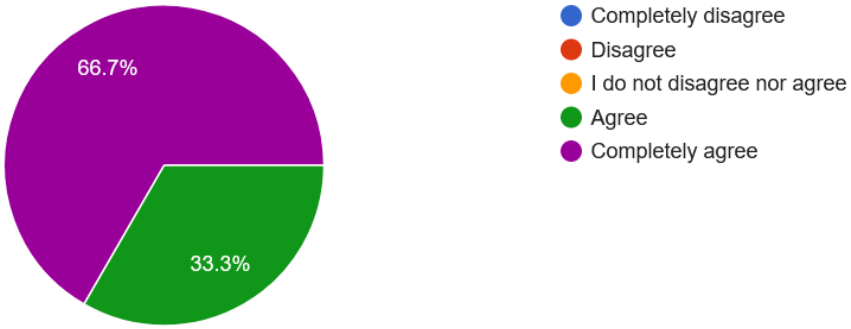

Figure 4.5: Survey respondents' Opinions on the User-Friendliness of the OpEx 4.0 Maturity Assessment Framework.

4.3.1.2 Perceived Value

The value from the framework is perceived as highly valuable. First and foremost, all survey participants stated that they considered the assessment results to be *true* for their organizations, stating that it reflected their current situation well. Five participants either agreed or completely agreed to the following statements:

"The insights provided by the framework are highly valuable, beneficial, helpful, and relevant for our organization."

and

"The insights provided by the framework are highly actionable and I can directly apply these insights to make significant improvements or changes."

See Figure 4.6 for a visualization of the responses.

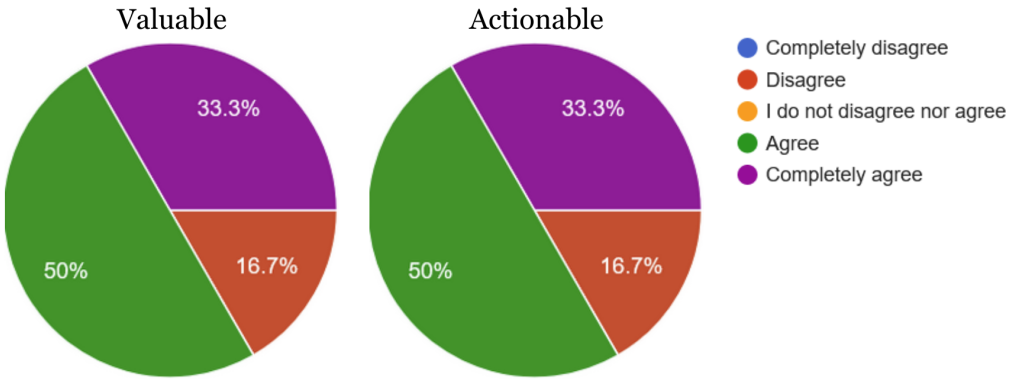

Figure 4.6: Survey respondents' perceived value of the insights provided by the OpEx 4.0 Maturity Assessment Framework.

The survey participant who disagreed that the insights were actionable and beneficial is the representative from Company 6. The representative stated that the reason for disagreeing was that the assessment needed data points and measures on EBIT, Delivery performance, working capital, etc.

To the question:

"Did the assessment highlight any new insights or areas for improvement that were previously overlooked?"

Four out of six respondents answered *No*, and two did not respond. Worth noting is that all other questions were answered by all participants. One of these participants pointed out in his response that this was a really "high" level assessment.

4.3.1.3 Future Application

The majority of participants expressed a favorable view regarding the future application of the framework. All respondents affirmed their organizations should continue pursuing OpEx 4.0, see Figure 4.7. Most of them stated that they need to develop their internal capabilities to succeed and one stated that they have the internal capabilities to do so. No one answered that they believed their organization needed and wanted external help.

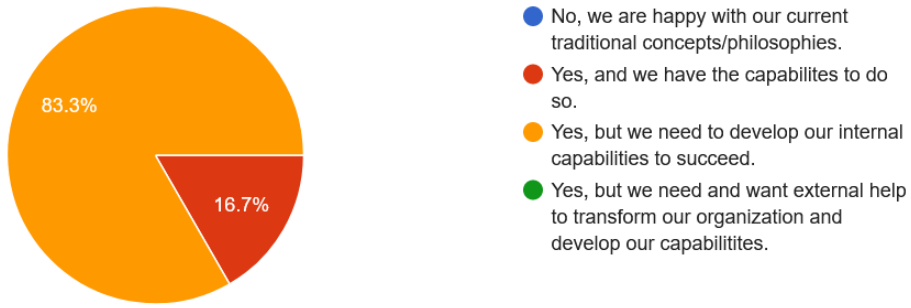

Figure 4.7: Survey respondent's future journey towards OpEx 4.0.

Notably, no one answered that they were happy with their current concept/philosophy for operational improvement. But, there was one contradictory response to the following question:

Would you consider using this framework again in the future?

One respondent indicated a preference for alternative methodologies over OpEx 4.0 to maintain a competitive advantage. Nonetheless, as illustrated in Figure 4.8, the collective outlook on applying the framework remains optimistic. Finally, on a scale from 1 to 5, the average likelihood of participants recommending this framework to colleagues or partner companies stands at 4.2, underscoring its perceived value and applicability.

Figure 4.8: Survey respondent's future applications of the framework.

4.3.2 Case Study Insights

This section aims to find general trends or specific data that can explain how well the framework does in terms of usability and reliability.

4.3.2.1 Framework Usability

Each company visit lasted between 2.5 to 3 hours on average. While some visits featured longer site tours with shorter interview sessions, and vice versa, these variations did not negatively affect the ability to conduct assessments. The framework consistently provided reliable results across all cases, regardless of industry type,

company size, or the complexity of the products being manufactured—characterized by factors such as component integration, technical solutions, multi-step production processes, and functionality.

The entire process of transcribing interviews, analyzing, and compiling the report typically required a full workday for two assessors. Despite this, scoring organizations on their OpEx 4.0 maturity proved straightforward. In most case studies, only zero to two sub-questions were omitted from the final results. It was crucial to consider the entirety of the visit and all responses to accurately determine the score for each theme, as some questions were inadvertently answered under different themes than initially planned.

Identifying strengths and areas for improvement was also straightforward, thanks to clear data points that stood out in terms of maturity and significance. These data points included direct observations, interview quotes, or specific maturity scores on individual themes or sub-questions. Providing recommendations was intuitive for assessors who had developed the framework, allowing them to either draw on their experience or directly suggest advancements to higher maturity levels. Typically, short-term recommendations targeted the most immediate weaknesses to facilitate a quick advancement in maturity levels, while long-term recommendations focused on more resource-intensive and challenging implementations that promised significant value if successful.

4.3.2.2 Reliability of Results

The reliability of the assessment outcomes was carefully validated following each case study. Data was thoroughly analyzed by the assessors, both individually and as a team, to ensure a balanced and objective evaluation. Each organization was described, ranked, and assigned maturity levels according to predefined standards.

There was a high degree of consistency in the maturity rankings assigned by different assessors, highlighting the clarity and effectiveness of the criteria used. The robustness of these results was further confirmed through a follow-up survey, in which all participants acknowledged that the findings were a true reflection of their organizational practices and maturity.

This consistent agreement across different evaluators and feedback from the participants underscores the reliability of the assessment process and the actionable insights it generates.

4.4 OpEx 4.0 in the Nordic Manufacturing Industry

Based on the 6 case studies, some general trends can be found and an initial, but not significant, analysis of the Nordic manufacturing industry can be done.

In Figure 4.9, the total scores for each company are displayed, accompanied by the overall average. Scores range from a low of 2.0 to a high of 3.8, with an average of 2.8. Most scores are close to or just below this mean, set on a 5-point scale. The variance in scores is relatively narrow: one out of the six organizations scores substantially below the average, while another scores significantly above it.

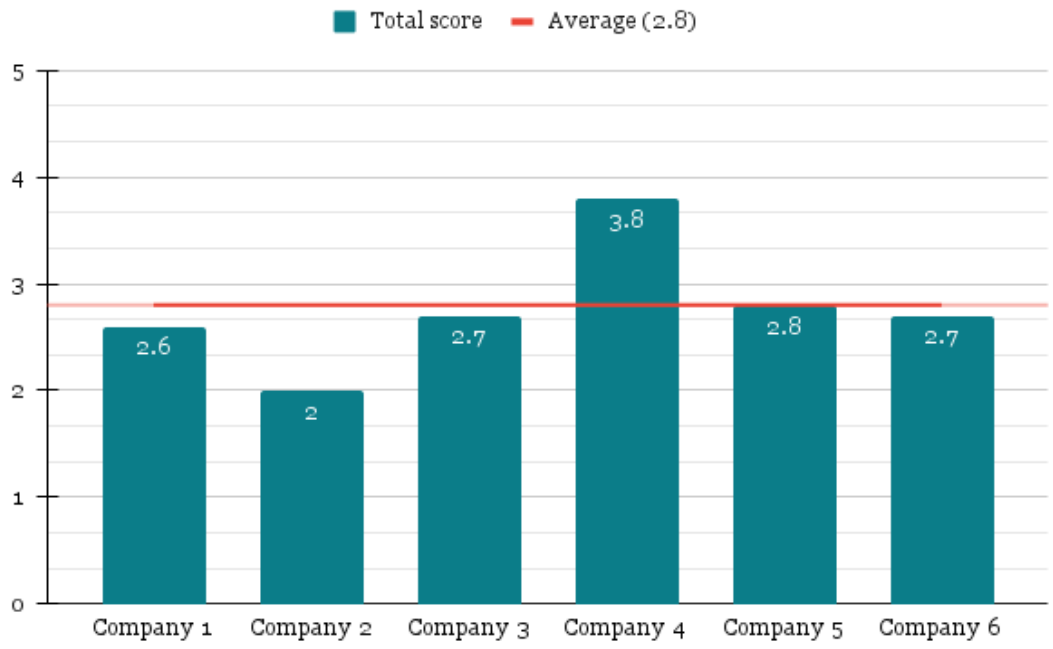

Figure 4.9: The total OpEx 4.0 maturity score for each company.

In Figure 4.10, along with the overall maturity scores, the maturity levels across different dimensions for each company are displayed. This visualization highlights how the aggregate score might obscure specific insights into an organization's performance across various dimensions. For instance, a high overall score could be largely influenced by superior performance in a few areas, which may overshadow weaknesses in others.

This phenomenon underscores the importance of examining individual dimension scores to gain a comprehensive understanding of each company's operational strengths and areas needing improvement. Such disparities suggest that while some companies excel in integrating OpEx principles, others may still be in the early stages of adopting these practices. These detailed dimensional insights are crucial for each

company to identify targeted areas for improvement rather than relying solely on the total maturity score. Tailored strategies can then be developed to enhance underperforming areas, ensuring a more balanced and effective approach to achieving OpEx.

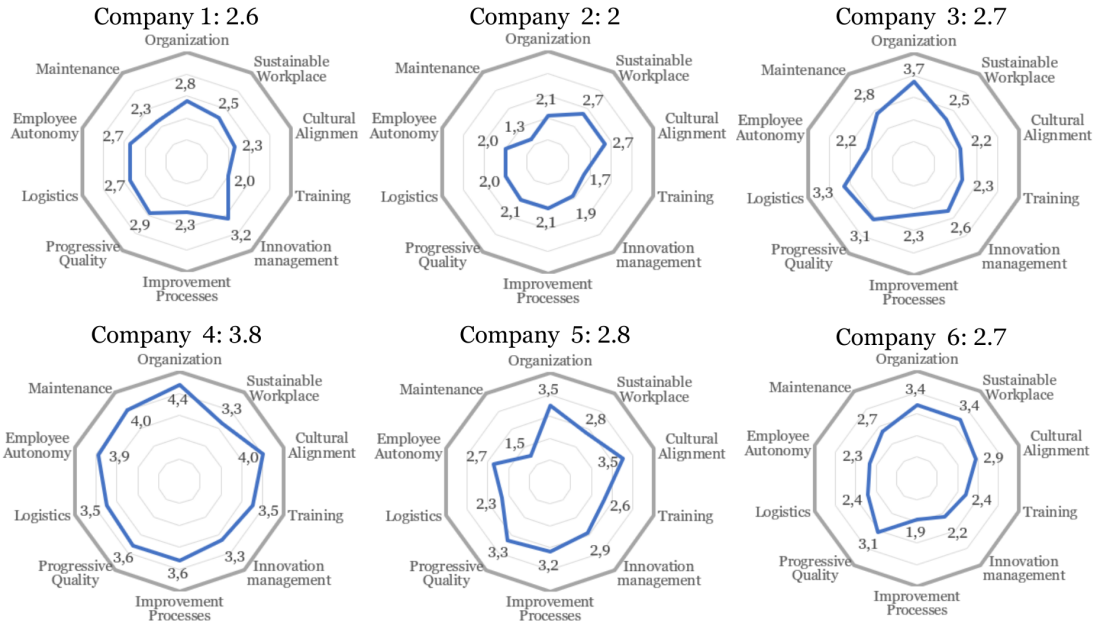

Figure 4.10: The total and each dimensional Maturity Level of OpEx 4.0.

The analysis of the maturity scores across different companies reveals a diverse landscape of OpEx. While conducting the OpEx 4.0 maturity assessment, it became evident that each company exhibited a unique profile in terms of its maturity scores. This distinctiveness is apparent not only in the scale of the scores but also in their geometric representation within the assessment framework.

No two companies showed highly similar maturity profiles, indicating a varied approach and adoption of OpEx 4.0 principles across the sampled organizations. Although some commonalities were observed in specific dimensions where multiple companies showed either strengths or weaknesses, the overall patterns varied significantly. This variability underscores the tailored nature of each organization's journey toward OpEx, influenced by their specific operational contexts, strategic priorities, and resource allocations. The differing geometric representations of these maturity profiles suggest that while companies may pursue similar goals of OpEx, their paths and progressions are uniquely shaped by internal and external factors specific to each entity.

Figure 4.11 displays the minimum, maximum, and average scores for each of the ten dimensions. The dimensions of 'Training' and 'Maintenance' received the lowest scores, both on average and at their minimums. In contrast, 'Organization' achieved the highest total and average scores. 'Sustainable workplace' showed the smallest

range between its minimum and maximum scores, while 'Maintenance' exhibited the largest variance. Furthermore, the scores across different dimensions showed significant variation, with the lowest-ranked area scoring 1.3 and the highest 4.4.

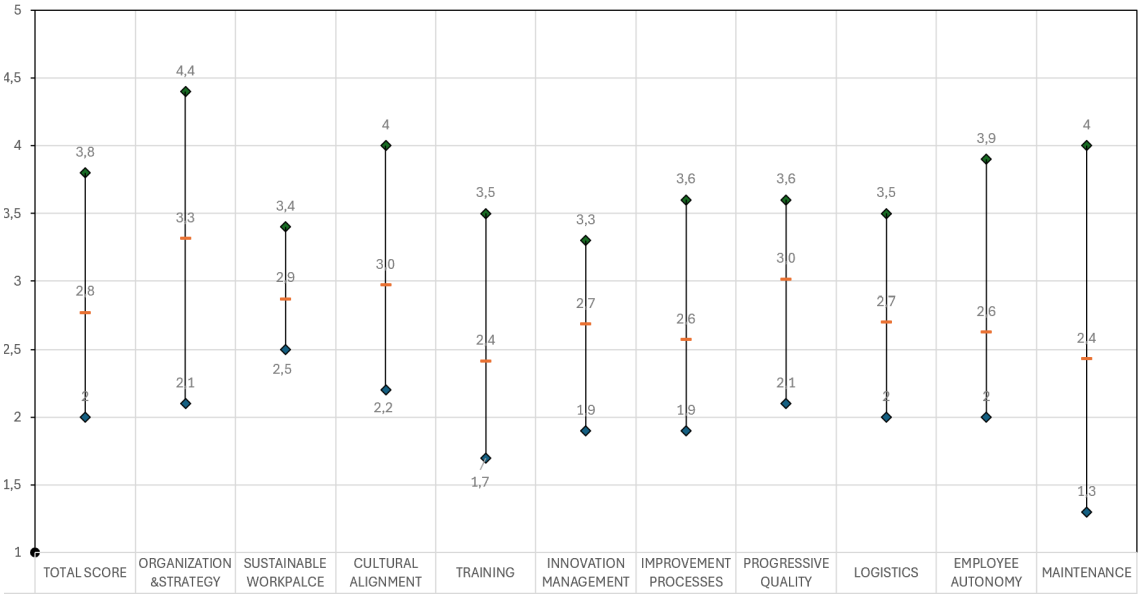

Figure 4.11: Score summary: average, min, and max across ten dimensions and total score.

5
Discussion

This master thesis delves into Operational Excellence 4.0 (OpEx 4.0), focusing on the integration and synergies between Industry 4.0 (I4.0) technologies and Operational Excellence (OpEx) principles. The initial hypothesis questioned whether OpEx 4.0 could truly emerge from merely combining I4.0 technologies with traditional OpEx principles. This discussion explores the distinct roles of these concepts in shaping OpEx 4.0, the critical elements of an OpEx 4.0 maturity assessment framework, and the challenges and opportunities it provides, and covers our methodology. Furthermore, it critically examines whether OpEx 4.0 represents a meaningful evolution in operational strategy or if it is merely another industry buzzword. This chapter aims to unpack these questions and assess the implications of our findings in the field of operational management.

5.1 Results

This section delves into the analysis and implications of the results from our investigation into the topic of OpEx 4.0 and the OpEx 4.0 maturity assessment tool. The structure follows the three research questions.

5.1.1 Operational Excellence in the Fourth Industrial Revolution

From the research on synergies between OpEx methodologies and I4.0 technologies, we can conclude that the concept of OpEx 4.0 extends beyond merely merging OpEx methodologies with I4.0 technologies. It involves strategically integrating these two to foster a symbiotic relationship in which each component enhances the other, leading to a more effective overall system. For example, technologies like data analytics and automation can enhance the efficiency and reliability of OpEx processes. In turn, the principles of OpEx can guide the implementation of I4.0 technologies in a manner that avoids merely automating inefficient processes, thereby preventing the automation of waste, and instead, ensures that technological upgrades result in significant improvements. OpEx 4.0 arguably aligns more closely with Industry 5.0 than with Industry 4.0, as the primary focus of I4.0 is on process automation and reducing human intervention. In contrast, Industry 5.0 emphasizes fostering and engaging human work (Maddikunta et al., 2022), a principle that OpEx 4.0 also supports. Additionally, a clear and comprehensive philosophy that delineates all necessary concepts is crucial to avoid confusion about what organizations should adopt.

For instance, while some advocate for implementing Industry 5.0 to better integrate human elements into technology, others, particularly some industry stakeholders in Germany, argue that I4.0 has not yet been fully realized (Liggesmeyer & Schöning, 2024). Establishing a well-defined concept and definition would eliminate such confusion, and OpEx 4.0 presents a compelling case for this clarity. The future of industrial success depends on the integration of human and machine capabilities. As industries evolve, the collaboration between humans and advanced technologies will become increasingly crucial. This integration leverages the strengths of both parties, such as the precision, efficiency, and consistency of machines, and the creativity, critical thinking, and problem-solving abilities of humans. The authors believe that by using the concept of OpEx 4.0, organizations can ensure they do not lose sight of the human element while pursuing technological advancement. This approach shifts the focus away from debates about whether to call something Industry 4.0 or Industry 5.0 and instead emphasizes the importance of integrating human aspects with technology by pursuing OpEx 4.0.

The fundamental distinction between academic research and industry perspectives on OpEx 4.0 lies in their focal points. Academic research primarily concentrates on the theoretical foundations and strategic frameworks essential for effectively integrating OpEx with I4.0. It examines the challenges, synergies, and critical success factors involved. The research also highlights the challenges and critical success factors of integrating OpEx and I4.0, emphasizing that such integration requires more than just applying new technologies. It involves rethinking processes to leverage these technologies effectively without compounding inefficiencies. On the other hand, industry insights are geared more toward practical implementations and the direct benefits of OpEx 4.0. Industry narratives often showcase successful case studies and emphasize the tangible outcomes of merging advanced technologies with OpEx strategies.

Additionally, although all I4.0 technologies are potentially beneficial, their deployment should be targeted and based on specific use cases. Their successful integration requires a well-thought-out strategic plan. This approach ensures that the technological enhancements align with specific operational needs, maximizing efficiency and effectiveness. The critical success factors indicate that the most important aspects of OpEx 4.0 generally derive from traditional OpEx practices, such as the need for standardization (Joshi et al., 2024), Strategic alignment (Bueno et al., 2023; Ozbiltekin-Pala et al., 2024), strong commitment from top management (A. Kumar et al., 2022; Wankhede et al., 2024), establishing a culture of continuous improvement, particularly in educating and engaging employees (Bueno et al., 2023), and implementation of Lean management before I4.0 adoption (Bueno et al., 2023). This implies that OpEx serves as the essential foundation, leveraging I4.0 technologies to elevate traditional practices into a more sophisticated system known as OpEx 4.0.

In conclusion, OpEx 4.0 effectively encompasses and integrates the practices of OpEx with I4.0 technologies by focusing on technological advancement and ensuring these advancements are strategically applied to enhance operational processes, guided by

the principles of OpEx.

5.1.2 The Critical Elements for a Successful and Viable Assessment

The critical elements identified in this thesis provide valuable insights into assessing OpEx 4.0 maturity. Initially, the focus was on establishing the framework's overall structure and capturing essential non-question aspects. Case 1 primarily addressed structural considerations, while Cases 2 to 4 delved into integrating OpEx and I4.0 effectively and structuring maturity levels. All interviewees brought diverse expertise in I4.0, OpEx, and assessment methodologies. This diversity allowed us to delve deeply into the most critical aspects and gain insights from multiple perspectives. We were able to follow the research cycle and analyze important aspects thoroughly, facilitating deep reflection and analysis. This approach enabled us to explore OpEx 4.0 broadly while honing in on specific areas of expertise, laying a robust foundation for subsequent cases.

A clear understanding of the framework's structure and maturity levels throughout our research process allowed for a systematic approach in subsequent cases. This ensured a thorough examination of each dimension's critical aspects and their relevance to OpEx 4.0. While Cases 5 through 10 theoretically could have led to only one new conceptual framework, in practice, any case had the potential to impact every dimension. Even if a case focused on one specific dimension, insights and suggestions from the interviewee could influence all dimensions. For instance, one interviewee underscored the importance of avoiding overly complex questions. As a result, the whole framework was changed to incorporate that new knowledge. Therefore, the number of conceptual frameworks may appear unconventional initially. However, they reflect the significant changes made based on insights from all cases and the significant amount of work put into the iterative development of the framework.

Although the later cases provided significant information regarding broad topics, they were also often very specific. For instance, during Case 7, concerns about balancing working standards and autonomy among shop-floor employees prompted an expansion of our literature review. This extended examination focused on the trade-offs between autonomy and adherence to working standards, identifying contexts and specific use cases where each is most appropriate. Consequently, the framework is designed to address these concerns by evaluating the balance between autonomy and following standard work protocols. This was a clear example of the conflicting questions brought up in Section 5.3 as a result of the thematic analysis.

However, most of the later cases did not significantly alter the specific dimensions. Generally, 1 or 2 out of 5 themes were completely shifted to another focus area, 3 out of 15 sub-questions were amended, and certain maturity levels were adjusted to ensure all important aspects were incorporated into the framework. This can be regarded as a well-balanced level of change. If more alterations had been made after each case, it might have suggested that insufficient initial knowledge and effort

were invested in the framework beforehand, potentially hindering the creation of a thoroughly crafted dimension from a single case interview. Conversely, if too few changes had been made, it could have indicated inadequacies in the case-study methodology or in how the authors conducted the interviews. However, with the appropriate degree of adjustment after each framework iteration, it can be concluded that the most critical aspects have been effectively captured. This ensures that the framework remains robust and relevant, aligning closely with the latest research findings and knowledge advancements within the diverse dimensions of OpEx 4.0. Although there is a risk of authors' subjective biases influencing results, efforts were made to mitigate this. For example, interviewees might suggest five crucial elements, and while we might have already included most of these, some aspects could be perceived as fully covered when they actually needed improvement. Despite striving for objectivity, confirmation bias can make it easier to affirm existing beliefs than to challenge and revise them. Nonetheless, we aimed to create the most accurate framework possible, and we hope the final result reflects this.

5.1.2.1 Literature-based Scrutiny of Framework

The literature-based scrutiny reveals that the framework largely replicates and extends existing knowledge on OpEx 4.0. Additionally, it incorporates new information to better align with current research. However, some discrepancies between the framework and existing literature have emerged. Below, we provide explanations for the noted disparities, along with an assessment of any crucial theoretical knowledge that may be missing.

Agreements
The framework addresses all of the 10 OpEx principles based on the Shingo model, as they are all covered at least once, either as a base for the question or incorporated into the maturity levels. Furthermore, the framework is mostly based on the most important I4.0 technologies, mentioned by Ibrahim and Kumar (2024) in Section 4.1.3. The framework ensures that the most relevant technologies are utilized for specific applications to enhance maturity levels. It aligns OpEx Methodologies with I4.0 technologies, advocating for their use only in appropriate contexts. Initially, the framework mandated specific technologies for reaching certain maturity levels. This approach was later modified to allow for reaching maturity through alternative means if the same outcomes could be achieved, either by specifying "...or similar technologies" or by clearly describing the requirements needed to attain higher maturity levels. Moreover, several traditional OpEx elements were either entirely removed or significantly expanded, resulting in a scenario where what was previously considered a level 5 maturity now corresponds more closely to a level 3 in our revised framework. This adaptation is supported by Li et al. (2017), as discussed in Section 2.3.2.

Conflicts
The framework does not incorporate all I4.0 technologies; of the 9 main concepts identified in 2.2.1, 8 are utilized at least once, but Cybersecurity is notably absent. The omission of cybersecurity might stem from its highly specialized and rapidly evolving nature, which requires specific technical expertise and continuous updates

that go beyond the scope of the general OpEx 4.0 maturity assessment. Incorporating cybersecurity could necessitate a more detailed and focused approach, potentially complicating the broader applicability of the framework in diverse organizational contexts. For example, within the 'Organization' area, one question addresses the company's progression strategy by requiring 'A clear road-map to integrate I4.0 technologies' for achieving higher maturity levels. While this implicitly suggests the inclusion of cybersecurity, it is not explicitly mentioned. Moreover, there appears to be an imbalance in how various I4.0 concepts are integrated. Notably, 5G technology, recognized as a critical enabler of I4.0 and Smart Manufacturing, is not mentioned at all. This oversight is similar to the limited attention given to cybersecurity. In contrast, digital twins are frequently referenced within the framework. Despite being deemed one of the less mature technologies in one of our case studies, the ease of visualizing and conceptualizing the theoretical benefits of digital twins may have led to them receiving disproportionate attention. Even though we used the WCM-I4.0 (D Orazio et al., 2020) and Lean-I4.0 (Pereira et al., 2019) matrices initially in the first conceptual framework, we cannot promise that these are fully incorporated through the whole framework at every possible and suitable maturity level after have gone through seven major iterations.

The Framework also fails to address the order of critical success factors and their importance for a successful integration. The reason for this is that the framework was initially developed as a tool to assess the maturity level of OpEx for organizations. While it is possible to create specific road-maps for organizations using the framework, that was not its primary purpose. It was later determined that road-maps for achieving higher maturity levels in OpEx 4.0 could be developed by initially assessing a company's current state. This process identifies the gaps where the company falls short of higher maturity levels, pinpointing areas of improvement. Based on these gaps, both short-term and long-term recommendations are formulated. Short-term efforts focus on enhancing lower maturity levels, while long-term strategies aim to reach the highest maturity levels.

5.1.3 Framework evaluation

This section discusses the application of the framework, with a focus on challenges, opportunities, and limitations.

5.1.3.1 Challenges

Continuous improvement is a core tenet of OpEx 4.0, and organizations should endeavor to enhance all aspects of their operations consistently and comprehensively and aspire to the highest possible standards across all operational areas. However, it may not always be feasible for every organization to achieve the highest maturity levels in every dimension simultaneously, particularly if resources are limited. For instance, Company 4 in the packaging industry, scored 0.5 points lower in innovation management compared to their overall performance. They might find that achieving the highest levels in innovation management is less critical to their im-

mediate operational success. This could be because their products, developed in close collaboration with specific customers, already meet customer needs effectively without advanced innovations such as AI and ML integration. In such cases, it might be more practical for these organizations to initially focus on other critical aspects of OpEx, as prioritizing areas to provide the most significant immediate benefits to allow for better resource allocation. Once these areas reach higher maturity levels, resources can then be redirected to enhance other aspects like innovation management. Despite the pragmatic need to prioritize due to resource constraints, organizations should ideally look to increase their investment in continuous improvement activities across the board. This would ensure that improvements are not just localized but are comprehensive, aligning with the OpEx goal of universal excellence.

The framework currently lacks specific guidelines on the weighted importance of different maturity areas, which could otherwise direct organizations more effectively toward crucial improvement areas. While many organizations might have an understanding of their potential improvement areas, an optimal framework would also guide the prioritization of these areas. Presently, it seems rational to focus first on areas scoring the lowest; however, this should be adapted based on each organization's unique context and industry needs. A more structured approach might involve weighting scores to reflect the relative importance tailored to each organization's specific circumstances, as suggested by academic insights such as those proposed by (Pansare et al., 2024). Such a strategy would refine the process of choosing focus areas, enabling organizations to allocate their resources more effectively and strategically.

5.1.3.2 Opportunities

Section 4.3 reveals that the developed framework offers numerous opportunities. It is recognized as user-friendly and provides actionable, beneficial insights. The results are reliable and replicable across various types of organizations, differing in size, industry, product complexity, and maturity levels, indicating that the framework can offer substantial opportunities and some challenges for diverse organizational contexts.

The survey responses indicated that while some participants encountered difficulties responding to certain dimensions, each challenging dimension was only mentioned once. This suggests that these issues might be more closely related to the participants' familiarity with their respective organizations than to the framework itself. It is also reasonable to assume that an individual working in a specific department might not possess complete knowledge about all aspects of their organization. Before conducting the interviews, the author hypothesized that the participants would struggle to answer all the questions. For instance, the authors anticipated that approximately three dimensions would remain unanswered or be deferred to another member of the organization. However, nearly all participants were able to respond to most of the questions. Nonetheless, it is possible that participants provided only a limited perspective on the questions asked and may have presented themselves as more knowledgeable than they actually were, potentially omitting significant infor-

mation. Despite this, the authors felt that the participants generally knew what they were talking about, even if their knowledge was broad rather than detailed. This confidence was partly because the questions asked were theme-specific, general questions, rather than detailed sub-questions, which might have been more challenging for the participants to answer. Furthermore, the interviewees held various job titles, such as quality/lean manager, supply chain manager, and Production manager. This diversity in roles could be seen as a strength, highlighting the framework's versatility and adaptability.

The overall score ranged from a low of 2.0 to a high of 3.8, with an average of 2.8. The lowest-ranked dimension scored 1.3, while the highest scored 4.4. This suggests that the framework is capable of providing results across organizations of varying maturity levels, demonstrating that all maturity levels have distinct use cases that can be applied in real-world scenarios. Many organizations assessed using the framework received closely clustered scores; Four out of six companies scored between 2.6 and 2.8. This clustering suggests that developing a framework with a greater number of maturity levels, such as seven, might enhance the ability to differentiate between companies more effectively. However, when analyzing the specific recommendations provided to each organization within this score range, significant variations are evident. This highlights that the total score alone may not provide a comprehensive indication of an organization's performance and it is crucial to delve into and analyze specific areas to pinpoint where improvements are necessary. The current maturity scale is well-balanced and built upon established theories that incorporate both OpEx and I4.0 as referenced in Section 3.2. Although restructuring the maturity scale could potentially increase the variance in total measurement numbers, it might not necessarily enhance the framework's ability to measure an organization's maturity level in OpEx 4.0, identify areas of weakness, or provide tailored recommendations for improvement. The identified weaknesses and the nature of the improvements suggested would likely remain consistent even if a broader maturity scale were implemented.

After each case study, the authors analyzed and ranked organizations' maturity levels by comparing organizational descriptions to predefined criteria, finding high consistency and agreement in their evaluations. This uniformity suggests that the results are reliable. The survey responses also suggest that the results are reliable. This consistent reproducibility of the analysis highlights the robustness and reliability of the framework. It suggests that different evaluators can apply it at various times and in diverse organizational contexts with little variation in outcomes. Such reliability is crucial for building trust in the framework's applicability and for fostering its adoption on a broader scale. Moreover, the ability to replicate results across different scenarios confirms the framework's utility as a diagnostic tool, capable of providing stable and dependable insights regardless of the evaluator's subjective perspective or the specific characteristics of the organization being assessed.

Almost all participants valued the framework for its practical and relevant insights, with all respondents affirming the usefulness and applicability of the provided infor-

mation for significant organizational enhancements, except for one. However, when questioned about previously overlooked areas for improvement, no one reported any new insights. This could indicate that the primary strength of the framework may not be to point out problem areas, but rather provide insights, action plans, and recommendations for improvements. It should be noted that this result is not entirely unexpected, as organizations typically possess a more comprehensive understanding of their operations than can be comprehended from a visit lasting 2.5 to 3 hours.

One participant did not agree with the results provided. In the survey, this participant mentioned that the framework could be improved by incorporating specific data points, such as EBIT (Earnings Before Interest and Taxes), delivery performance, and working capital. This suggests that the participant wanted an approach and results that were more focused on definitive numbers. The call for specific data points indicates a preference for measures that are easily quantifiable and objective. The participant likely felt that such metrics would reduce ambiguity and increase the reliability of the framework's insights. While this feedback highlights potential improvements for the framework, it could also be seen as a suggestion to shift the assessment focus away from the core principles and critical aspects of OpEx 4.0, as described in RQ2. Additionally, there could be other reasons for the participant's disagreement beyond the results themselves. The participant may have had preconceived notions or biases that influenced their perception of the framework's findings. They might also be part of a culture resistant to change and find the suggestions too radical and critical of existing practices or power structures, or they may have misinterpreted the results. As stated in Section 4.3, the negative participant expressed skepticism and disbelief that the insights would be valuable or novel before even starting the assessment. Conversely, the other 5 companies expressed neutrality or outright optimism before the assessment, which might also influence their positive outlook on the insights provided.

Regarding the question, 'Can the results be used to create road-maps for specific companies?', it appears highly likely that the framework can be utilized to develop both short-term and long-term action plans. While organizations may require additional support to implement these changes, the framework not only identifies improvement opportunities and actionable recommendations but also positions the organizations relative to industry benchmarks.

An in-depth analysis could most likely also be conducted using the framework, as it is designed to evaluate the most critical aspects of OpEx 4.0. The questions within the framework are strategically phrased to gather a broad spectrum of information from a single inquiry. This allows responses to range from concise to detailed, depending on how respondents choose to discuss the extent or management of specific issues. The conductor(s) of the assessment, who desirably are experts within OpEx 4.0 and adjacent topics, could thereafter delve deeper into important aspects that need to be more detailed and analyzed. Additionally, the framework's structure, which organizes each section into one general question followed by three more specific questions related to the main topic, further facilitates comprehensive analysis.

This flexible approach enables the framework to adapt to both quick-scan and in-depth evaluation needs effectively.

5.1.3.3 Limitations

The authors sometimes had to rely on the trustworthiness of the interviewees' responses. For instance, when interviewees claimed to have a proficient process in place, the authors had to accept these assertions at face value, even though the actual quality of the process might differ from the interviewees' perceptions. This acceptance might explain why participants agreed with the study's findings while also reporting no new areas for improvement. The inability to verify these claims or investigate deeper into the root causes presented significant limitations in assessing the true efficacy of the stated processes.

Requiring the conductor to be on-site for the site tour occasionally posed constraints, prompting the exploration of off-site assessments. The assessments depended largely on interviewees' descriptions, which were assumed to be accurate, making off-site assessments possible. However, the significance of the site tour in the maturity assessment cannot be overstated. The framework equips the conductor with precise and detailed insights into workflow inefficiencies and potential enhancements. Observing issues within their real-world context allows the conductor to fully understand their complexity and effectively evaluate the effectiveness of technologies, visual communication, cognitive support, physical ergonomics, and more. This comprehensive understanding aids the conductor in more accurately reassessing interviewees' responses and aligning them with the correct maturity levels. Consequently, while off-site assessments are possible, they are estimated to be less precise and risk missing critical areas that require attention.

5.2 The Nordic Manufacturing industry

The average OpEx 4.0 maturity result is 2.8 out of 5, with minimal deviation. One of the organizations scored notably below the average and one above it. This trend suggests that many organizations encounter similar hurdles in attaining OpEx within the context of I4.0.

In the OpEx domain, organizations must prioritize cultivating a comprehensive understanding of all organizational dimensions. This entails implementing more structured procedures for identifying, analyzing, and mitigating inefficiencies. Additionally, there is a need to actively involve and engage all employees, as their potential contribution is often underappreciated. The application of OpEx principles tends to be sporadic or semi-structured, manifesting only in specific areas and absent in others, whereas organizations should aspire to achieve complete, widespread, and seamless integration of OpEx principles across all domains. I4.0 technologies remain significantly underutilized, evident only in a few isolated instances within the evaluated organizations. Potential improvements include the adoption of basic technologies that could significantly enhance operations. For example, transitioning from manual entry or scanning of production processes by operators to automated systems could facilitate the seamless acquisition and dissemination of crucial production flow data. Moreover, while information may be automatically captured in data systems, its use for analysis or improvement through advanced analytics or AI is exceedingly rare. Additionally, it is uncommon for a clear road-map to integrate I4.0 technologies to be implemented.

Dimensions such as 'Innovation Management', 'Improvement Processes', 'Employee Autonomy', and 'Logistics' all scored below average, indicating room for improvement. For example, Innovation management scores suggest that organizations commonly fall short in optimizing the introduction of new products and equipment. Research and development often operate in isolation rather than collaborating across teams, hindering the incorporation of valuable insights from daily operators. This lack of cross-functional collaboration impacts design for manufacturing principles and sustainability considerations during equipment procurement. The lowest total scores, as well as the lowest score for any maturity level, were the dimensions of Training and Maintenance. This indicates that these areas have the greatest potential for improvement.

While many organizations recognize the benefits of planned maintenance over reactive maintenance, there is still a prevalent reliance on traditional approaches. Maintenance strategies often revolve around strictly adhering to manufacturers' recommendations on schedule and have not opted for a shift towards a Smart Maintenance (SM) strategy. SM emphasizes collective knowledge, and data-driven decision-making, with internal and external integration leveraging advanced technologies such as smart/IoT sensors to enable predictive maintenance algorithms and AI-driven analytics. By adopting an SM strategy, organizations can optimize maintenance schedules and predict machine failures more accurately. Activities can be dynami-

cally adjusted based on machine conditions, production demand, and other relevant factors, resulting in improved up-time and reduced maintenance costs. Many of the organizations assessed organizations have not heard about the latest advances in maintenance, do not deem them valuable, or have not yet implemented them into their operations. This is also connected to the fact that most organizations still have much room for improvement regarding implementing I4.0 technologies.

Organizations typically provide onboarding training for new employees, but subsequent training often receives less attention. Additionally, case studies indicate a significant lack of diverse problem-solving methods, such as PDCA or DMAIC, being taught to operators. The training tends to be generic and does not adequately cover company-specific losses or skills relevant to future needs (such as analytical thinking and complex problem-solving methods). In contrast, the highest observed maturity level was in the 'Organization' dimension, which deals with the organization's structure and strategic procedures. This stark contrast between poor training outcomes and high scores in organizational strategy underscores the risks of a strict top-down approach. Such an approach often leads to strategies developed by top management that are not effectively communicated or implemented across the organization. This disconnect between the strategies of management and the understanding of non-management white-collar and shop-floor employees can result in lower engagement and impede efforts to improve the business, as discussed in Section 4.1. Additionally, with the increasing demands required for I4.0 technologies and skilled employees with advanced problem-solving capabilities, there's a risk of falling behind competitors if training and skill development aren't prioritized for organizations within the Nordic manufacturing industry.

Another notable trend is the widespread lack of automation and communication capabilities in newly acquired equipment and machines, essential for I4.0 and OpEx 4.0 readiness. Many organizations appear to underestimate the significance of this aspect. Additionally, organizations often fail to effectively capture and leverage lessons learned from past product launches to improve future projects. This deficiency is closely linked to inadequate data capture, data storage, and data utilization practices, which remain underutilized both with and without I4.0 technologies.

Some organizations had data storage and knowledge-sharing platforms. However, these platforms were frequently underdeveloped and inadequate achieving higher maturity levels of OpEx 4.0. This inadequacy relates to the system's capabilities and the extent to which they were effectively utilized and understood by employees. Often, these platforms lacked cross-collaboration features, failing to deliver relevant information to the appropriate employees while filtering out irrelevant data. The organizations lacked smart data utilization, structured processes, automated data entry, visualization capabilities, and more. These deficiencies hindered the organization's ability to leverage data effectively and optimize processes on a global scale.

Despite Logistics scoring low on average, there was generally a high level of ambition. Many organizations expressed a desire to implement a more automated logis-

tics system, preferably utilizing AGVs. However, this ambition seemed premature, lacking fulfillment of basic prerequisites and clear implementation road-maps. For example, organizations face challenges such as incomplete value stream mapping, discrepancies in material balance, and insufficient 5S implementation, all hindering the readiness for AGV integration. However, the same desire to use other I4.0 technologies was not expressed, such as a fully automated inventory management system powered by AI and IoT, dynamically adjusting inventory levels in real-time based on predictive analytics. Such technologies could optimize inventory levels to meet customer demand while minimizing costs and avoiding stock-outs. Both AGVs and an AI-powered automatic inventory system could potentially enhance organizational efficiency. However, the preference for AGVs might stem from their tangible and straightforward nature, whereas AI-powered systems may appear more complex and abstract. Applying and translating this to all areas of OpEx 4.0 suggests that many organizations encounter challenges because they do not fully comprehend all the potential benefits that OpEx 4.0 could offer, thereby impeding progress toward OpEx 4.0.

The dimension 'Sustainable Workplace' showed the smallest difference between its highest and lowest scores, ranging from 2.5 to 3.4. Notably, sustainability had the second-lowest maximum score but the highest minimum score of all assessed dimensions, indicating a uniform approach to sustainability initiatives across organizations. This uniformity might be influenced by strict laws and regulations governing sustainability in the Nordic manufacturing industry, which set a baseline for all organizations and contribute to consistently higher minimum scores. Organizations likely focus on improving sustainability to comply with these regulations. This focus on compliance may extend to other organizational processes, with companies typically only modifying their procedures when they see a clear necessity, whether for legal compliance or other benefits. Despite maintaining a higher baseline for sustainability, many companies overlook deeper sustainability efforts like life-cycle analysis, circularity, and the integration of I4.0 technologies such as AI to optimize resource consumption. This lack of deeper engagement may stem from organizations not recognizing the additional benefits these advancements could offer, or that sustainability is arguably something new in a traditional rigid industry.

The authors were surprised by the limited interest from organizations wanting to participate in the study. Initially, we believed that most organizations would be eager to participate and allow us to interview them, given the potential benefits of having two Chalmers students provide valuable information and suggestions for improvement across several dimensions of the organization in a very short time. However, it appeared that most organizations did not perceive it as beneficial to them but rather saw it only as an act of helping two students in need. Many organizations did not have two or three spare hours for an activity they deemed non-essential and unhelpful. This was surprising to the authors, considering the earlier chapters' description of OpEx 4.0, its drivers, and the benefits it can provide. However, it is also important to note that the authors have a background in production engineering and have extensively discussed topics related to I4.0 and continuous improvements.

This background likely influenced our perception of these topics as more interesting and valuable compared to individuals with different backgrounds and knowledge.

5.3 Methodology

The research strategy employed in this master's thesis proved effective, successfully addressing all three of the original research questions. While the literature review could have been more rigorous and systematic, it is uncertain how much this would have enhanced the actual framework. As discussed in the theory chapter and in Section 4.1, the concepts of I4.0, OpEx, and OpEx 4.0 are subject to a wide range of definitions. Further exploration into these areas might have only introduced more individual interpretations and opinions, which could complicate rather than clarify the study's objectives.

Utilizing an adapted and customized structured-case methodology proved effective for developing an OpEx 4.0 maturity assessment framework. Initially, the use of multiple 'scans' from EFESO combined with the thematic analysis set us up to attempt measuring various aspects simultaneously. However, this approach occasionally hindered rather than helped progress. Many dimensions and themes, although correlated or adjacent, were not identical. This led us to group questions that addressed multiple or contradictory aspects, to cover all possible angles. Although thematic analysis was a time-consuming part of the thesis, the framework has ultimately been reworked. In hindsight, focusing on refining a single, well-structured scan might have been more efficient.

This study employed convenience sampling, rather than purposeful sampling, to select case companies and interviewees, focusing on organizations and individuals that were easily accessible (Etikan et al., 2016). Despite the lack of a strict sampling strategy, the participating organizations represented distinct characteristics, primarily at a similar maturity level in OpEx 4.0. During the framework development using the structured case-study methodology, convenience sampling was employed to find suitable interviewees. Most interviewees were known to the authors, such as researchers at Chalmers, or were industry experts recommended for participation through EFESO, which facilitated their involvement. This familiarity likely eased the process of securing their time and input. If another researcher were to replicate this study, they might face challenges in accessing the same network of significant participants, potentially impacting their results. Despite using convenience sampling, the demands for interviewing the most relevant and significant people were met. Nonetheless, a study employing purposeful sampling might yield different results, as it could involve contacting other experts with potentially varying opinions, thereby influencing the outcomes differently. Similarly, the selection of case companies was based on convenience sampling rather than strict purposeful sampling. This approach involved contacting organizations that were easily accessible, without adhering to a specific sampling strategy to ensure all sample members had distinct characteristics or features. However, by chance, the participating organizations represented entities with distinct characteristics. However, the majority of the organizations approached were not interested in participating, which meant there was limited opportunity to exclude organizations from the study as long as they met the basic criteria. Although most of them had a similar maturity level in

OpEx 4.0, it is possible that only organizations with a certain maturity level were willing to participate, which might have influenced the analysis of the Nordic manufacturing industry.

The authors' backgrounds as Chalmers students significantly shaped the study's perspective on OpEx 4.0 in the Nordic manufacturing industry. In conducting this study, the authors' values, experiences, and perspectives as researchers significantly influenced the methodology and overall approach. As students at the Chalmers University of Technology, the author's academic and professional backgrounds provided a unique lens through which they explored OpEx 4.0 within the Nordic manufacturing industry. Their commitment to advancing knowledge in the field of OpEx and belief in the transformative potential of I4.0 technologies guided the research focus. This perspective was rooted in their education and prior experiences, which emphasize systematic approaches to improving manufacturing processes. Furthermore, Their main aim has always been to create and develop the best possible framework and write a robust master's thesis, contributing valuable insights to both research and practical applications of OpEx 4.0. However, the authors were also mindful of the pillars of qualitative research, ensuring trustworthiness in establishing the credibility and reliability of qualitative findings (Ahmed, 2024). This includes elements such as credibility, transferability, dependability, and confirmability. This was done to ensure that the authors could declare that they have no conflicts of interest.

5.4 Theoretical and Practical Implications

This thesis contributes theoretically and practically to the field of OpEx 4.0, enhancing our understanding of how I4.0 technologies can integrate with and enhance OpEx strategies within the manufacturing sector. Here, we outline the contributions of this work to academic research and industrial practices.

The theoretical contributions include:

1. **Clarification of OpEx 4.0**: By providing a detailed examination of the intersection between OpEx principles and I4.0 technologies, this research clarifies the conceptual framework of OpEx 4.0. It delineates the critical roles that strategic alignment and technological implementation play in this emerging field, contributing to a clearer academic definition of OpEx 4.0.
2. **Integration of OpEx and Industry 4.0 Frameworks**: This thesis offers a novel perspective on integrating traditional OpEx methodologies with advanced I4.0 technologies. The study highlights the synergy between these elements, suggesting a model where technology and operational strategies complement each other to drive more effective organizational improvements.
3. **Identification of Critical Success Factors**: This work identifies and elaborates on the critical success factors necessary for the successful integration of OpEx 4.0. This includes top management commitment, the need for standardization, strategic alignment, and a strong cultural foundation for continuous improvement.
4. **Extended Framework for OpEx 4.0 Maturity Levels**: The development of a comprehensive maturity assessment framework provides a structured way to evaluate organizational readiness and implementation success of OpEx 4.0, which can serve as a foundation for further academic research.

The practical and industrial contributions include:

1. **Maturity Assessment Tool**: The OpEx 4.0 maturity assessment framework developed in this thesis serves as a practical tool for organizations to assess their current state of integration between OpEx strategies and I4.0 technologies. This tool can guide organizations in identifying strengths and areas for improvement.
2. **Road-map for Implementation**: The findings from this thesis and the insights the framework yield provide a clear road-map for organizations looking to integrate OpEx 4.0. It highlights the importance of aligning technological upgrades with strategic operational improvements to avoid the pitfalls of automating inefficient processes.
3. **Guidance on Technology Utilization**: This thesis offers practical insights into the selective application of I4.0 technologies based on specific operational needs and strategic goals, helping companies to make more informed decisions about technology investments.

5.5 Further research

We have identified three primary areas for further research to build upon this master's thesis. First, there is a need for additional research to refine and develop the maturity levels. The combined maturity levels proposed in this thesis are the first of their kind and have not been extensively tested. Consequently, all 750 individual data points associated with these maturity levels are unique to this thesis. Future research should aim to standardize and refine these maturity levels, ensuring they are updated to reflect the latest research and real-world industry examples.

Secondly, conducting a comprehensive market-wide analysis of the Nordic manufacturing industry would be valuable. This thesis was limited to just six companies that agreed to participate. Expanding the scope to include a broader range of companies would address many of the uncertainties observed in our results and analysis. If pursued as the primary focus of a future thesis, this approach would allow for a more detailed consideration of various aspects, enable a deeper investigation into the industry, and critically examine OpEx 4.0 as a new emerging operational improvement concept.

Thirdly, it would be practical to collaborate with an organization to apply and refine the OpEx 4.0 framework. This partnership could involve working alongside industry consultants and experts to test and improve the framework. Such an approach would not only help validate the OpEx 4.0 concepts but also offer insights into the practical challenges and obstacles of digital transformation. This collaborative effort would bridge the gap between academic research and real-world application, enhancing our understanding of how OpEx 4.0 operates in actual industrial environments and identifying effective strategies for navigating digital transformation.

6
Conclusion

Operational Excellence 4.0 (OpEx 4.0) is an emerging concept that combines traditional operational excellence with Industry 4.0 (I4.0). Clear road-maps are crucial to guide the implementation of OpEx 4.0 effectively, translating theoretical concepts into practical strategies. As OpEx 4.0 evolves into something more tangible and understandable in the coming years, this thesis aims to serve as a foundational step in that direction.

In OpEx 4.0, I4.0 accelerates traditional OpEx and sets up organizations for sustainable growth and competitiveness. OpEx 4.0 frames technology to accelerate operational excellence in the future factory, without forgetting about individuals, personal development, fulfillment, and satisfied workers. The synergies between OpEx and I4.0 consist of continuous improvement, process optimization, customer focus, adaptation to change, and many traditional OpEx practices that I4.0 supports and accelerates. The implementation challenges include overemphasis on technical use cases, internal capability deficits, lack of standardization and vision, leadership engagement and training, high integration costs, resistance, knowledge and resource limitations, lack of road-maps and support, and finally absence of clear business cases. The CSFs to overcome these implementation challenges include top management commitment, lean management implementation, aligned business strategies, well-defined processes, balanced technology adoption, appropriate IT infrastructure, culture of continuous improvement, personnel training, smart manufacturing strategies, deep process understanding, strategic investment planning, horizontal/vertical integration, and change management theories and/or practices can support OpEx 4.0 implementation.

Our maturity assessment framework encapsulates the critical elements of OpEx 4.0 and filters outdated and irrelevant aspects, positioning them as foundational prerequisites rather than maturity indicators. This nuanced approach ensures that the framework remains relevant and adaptable to the evolving landscape of operational excellence in the context of I4.0. The ten dimensions of OpEx 4.0 are *Organization*, *Sustainable workplace*, *Cultural alignment*, *Training*, *Innovation management*, *Improvement processes*, *Progressive quality*, *Logistics*, *Employee autonomy*, and *Maintenance*. We also conclude that OpEx 4.0 maturity levels combine and measure the development path an organization has gotten in its OpEx journey and which capabilities they have through emerging I4.0 technology.

The case studies and subsequent survey responses clarify the challenges and opportu-

nities associated with the framework, its potential applications, and its limitations. It confirms the framework's user-friendliness and efficiency in delivering actionable, beneficial insights. It consistently produces reliable and replicable results across various organizations, varying in size, product complexity, and maturity levels. The framework facilitates the creation of tailored road-maps, enabling strategic positioning relative to industry benchmarks, and making tailored improvements based on the frameworks.

The main challenges and opportunities within the Nordic manufacturing industry are found to be: Enhancing employee engagement and empowerment to foster a more motivated and productive workforce, improving communication strategies to facilitate cross-collaboration among different departments and teams, implementing simpler, less complex technologies that are easier to adopt and have fewer barriers to implementation, increasing the utilization of data to drive decision-making and improve operational efficiencies, leveraging artificial intelligence and machine learning to enhance data analysis capabilities across various functions, cultivating a culture of continuous improvement to consistently refine processes and practices, expanding sustainability initiatives to meet environmental goals and improve social responsibility. Many organizations are found to be slightly below the average maturity level on the framework's scale, indicating common obstacles in striving for OpEx 4.0. The highest scores are typically observed in the dimension *Organization* indicating minimal room for improvement. Conversely, the lowest scores in *Training* and *Maintenance* suggest significant potential for enhancement, pointing to a prevalent top-down strategy with limited employee involvement and under-utilization of digital technologies.

Our research confirms that OpEx 4.0 significantly evolves from traditional operational excellence, offering a practical framework that aligns with the complexities of the modern industrial landscape. This framework effectively integrates I4.0 technologies, providing Nordic manufacturing companies with the tools to thrive in a competitive global market fraught with technological and geopolitical challenges. Change management practices within this framework are crucial, as many transformations under I4.0 falter without them. These practices, aligned with the principles of OpEx 4.0, emphasize continuous, incremental improvements, ensuring that transformations are sustainable and progressively enhanced over time. Thus, this thesis plays a critical role in guiding companies through the complexities of merging technology with traditional processes and workforce dynamics, ensuring their success in the new industrial era.

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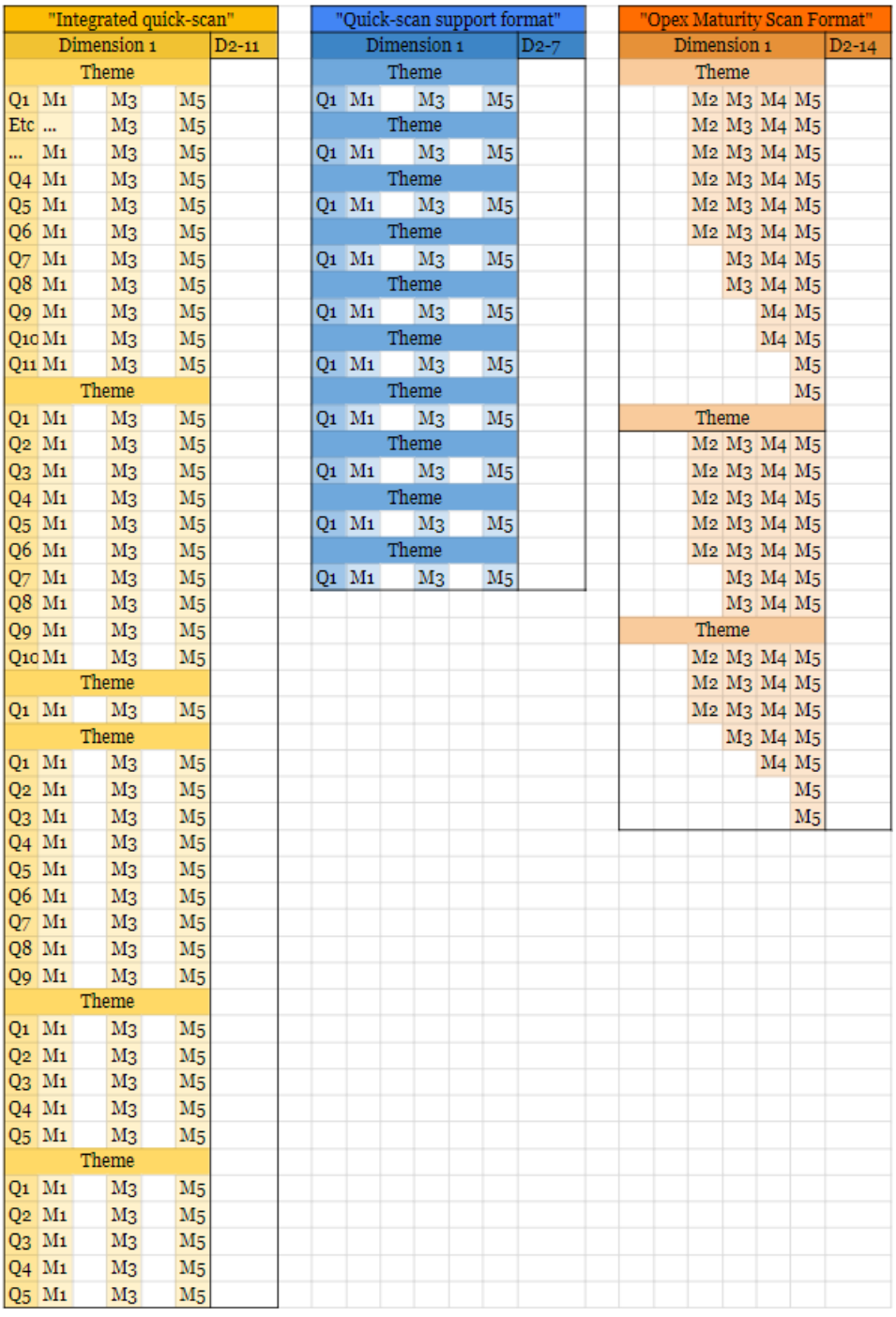
A

Appendix

A.1 Three different OpEx maturity assessment frameworks provided by EFESO



"Integrated quick-scan"											
Dimension 1						D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Theme															
Q1	M1		M3		M5										
Q2	M1		M3		M5										
Q3	M1		M3		M5										
Q4	M1		M3		M5										
Q5	M1		M3		M5										
Q6	M1		M3		M5										
Q7	M1		M3		M5										
Q8	M1		M3		M5										
Q9	M1		M3		M5										
Q10	M1		M3		M5										
Q11	M1		M3		M5										
Theme															
Q1	M1		M3		M5										
Q2	M1		M3		M5										
Q3	M1		M3		M5										
Q4	M1		M3		M5										
Q5	M1		M3		M5										
Q6	M1		M3		M5										
Q7	M1		M3		M5										
Q8	M1		M3		M5										
Q9	M1		M3		M5										
Q10	M1		M3		M5										
Theme															
Q1	M1		M3		M5										
Theme															
Q1	M1		M3		M5										
Q2	M1		M3		M5										
Q3	M1		M3		M5										
Q4	M1		M3		M5										
Q5	M1		M3		M5										
Q6	M1		M3		M5										
Q7	M1		M3		M5										
Q8	M1		M3		M5										
Q9	M1		M3		M5										
Theme															
Q1	M1		M3		M5										
Q2	M1		M3		M5										

11 dimensions
6 to 18 themes per dimension
1 - 12 questions per theme
1, 3 and 5 exclusively for maturity levels

<table>
<tr><th colspan="12">"Quick-scan support format"</th></tr>
<tr><th colspan="6">Dimension 1</th><th>D2</th><th>D3</th><th>D4</th><th>D5</th><th>D6</th><th>D7</th></tr>
<tr><td colspan="6">Theme</td><td colspan="6" rowspan="20">7 dimensions
10 themes per dimension
1 question per theme
1, 3 and 5 exclusively for maturity levels</td></tr>
<tr><td>Q1</td><td>M1</td><td></td><td>M3</td><td></td><td>M5</td></tr>
<tr><td colspan="6">Theme</td></tr>
<tr><td>Q1</td><td>M1</td><td></td><td>M3</td><td></td><td>M5</td></tr>
<tr><td colspan="6">Theme</td></tr>
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<tr><td colspan="6">Theme</td></tr>
<tr><td>Q1</td><td>M1</td><td></td><td>M3</td><td></td><td>M5</td></tr>
</table>

"Opex Maturity Scan Format"													
Dimension 1				D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
Theme																
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
	M3	M4	M5													
	M3	M4	M5													
		M4	M5													
		M4	M5													
			M5													
			M5													
Theme																
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
	M3	M4	M5													
	M3	M4	M5													
Theme																
M2	M3	M4	M5													
M2	M3	M4	M5													
M2	M3	M4	M5													
	M3	M4	M5													
		M4	M5													
			M5													
			M5													

14 dimension
2 - 5 themes per dimension
0 questions per theme
2 - 5 exclusively for maturity levels
Maturity levels expand as maturity increases, varies depending on the thene

A.2 OpEx 4.0 Maturity Assessment Framework

Introduction to OpEx 4.0 maturity assessment framework

Welcome to our OpEx 4.0 Maturity Assessment Framework. This tool is designed to provide a comprehensive evaluation of an organization's maturity in embracing Operational Excellence 4.0 principles, leveraging cutting-edge research, industry insights, and detailed case studies. Our goal is to assist organizations in understanding your current position and guiding you toward the path of continuous improvement and innovation.

Developing this maturity assessment framework was part of the Master Thesis "Accelerating Operational Excellence through Industry 4.0 Technologies: Developing and Evaluating an OpEx 4.0 Maturity Assessment Framework for the Nordic Manufacturing Industry", at Chalmers University of Technology within Production Engineering in the spring of 2024 by Albin Mårdh and Jonathan Malmqvist.

Our framework is crafted into ten main dimensions, each subdivided into five distinct themes, covering aspects from organizational structure to innovation management. Each theme begins with a general question to gauge initial understanding, followed by 1 to 3 deeper, follow-up questions based on responses. This structure ensures a thorough exploration of each dimension within a manageable 2 to 4-hour session, including a site tour and focused interviews.

The assessment is conducted through guided site tours and targeted semi-structured interviews with key personnel. Interviews are designed to flow naturally, minimizing the need for extensive probing and allowing respondents to express detailed insights comfortably. We advise interviewees to:

- Include specific examples in their responses.
- Focus on describing the actual situation rather than ideal scenarios.
- Be honest if uncertain about answers.
- Detail the frequency of key processes, whether reactive or proactive.

Post-interview, responses are transcribed, and analyzed to ascertain the organization's maturity level across each dimension. Each area is scored based on the depth and relevance of the responses to the structured questions, and these scores are then averaged to determine the overall maturity level. The framework categorizes maturity from Level 1 (nascent) to Level 5 (advanced), each reflecting progressive integration and sophistication in implementing OpEx 4.0 principles, see next page for a close up view of the maturity levels.

Following the assessment, a detailed report is shared with the organization, highlighting strengths, areas for improvement, and practical steps towards advancement. This report includes a one-page summary for a quick overview, followed by a detailed breakdown of findings per area. We encourage feedback via a short questionnaire, which helps refine the assessment process and framework.

Thank you for engaging with our OpEx 4.0 Maturity Assessment Framework. If you want to know more about OpEx 4.0 or how to conduct maturity assessments, feel free to read our thesis in its entirety. Your feedback and collaboration are invaluable to us, and we are excited to see how together we can accelerate organizations toward Operational Excellence 4.0.

The 10 Dimensions of Operational Excellence 4.0:					
Organization	*The structure and procedures within the organization that govern strategic approach, target setting, operational management, and communication.*				
Sustainable workplace	*An integrated approach focusing on employee safety, environmental sustainability, and societal well-being, guided by the Triple Bottom Line which emphasizes social and environmental considerations alongside the economic sustainability inherent in OpEx 4.0.*				
Cultural alignment	*The integration and embodiment of the organization's core values within its culture, managing and encouraging specific behaviors throughout the company.*				
Training	*The methods and practices for training management and employees to excel in modern, high-performance production environments.*				
Innovation management	*The adoption and integration of sustainable design, lean principles, operational foresight, and continuous learning to drive efficient and responsible innovation within the organization.*				
Improvement processes	*The systematic identification and addressing of bottlenecks and weaknesses to ensure continuous and effective organizational improvements.*				
Progressive quality	*The processes ensuring product quality, addressing quality issues, and enhancing process efficiency through rigorous testing and analysis.*				
Logistics	*The organization's understanding of customer value and demand, application of lean flow principles, flexibility in handling disruptions, inventory management, and end-to-end logistics efficiency.*				
Employee Autonomy	*Support and empowerment of employees and teams for autonomous, supervisor-less, and self-directed work, evaluating how workplace conditions impact daily tasks and decision-making.*				
Maintenance	*The implemented maintenance strategy and its performance in terms of data-driven decisions, human capital resources, internal and external integration.*				
The Maturity Levels for OpErational Excellence 4.0:					
Maturity Levels:	1	2	3	4	5
Description:	- No active implementation of OpEx principles and processes. - Basic infrastructure in place enabling connectivity.	- Sporadic, non-systematic application of OpEx principles and processes. - Initial data collection and storage, beginning to harness digital and seeing capabilities.	- Systematic and structured OpEx processes are established. - Advanced data utilization with analysis and contextualization, enhancing organizational understanding.	- OpEx principles and processes are widely and successfully implemented. - Integration of advanced analytics and systems for predictive insights.	- Full and seamless integration of OpEx principles, with operations exhibiting minimal deviations. - Leveraging digital technologies for automating and optimizing processes. The organization utilizes emerging technology to accelerate its efforts towards Opertational Excellence.

	Organization The structure and procedures within the organization that govern strategic approach, target setting, operational management, and communication.					
	Maturity levels:	1	2	3	4	5
Strategy deployment	**Strategy deployment**					
	How does your organization deploy your company's strategy into its operations?					
	How is your progression strategy developed, managed, and translated into actions at all organizational levels?	- No progressions strategy exists.	- Top management has created a strategy not in use - Initial attempts to link strategy with departmental goals, but often needs more alignment and clarity on implementation.	- Top management has created a strategy and that is followed up. - ~50% of the employees participate - There is a strategy to implement I4.0 technologies	- The progression strategy is developed with input from across the organization - Management of the strategy includes continuous improvement processes, with feedback mechanisms in place for real-time adjustments. - Actions derived from the strategy are clearly communicated and implemented across all organizational levels, with more than 75% employee participation in execution.	- A strategy including different pathways of capability building and direct results are included - Reviewed Quarterly - Strategy is ingrained in the organizational culture, with all employees actively engaged in its execution. - There is a clear roadmap to integrate I4.0 technologies
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

Sustainable Workplace

An integrated approach focusing on employee safety, environmental sustainability, and societal well-being, guided by the Triple Bottom Line which emphasizes social and environmental considerations alongside the economic sustainability inherent in OpEx 4.0.

	Maturity levels:	1	2	3	4	5
Sustainable Organization	**Sustainable Organization**					
	How are sustainability goals integrated into your business strategy and operational processes?					
	How is sustainability integrated into your corporate strategy and operationalized across all departments?	- Sustainability is not at all considered in the corporate strategy. - There is no awareness or application of sustainability principles across departments.	- Sustainability concepts are recognized within the corporate strategy. - Only a few departments have begun to consider sustainability in their operations, and awareness is limited to certain levels within the organization.	- Sustainability is partially considered in the corporate strategy. - Various levels within the organization are aware of the strategy, growing but uneven commitment to sustainability.	- Sustainability is fully integrated into the corporate strategy and actively considered in most departments. - The organization employs advanced analytics to assess and enhance sustainability performance across different areas. - A majority of employees are aware and engaged in sustainability initiatives.	- Sustainability is deeply embedded in the corporate strategy and operational processes of every department. - AI and IoT technologies are used to monitor, manage, and optimize sustainability performance in real-time, ensuring alignment with strategic goals. - Sustainability awareness and practices are widespread across all organizational levels.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Cultural Alignment The integration and embodiment of the organization's core values within its culture, managing and encouraging specific behaviors throughout the company.					
	Maturity levels:	1	2	3	4	5
	Core Values and Beliefs					
	How are the organization's core values integrated and lived within the company?					
	How are the organization's core values actively integrated into daily operations, decision-making processes, and employee behaviors across all levels?	- Basic communication of core values.	- Core values communicated and understood by most employees.	- Core values clearly communicated and understood by all employees.	- Core values widely understood - Managers increasingly lead cross-functional improvement activities.	- Core values deeply ingrained in the organizational culture. - Mechanisms to gauge employee motivation and participation. - Managers actively lead cross-functional improvement activities.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Training The methods and practices for training management and employees to excel in modern, high-performance production environments.					
	Maturity levels:	1	2	3	4	5
Skill gap analysis	**Skill gap analysis**					
	How does your organization address the gap between the skills of the employees and important skills for market competitiveness?					
	How does the company address which skills are required to stay competitive in your market segment?	- The company lacks a structured process for identifying and addressing skill requirements for competitiveness.	- The company collects data sporadically to assess skill requirements for competitiveness. - There is limited understanding of the full scope of skill requirements across the organization and industry trends influencing competitiveness.	- The company has established a good process for identifying skill requirements in most areas. - Skill assessments are conducted regularly, covering a wide range of skills and competencies. - However, there may be gaps in considering all aspects of skill requirements, such as emerging technologies or future market trends.	- The company has a good process for identifying skill requirements that is consistently applied across the organization. - Skill assessments consider emerging technologies and future market trends. - The company proactively anticipates future skill needs based on predictive analytics and data-driven insights.	- The company has optimized its approach to address skill requirements for competitiveness - Utilize advanced data analytics and machine learning for predicting future skill needs to always stay competitive - Continuous feedback loops and iterative improvements ensure that the company remains agile and responsive to evolving skill demands in its market segment.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Innovation management The adoption and integration of sustainable design, lean principles, operational foresight, and continuous learning to drive efficient and responsible innovation within the organization.					
	Maturity levels:	1	2	3	4	5
Sustainable Innovation and Design	**Sustainable Innovation and Design**					
	How does your organization ensure that sustainability is a core consideration in its innovation and product design processes?					
	What sustainability criteria are included in your innovation management process?	- No sustainability criteria are included in the innovation management process.	- Basic sustainability criteria are sporadically applied to some projects, but there is no systematic approach.	- Specific sustainability criteria related to product design are identified and consistently applied. - These criteria start to influence decision-making in the innovation process, although integration may not be fully systematic across all areas.	- A broad range of sustainability criteria covering various aspects of sustainability (environmental, social, economic) is integrated into the innovation management process. - These criteria are systematically applied to all innovation projects, with regular reviews and updates to ensure relevance and effectiveness.	- Sustainability criteria are deeply embedded in every aspect of the innovation management process, ensuring sustainable product design and beyond. - AI and machine learning tools are utilized to continuously analyze and optimize these criteria in real-time, ensuring that the innovation process is aligned with the latest sustainability standards and practices.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Improvement processes The systematic identification and addressing of bottlenecks and weaknesses to ensure continuous and effective organizational improvements.					
	Maturity levels:	1	2	3	4	5
Loss Intelligence	**Loss Intelligence**					
	How does your organization identify and analyze losses?					
	Is there a clear understanding of productivity results, improvement opportunities (OEE, Q, Productivity), and core production areas based on data and facts?	- Productivity is measured, but losses are not calculated. - There is no systematic basis for calculating the effectiveness, quality, and productivity of specific production units. - Core areas are sporadically defined based on operational experience.	- Productivity and losses are measured, and there is an initial effort to link these measurements to specific production units. - Basic connectivity tools are employed to gather data, but comprehensive analysis and real-time tracking are lacking. - Core production areas begin to be identified with some data support, but the approach is still fragmented.	- Core areas are partly defined based on data in most production units. - There is a basic understanding of productivity losses linked to OEE and organizational losses. - Effectiveness, quality, and productivity are calculated for particular production units. - Data visualization tools are used to present and discuss productivity results, facilitating a deeper understanding and initial predictive insights.	- Advanced data analytics and predictive modeling are used to deeply understand productivity results and identify improvement opportunities. - Core production areas are clearly defined and continuously refined based on comprehensive data analysis. - The organization begins to predict potential losses and efficiency gains using historical data trends and predictive analytics, guiding proactive improvements.	- Core areas are precisely defined based on a cost breakdown and cost loss tree methodology. - An advanced calculation system, integrated with real-time data collection and IoT technology, determines the effectiveness, quality, and productivity of specific production units. - A comprehensive model of OEE losses, organizational losses, and crew saturation is utilized, supported by AI and machine learning, to analyze and predict productivity improvement opportunities actively. - The approach is fully automated and optimized, with continuous, data-driven adjustments to production processes to maximize efficiency and effectiveness.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Progressive Quality The processes ensuring product quality, addressing quality issues, and enhancing process efficiency through rigorous testing and analysis.					
	Maturity levels:	1	2	3	4	5
Customer focus and satisfaction	**Customer focus and satisfaction**					
	How do you work with understanding customer needs, gathering feedback and addressing complaints?					
	How is customer feedback collected, analyzed, and used to drive improvements in products and services?	- There are no formal mechanisms in place to collect customer feedback.	- Feedback is collected sporadically, often through informal channels like emails or direct customer complaints without a consistent process. - Basic review of the feedback collected without deep analysis or systematic categorization.	- Established processes for collecting feedback using standardized forms, surveys, and direct customer interactions. - Introduction of basic digital platforms for feedback collection. - Feedback is discussed in periodic meetings, and some insights lead to targeted actions for improving products and services	- Comprehensive feedback collection mechanisms - Advanced data analytics tools are used to analyze customer feedback, identifying trends, patterns, and actionable insights systematically. - Feedback insights are integrated into continuous improvement cycles -Cross-functional teams work on implementing improvements informed by data-driven insights.	- Fully automated, real-time feedback collection across multiple channels, leveraging AI and machine learning for immediate analysis and categorization. - Integration of feedback analysis with product development and customer service platforms for real-time insights. - Customer feedback directly feeds into an automated, dynamic decision-making process for product and service enhancements. - Continuous, automated updates to products and services based on real-time customer insights.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Logistics The organization's understanding of customer value and demand, application of lean flow principles, flexibility in handling disruptions, inventory management, and end-to-end logistics efficiency.					
	Maturity levels:	1	2	3	4	5
Understanding customer value and demand	**Understanding customer value and demand**					
	How does your organization align its operations with the demands of your customers?					
	Is customer value and demand defined and well understood?	- Customer value and demand is unknown/have not been defined.	- Customer value is defined for the pilot and the average demand is well understood. - Data is saved on a cross-department platform for everyone to see, enhancing connectivity and visibility across the organization.	- Customer value is defined for all value streams. - Demand is understood in detail with seasonality and impact of sale campaigns etc. - Data is transformed into actionable insights by connecting it to business procedures/processes, enhancing understanding through coherent and useful visibility.	- Customer value is predicted using ML for all value streams, showcasing an advanced level of predictive analytics. - Demand is precisely forecasted, considering seasonality and sales campaigns, using predictive models. - Business procedures/processes are dynamically adjusted based on predictive insights, indicating the onset of automation.	- The prediction of customer value and demand using ML is deeply integrated across all value streams. - Advanced predictive analytics and AI are used to understand demand intricacies, including seasonality and campaign impacts. - Automated optimization and adjustments are implemented across all adjacent processes/departments to proactively meet predicted behavior/demand, representing the pinnacle of Industry 4.0 automation and optimization technologies.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

Employee Autonomy

Support and empowerment of employees and teams for autonomous, supervisor-less, and self-directed work, evaluating how workplace conditions impact daily tasks and decision-making.

	Maturity levels:	1	2	3	4	5
AM action plan and implementation	**Employee Autonomy implementation**					
	What actions does your organization take to increase the level of autonomy of your operators?					
	How do you balance the implementation of standardized processes with fostering a culture of team proactivity and autonomy? *Can you provide examples of how you encourage participative decision-making and promote inter-team collaboration to drive continuous improvement and innovation within your teams?	- Decision-making is largely top-down, with minimal input from team members. - There's a lack of formal structures to promote inter-team collaboration and participative decision-making.	- There's an acknowledgment of the need for balance between standardization and autonomy. - Some initiatives or pilot projects might be in place to encourage team input or collaboration, but these are not yet standardized or fully integrated into daily operations. - Teams begin to engage in problem-solving, but these activities are inconsistent and not yet fully supported by management. - Ownership for machines and areas is clearly defined. - Teams have access to digital dashboards and basic data analytics, enhancing visibility into processes and performance.	- The organization has defined processes to ensure a balance between lean standardization and team autonomy. - There are clear mechanisms for participative decision-making, and teams are encouraged to contribute to continuous improvement. - Inter-team collaboration is promoted, with some structures and processes in place to support it, facilitated by digital platforms, though there may be room for deeper integration. - IoT devices are integrated into processes, enhancing data collection and enabling teams to better understand their impact on operations.	- At this level, there are well-established systems and processes that support team autonomy and participative decision-making within the framework of standardized operations. - The impact of these processes is regularly measured, and results are fed back into continuous improvement loops. - Teams have clear autonomy within defined boundaries, and there's a strong culture of collaboration and proactive problem-solving. - Predictive analytics and AI capabilities are integrated, allowing teams and management to anticipate process outcomes and identify improvement opportunities proactively.	- The organization exhibits a culture where continuous improvement, team autonomy, and participative decision-making are deeply embedded and operate seamlessly. - Processes are not only standardized but also continuously optimized based on team input and collaborative innovation. - There's a strong sense of ownership at all levels, with teams proactively identifying and implementing improvements. - The organization is agile, capable of quickly adapting to changes while maintaining operational excellence. - Autonomous systems and AI-driven analytics are fully integrated, optimizing processes in real-time based on continuous team input and collaborative innovation. - Machine learning, advanced robotics, and co-bots, are employed to automate routine tasks, freeing teams to focus on strategic improvement and innovation. - Digital models or shadows are used for simulation and scenario planning, aiding in decision-making and fostering a proactive improvement culture.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

	Maturity levels:	1	2	3	4	5
Maintenance Strategy	**Maintenance strategy**					
	What is your maintenance strategy and how is it implemented?					
	What factors are considered when formulating your organization's maintenance strategy	- Maintenance activities are primarily reactive, with little to no planning involved	- Some planned maintenance activities may occur, but they are sporadic and inconsistent.	- Planned maintenance activities are implemented in approximately 50% of cases. - Efforts are made to schedule maintenance tasks, but execution may still be irregular. - Basic planning processes are in place, but adherence varies across the organization.	- MTBF/MTTR metrics are systematically tracked and analyzed, informing maintenance strategy. - Implementation of planned maintenance activities significantly reduces MTTR, contributing to improved MTBF. - Adoption of predictive maintenance techniques further enhances MTBF by identifying and addressing issues proactively.	- At least 95% of maintenance activities are planned. - Maintenance planning is automated and optimized, leveraging advanced algorithms and real-time data analytics. - Seamless integration of Industry 4.0 technologies ensures proactive maintenance scheduling, minimizing unplanned downtime. - Continuous refinement of planning processes ensures maximum efficiency and effectiveness in maintenance activities.
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 2	**Theme 2**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 3	**Theme 3**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 4	**Theme 4**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
Theme 5	**Theme 5**					
	Theme-specifc question					
	Sub-question 1	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 2	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5
	Sub-question 3	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5

Maintenance

The implemented maintenance strategy and its performance in terms of data-driven decisions, human capital resources, internal and external integration.

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