IOSUD - Polytechnic University Timișoara
Doctoral School of Engineering

Research Studies on Cost Management for Production Capacity and Operational Optimization in the Framework of Industry 4.0

Doctoral Thesis – Abstract
A thesis submitted for obtaining
the Scientific Title of PhD at
Politehnica University Timisoara
in the Field of Engineering and Management

author Dipl. Kffr. M.A. Eng. Elif OCAKCI (OCAKCI-NIEMANN)
Scientific Supervisor Prof.univ.dr.eng. Anca DRAGHICI

month 9, year 2025

1. Background and Motivation: The Fourth Industrial Revolution

The emergence of the Fourth Industrial Revolution, commonly known as Industry 4.0, marks a profound transformation of industrial production, operational strategies and economic organization. Industry 4.0 (I4.0) is characterized by the integration of cyber-physical systems (CPS), the Internet of Things (IoT), Big Data Analytics (BDA), cloud computing and Artificial Intelligence (AI). These technologies enable smart, connected production environments that operate with a high degree of automation and real-time responsiveness (Lasi et al., 2014; Xu et al., 2018). This is not merely a technological evolution of existing systems, but a paradigm shifts in the way companies manage costs, utilize capacity and optimize operational processes, especially in increasingly complex and volatile markets.

Traditional cost management systems, often based on retrospective and linear approaches, are proving inadequate in the dynamic, data-intensive environments of Industry 4.0. Real-time data generated by IoT devices, combined with predictive analytics and AI-powered decision making, open new opportunities for fine-grained cost control and optimization (Oesterreich & Teuteberg, 2016). This development is transforming cost management from a static accounting function to a strategic, data-based competence.

In addition, production capacity and operational optimization - two key pillars of competitiveness in the manufacturing industry - are also being redefined by Industry 4.0 technologies. Embedded sensor networks, digital twins and intelligent planning systems enable unprecedented levels of responsiveness and efficiency (Lu, 2017). This dissertation is motivated by the urgent need to develop an integrated understanding of how these technologies can be used not only for operational improvement but also for effective cost control in smart manufacturing systems.

2. The Evolving Challenges in Manufacturing: Cost, Capacity, and Competition

Modern industrial companies face several challenges: increasing cost pressure, dynamic capacity requirements, variability in the production environment (Dequeant et al., 2016), the need

for more resilience in supply chains (Ralston & Blackhurst, 2020) and intensified global competition. Since 2021, many manufacturing firms have been facing severe issues due to a combination of pandemic-related disruptions and geopolitical conflicts such as the war in Ukraine. These overlapping crises have caused interruptions in material flows, unexpected shortages of key components, and significant increases in logistics and energy costs. As a result, companies are under growing pressure to reassess their supply chain structures and make them more adaptive and crisis-resilient (Bai et al., 2024; Srai et al., 2023). These factors significantly increase the complexity of industrial processes and increasingly overwhelm classic production systems and traditional management tools.

A key challenge here is the management of production costs, which are constantly rising in modern value-added networks. In addition to rising raw material prices and personnel costs, the main reasons for this are more complex production systems and higher demands on product quality and customization (Stock & Seliger, 2016; Jagatheesaperum et al., 2021). Companies are therefore increasingly required to make their production processes more efficient and transparent with the objective to optimize their cost structure in the long term and remain competitive (Porter & Heppelmann, 2015; Khan et al., 2025). Cost management is made particularly difficult by rising energy prices, higher labour costs, and investments in sustainable production methods. Conventional systems based on static overhead surcharges and fixed assumptions about production volumes are reaching their limits in a volatile market environment and provide only an inadequate basis for decision-making (Kaplan & Anderson, 2007). In contrast, digital technologies enable real-time transparency concerning cost drivers and support forward-looking, adaptive cost control (Porter & Heppelmann, 2015; Strandhagen et al., 2017).

Ensuring sufficient and flexible production capacities is another challenge. The growing demand for customized products requires manufacturing facilities to be able to respond flexibly and dynamically to fluctuating requirements (Lasi et al., 2014; Platform Industry 4.0, 2023). Traditional rigid production systems are increasingly reaching their limits. The implementation of digital technologies, such as cyber-physical systems (CPS), enables companies to control their capacity planning more precisely and respond more quickly to market changes (Wang et al., 2016; Platform Industry 4.0, 2023).

Increasing global competition is further intensifying the demands of the manufacturing industry. Companies are not only forced to manage costs and capacities efficiently but must also position themselves strategically to secure long-term competitive advantages (Müller et al., 2018). Hybrid competitive strategies that combine efficiency and differentiation are becoming particularly important (Precedence Research, 2025). The ability to quickly adapt and leverage new digital business models and innovations will be crucial in this regard (Herman et al., 2016).

In addition to technological transformation, organizational and cultural aspects are crucial for the successful implementation of Industry 4.0 technologies. A development-oriented corporate culture correlates significantly with the use and success of digital technologies in production (Wiese et al.,2024; acatech, 2024).

In summary, manufacturing companies are faced with the task of continuously and systematically adapting their cost structures, capacity planning, and competitive strategies to new technological developments and market requirements. Industry 4.0 technologies offer decisive starting points for efficiently meeting these challenges and securing sustainable competitive advantages. Costs, capacity, and competition are therefore no longer isolated control areas, but are closely interwoven within a digital ecosystem that requires integrated management approaches.

3. Problem Statement

3.1. Limitations of Traditional Cost Management in a Digital Era

Traditional cost systems such as standard costing and Activity-Based Costing (ABC) were designed for stable, hierarchical production systems. In the dynamic, decentralized, and data-rich environments enabled by Industry 4.0, these models fall short. They often fail to capture the complexity of cost drivers in smart production systems, such as data processing costs, digital asset utilization, or energy fluctuations monitored in real time (Hansen & Mowen, 2021).

Moreover, conventional cost models are poorly aligned with the continuous flow of information generated by IoT sensors and smart equipment. As such, they are not sufficiently agile to inform just-in-time (JIT) pricing, resource allocation, or cost-to-serve analyses under dynamic conditions (Gunasekaran et al., 2017).

3.2. The Need for an Integrated Approach to Cost, Capacity, and Operations

The separation of cost accounting, capacity planning, and operational management leads to blind spots in decision-making. Different organizational functions often rely on their own distinct data inputs and operate under separate assumptions, which makes coordinated decision making and agile response much more challenging (Otley, 2016). Industry 4.0, on the other hand, enables data convergence across production, logistics, finance, and quality assurance systems, thus enables the possibility of integrated, real-time decision support (Brettel et al., 2014).

To exploit this potential, a new conceptual framework is needed—one that connects digital technologies with business decision-making processes to increase cost transparency, align capacities with demand volatility, and improve operational performance. This dissertation aims to close this central gap in theory and practice.

4. Research Objectives and Questions

4.1. Research Objectives

This dissertation pursues the overarching goal of systematically analysing, structuring and further developing cost management in the context of industrial production processes under the conditions of digital transformation through Industry 4.0. Based on this objective, five specific research goals can be derived:

Objective 1: Analyse the transformation of cost categories through Industry 4.0

The study aims to show how Industry 4.0 technologies and digitalized control mechanisms change the perception, evaluation and prioritization of operational cost categories in industrial production. It should be worked out whether and in what form new cost items - such as sustainability or data management costs - are integrated into operational controlling.

Objective 2: Evaluation of the effectiveness of digital cost management practices

The objective is to conduct a differentiated evaluation of those cost management practices that are considered particularly suitable for optimizing production capacities and increasing operational efficiency in the context of digital transformation processes. The study should work out how traditional methods (e.g. lean accounting, ABC/TDABC) and modern data-based approaches (e.g. predictive analytics, real-time costing) differ in their suitability.

Objective 3: Investigation of data-based decision support systems

The thesis aims to investigate the impact of data-based decision support systems, real-time information platforms and automated reports on operational control and cost transparency in industrial companies. The aim is to determine the role of ERP/MES systems, IoT architecture and analytical tools for controlling and strategic production management.

Objective 4: Evaluation of the contributions of Industry 4.0 to sustainability and resilience

The study aims to clarify the extent to which Industry 4.0 technologies contribute to the integration of sustainability goals (e.g. CO_2 reduction, energy efficiency) and resilience strategies (e.g. responsiveness to disruptions) - especially in the context of exogenous shocks such as the COVID-19 pandemic. Both strategic and operational impact levels will be analysed.

Objective 5: Identification of structural barriers to digital transformation in cost management

The aim is to identify structural, organizational and technical barriers that hinder the effective implementation of digital cost optimization strategies. In addition, strategic approaches are to be developed as to how companies can meet these challenges - for example through training, governance adjustments or technology selection.

These research objectives serve to operationalize the research questions in a scientifically sound manner. They structure the subsequent empirical and theoretical analyses and form the basis for deriving findings, recommendations for action and future research needs in Chapter 5.

4.2. Research Questions

Based on the previously defined research objectives, it is necessary to translate the central findings of this work into research-guiding questions. The research objectives serve as a conceptual framework that defines the thematic focus and target structure of the study. They address key aspects of digital transformation in industrial cost management, including technological factors, organizational conditions, process impact paths, and strategic targets such as efficiency, resilience, and sustainability. To enable systematic empirical and theoretical analysis of these target areas, five specific research questions are derived below.

These form the analytical core of the work and structure the investigation in terms of content and methodology. Each question is designed so that it can be assigned to one or more research objectives and at the same time enables an operational approach to the analysis of the empirical data. These research questions are answered in the context of a literature review (Chapter 3), an empirical investigation (Chapter 4), and a concluding reflection and integration of the results (Chapter 5). As the central research question will serve:

How can Industry 4.0 technologies be integrated into cost management and production capacity planning to enhance operational performance in manufacturing firms?

This central research question is divided into five sub questions which help to structure the research findings in a differentiated manner:

1. How does digitalization change the evaluation and prioritization of cost categories in industrial production, especially under the influence of Industry 4.0 technologies?
2. Which cost management practices are perceived as particularly effective in the industrial environment for optimizing production capacities and operational efficiency - and how do they differ in their suitability?
3. How do data-based decision-making and real-time information systems influence operational control and cost transparency in Industry 4.0?
4. To what extent do Industry 4.0 technologies contribute to the integration of

sustainability goals and resilience strategies, especially under the conditions of the COVID-19 pandemic?

5. What structural challenges make the implementation of digital cost optimization measures more difficult - and how can companies counter these in terms of strategic transformation?

The structure of these questions will serve as a structured guideline for the research and the evaluation of the findings in the following chapters.

5. Scope and Limitation of the Research

This study focuses on analysing Industry 4.0 technologies in terms of their impact on cost management, capacity control, and competitiveness in industrial manufacturing. The focus is on manufacturing companies in industrial sectors that have a strong affinity for digitized and automated production systems. Sectors outside industrial manufacturing - such as the service or agricultural sectors - are not included, as the dynamics of costs and capacity differ significantly in these sectors. The study is not limited to a specific region, but primarily considers companies in industrialized countries, as these are pioneers in the implementation of Industry 4.0 technologies. Due to the complexity and dynamic nature of the topic, the study is limited to qualitative and quantitative analyses of existing scientific literature and selected practical examples. A questionnaire was also used to generate empirical data. While the questionnaire was answered worldwide, the statistics used in the study are largely based on the German population and industry. One limitation is that, in addition to the questionnaire, the analysis is primarily based on secondary data and existing scientific publications. Extensive empirical studies on international markets are not part of this study. Due to the continuous evolution of technology, this study may not reflect developments that occurred after its completion, especially in areas related to emerging tools or organizational models. The time limitation of the available literature up to and including 2025 represents a further limitation of the study.

The main limitations of the study are:

- Differences in the maturity of Industry 4.0 adoption between companies and regions;
- Limited availability and consistency of relevant data;
- Limited transferability of results to non-industrial or non-technology-intensive companies;
- Potential obsolescence of technological details due to the rapid development of digital tools.

These limitations are outlined intentionally to maintain the study's clarity and focus, while preserving its core relevance for both academic and practical contexts.

6. Structure and Research Methodology

The thesis is structured into eight chapters. According to Figure 1 the first chapter contains an introduction to the topic and presents the research background, problem statement, objectives, significance, and scope and limitations of the executed research.

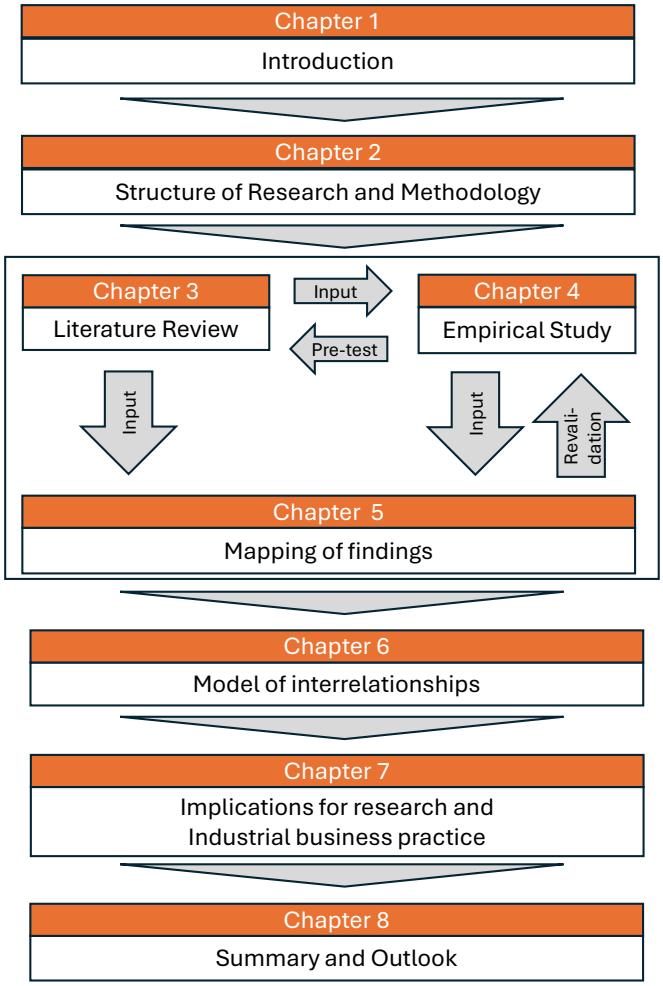

Figure 1: Research Methodology of the Thesis (source: own graph)

Chapter 2 describes the research methodology and explains in detail the research design, data sources, analytical tools and validation methods used in chapters 3 and 4.

Chapter 3 presents the findings of the literature review. The chapter examines existing theories and research on cost management, capacity optimization, and digital manufacturing.

Chapter 4 analyses the results of the empirical study executed with participants from industry. The results of the literature research and the empirical findings will be mapped and discussed in Chapter 5. Regarding the research objectives and the research questions the results served to develop a framework of interrelationships between Industry 4.0, production capacity, cost efficiency, resilience and sustainability. This framework is presented in Chapter 6 and serves as a synopsis of the theoretical and empirical research results.

Based on the research results and the framework, Chapter 7 presents the general conclusions, original contribution and proposals of future research studies. In addition, the chapter content derives and proposes implications for academic research and recommendations for industrial business practice.

Chapter 8 summarizes the executed research process, highlights key findings, and outlines possible future developments.

7. Contributions and Implciations

5.1. Contribution to Academic Theory

This study expands scientific understanding by linking cost accounting theory with digital operations management. It enriches the theoretical discourse in the field of management accounting by adapting cost accounting models to real-time data environments and extends systems theory to include digital interdependencies in industrial manufacturing (Otley, 2016).

The interdisciplinary framework developed in this dissertation contributes to a theoretical foundation for understanding how Industry 4.0 is changing cost behaviour, resource planning, and performance metrics. It thus bridges the gap between accounting, operations research, and information systems.

5.2. Practical Implications for Industry and Policy

For industry, this research provides a practical framework for the targeted use of Industry 4.0 technologies to manage costs and capacities. It shows companies the advantages and disadvantages and supports them in making informed decisions about the introduction of intelligent technologies. It also provides valuable inputs for policymakers: the results identify key success factors for the digital transformation and show how suitable incentive structures can be designed. For highly industrialized economies, this offers starting points for sustainably strengthening innovative strength and competitiveness through a targeted industrial policy.

5.3. Perspectives

The dissertation demonstrates that Industry 4.0 technologies offer significant potential for transforming cost management and production capacity planning. However, success depends on strategic integration, continuous competence development, and a willingness to rethink traditional management approaches. The COVID-19 pandemic has reinforced the importance of digital resilience and prompted companies to accelerate their digitalization strategies. Research shows that the successful implementation of Industry 4.0 in cost management requires not only technological changes, but also organizational and cultural changes. Companies that successfully master this holistic transformation can achieve sustainable competitive advantages while contributing to the achievement of sustainability and resilience goals.

8. Selected bibliography

[1] acatech. (2024). Kurzformat Erfolg im Mittelstand. Acatech

[2] Bai, X., Fernández Villaverde, J., Li, Y., & Zanetti, F. (2024). The causal effects of global supply chain disruptions on macroeconomic outcomes: Evidence and Theory (NBER Working Paper No. 32098). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w32098

[3] Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M. (2014). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. International Journal of Information and Communication Engineering, 8(1), 37–44.

[4] Dequeant, K., Vialletelle, P., Lemaire, P., & Espinouse, M. (2016). A literature review on variability in semiconductor manufacturing: The next forward leap to Industry 4.0. Proceedings of the Winter Simulation Conference, 1–8. https://dl.acm.org/doi/10.5555/3042094.3042419

[5] Gunasekaran, A., Papadopoulos, T., Dubey, R., Fosso, S.W., Childe, S. J., Hazen, B., Akter, S. (2017). Big data and predictive analytics for supply chain and organizational performance, Journal of Business Research, Volume 70, Pages 308-317. https://doi.org/10.1016/j.jbusres.2016.08.004.

[6] Hansen, D. R., Mowen, M. M., & Heitger, D. L. (2021). Cost Management. Cengage Learning.

[7] Hermann, M., Pentek, T., & Otto, B. (2016). Design Principles for Industrie 4.0 Scenarios," 2016 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, USA, 2016, pp. 3928-3937, https://doi:10.1109/HICSS.2016.488

[8] Jagatheesaperumal, S. K., Rahouti, M., Ahmad, K., Al-Fuqaha, A., & Guizani, M. (2021). The duo of artificial intelligence and big data for Industry 4.0: Review of applications, techniques, challenges, and future research directions. IEEE Internet of Things Journal, 9(15), 12861–12885. https://doi.org/10.1109/JIOT.2021.3139827

[9] Kaplan, R. S., & Anderson, S. R. (2007). Time-Driven Activity-Based Costing: A Simpler and More Powerful Path to Higher Profits. Harvard Business Press.

[10] Khan, M. I., Yasmeen, T., Khan, M., Hadi, N. U., Asif, M., Farooq, M., & Al-Ghamdi, S. G. (2025). Integrating industry 4.0 for enhanced sustainability: Pathways and prospects. Sustainable Production and Consumption, 54, 149–189. https://doi.org/10.1016/j.spc.2024.12.012

[11] Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. Business & Information Systems Engineering, 6(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

[12] Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration, 6, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

[13] Müller, J. M., Buliga, O., & Voigt, K.-I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, 132, 2–17. https://doi.org/10.1016/j.techfore.2017.12.019

[14] Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Computers in Industry, 83, 121–139. https://doi.org/10.1016/j.compind.2016.09.006

[15] Otley, D. T. (2016). The contingency theory of management accounting and control: 1980–2014. Management Accounting Research, 31, 45–62. https://doi.org/10.1016/j.mar.2016.02.001

[16] Plattform Industrie 4.0. (n.d.). Chancen durch Industrie 4.0: Von smarten Objekten und vernetzten Maschinen zurück zum Menschen. https://www.plattform-i40.de/PI40/Redaktion/DE/Standardartikel/chancen-durch-industrie-40.html

[17] Porter, M. E., & Heppelmann, J. E. (2015). How smart, connected products are transforming companies. Harvard Business Review, 93(10), 96–114.

[18] Precedence Research. (2025). Industry 4.0 market size, share & growth analysis 2025–2034. Precedence Research. Industry 4.0 Market Size to Hit Around USD 884.84 Billion By 2034

[19] Ralston, P., & Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: A driver of capability enhancement or capability loss? International Journal of Production Research, 58(16), 5006–5019. https://doi.org/10.1080/00207543.2020.1736724

[20] Srai, J. et al. (2023). Operations locked in amid geopolitical conflicts: A study of the 2022 disruptions. International Journal of Operations & Production Management.

[21] Strandhagen, J. & Alfnes, E. & Strandhagen, J. Ola & Vallandingham, L. (2017). The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study. Advances in Manufacturing. 5. https://doi.org/10.1007/s40436-017-0200-y

[22] Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in Industry 4.0. Procedia CIRP, 40, 536–541. https://doi.org/10.1016/j.procir.2016.01.129

[23] Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: State of the Art and Future Trends. International Journal of Production Research, 56, 2941–2962. https://doi.org/10.1080/00207543.2018.1444806

[24] Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C. (2016). Towards Smart Factory for Industry 4.0: A self-organized multi-agent system with big data-based feedback and coordination. Computer Networks, 101, 158–168.

[25] Wiese, S. A., Lehmann, J., & Beckmann, M. (2024). Organizational culture and usage of Industry 4.0 technologies. Evidence from Swiss businesses. arXiv preprint arXiv:2412.12752.