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EFFECT OF DIGITAL PROCESS MATURITY ON THE EFFICIENCY OF PRODUCT DEVELOPMENT IN MECHANICAL ENGINEERING

DOCTORAL THESIS

Submitted for the Scientific Doctor's Degree *(Ph.D.)* in Social Sciences

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Table of content

List of abbreviations

CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CMMI	Capability maturity Model Integration
-DEV	… for Development
DM	Digital process maturity
EF	Financial efficiency
ET	Technical efficiency
EFQM	European Foundation for Quality Management
GST	General Systems Theory
H	Hypothesis
IT	Information Technology
KMO	Kaiser-Mayer-Olkin Criterion
MM	Maturity model application
MK	Knowledge related moderators
MC	Control-related moderators
MP	Business related moderators
MR	Risk-related moderators
MBO	Management by Objectives
PDCA	Plan-Do-Check-Act (Cycle)
PEMM	Process & Enterprise Maturity Model
PERT	Program evaluation review techniques
PPBS	Planning, Programming, and Budgeting Systems
QMMG	Quality Management Maturity Grid
Sig.	Significance

Std.Dev.	Standard deviation
TQM	Total Quality Management
Var.	Variance

List of figures

List of tables

Summary

The thesis analyses “The effect of digital process maturity on the efficiency of product development in mechanical engineering” are based on a mixed-method approach.

It draws on Organizational Systems Theory and reconnects it to the knowledge-based perspective, the dynamic capabilities approach and agile development concept to develop a basic model outlining the causal impact of digital process maturity and specifically maturity model application on efficiency in digitalization.

A comprehensive review of earlier empirical research is conducted to assess the impact of digital process maturity on technical and financial efficiency. Knowledge-, control-, risk- and business-related moderators of the relationship are identified, and a comprehensive research model including five research hypotheses is drafted for further analysis in the German mechanical engineering sector.

Based on four interviews in mechanical engineering companies, the model categories are adjusted to the business sector. A survey (n =140) among German businesses in mainly mechanical engineering was conducted to test the hypotheses using mean value comparison, regression modelling and moderation analysis.

The dissertation finds that businesses applying maturity modeling gain higher digital process maturity than their non-applying competitors. Digital process maturity significantly enhances technical and financial efficiency. Knowledge, control and risk related factors control this relationship.

Recommendations to business practice and academic research are developed: Further research in digitalization maturity management is required to analyze the impact and moderators on efficiency in more detail. Businesses should apply maturity models to manage and improve their digitalization processes. Digitalization is essential for businesses in the German mechanical engineering sector to succeed in an increasingly international business environment.

Key terms: Product development; technical efficiency; mechanical engineering; maturity model; digital process maturity.

Introduction

This thesis deals with the effect of digital process maturity on efficiency in product development.

Actuality of the topic

Mechanical Engineering is in a constant challenge for new and better technologies, especially German and Austrian companies face increasing international challenge. Despite this, there are other areas of conflict to face.

Advice to Adapt Businesses to Novel Technologies

The German Federal Ministry of Economics and Technology advises in the Industrial Strategy 2030 businesses to adapt to novel technological developments more rapidly to maintain their international competitiveness and develop technological core competences. Building on technological progress German businesses will be able to survive and prosper even under the impending conditions of global currency uncertainty and potential export restrictions.[1]

Contribution of Digitalization

Recent innovations in digitalization could contribute to enhance the efficiency and in Germany's mechanical engineering. Simulation software, also known as CAE (Computer Aided Engineering), supports product development by virtual mapping of real problems. Partial aspects are structural mechanics, system simulation, fluid dynamics and all possible combinations to virtually evaluate future behavior.[2]

Reluctance to Major Digital Advancements:

German industrial companies are generally moderately positioned overall; they rank in the middle range on the innovation index (49 out of a possible 100 points). As for agility, the current status quo is slightly better (66 out of 100 points), but here too, the majority of companies are still lagging behind expectations. An overwhelming majority (95%) are focused on improving existing products or services, as well as tapping into new customer

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[1] FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY (BMWi). Industrial Strategy 2030. 2019, pp. 20-24.

[2] CHANG, Kuang-Hua. *Product design modeling using CAD/CAE.* Amsterdam: Elsevier; Academic Press, 2014. The Computer Aided Engineering Design Series.

groups (90%). Only 64% are concentrating on adapting business processes or operational workflows as part of digitalization efforts. In terms of the application of specific software, 88% use computer-aided design (CAD), but only 51% use Computer-Aided Manufacturing (CAM), and 36% use Computer-Aided Engineering (CAE). The surveyed companies perceive the greatest challenges regarding digitization in product development to be the complexity of the topic (17%), requirements concerning data protection (14%), and the shortage of skilled professionals (13%).[3]

The reluctance to apply digital technologies, on the other hand, could in fact be the major cost driver and obstacle to fundamental innovation in the German machinery and automotive industry: The Change Readiness Index of German companies changed only marginally from 55 to 56 between 2019 and 2022 (0= not at all, 100= completely). Despite turbulent times, companies were only able to increase their adaptability slightly. [4] The improvement of internal processes and the further development of products and services are key success factors for all companies in the industry. Agile methods and suitable software applications can make product development faster, more efficient and more innovative. However, there are also numerous challenges and hurdles in the digitization of development processes. The lack of human resources and concerns about one's own data and IT security are currently some of the greatest challenges in German industry. German industrial companies most frequently state data protection as a challenge in digitization (88%), followed by the complexity of digitization (83%). Three quarters of the industrial companies see themselves inhibited in the digital transformation by the high requirements for IT security (78%) and the shortage of skilled workers (74%).[5]

The assumption that the reluctance towards digital technologies in the German mechanical engineering business contributes to lags and failure of innovation projects lies at hand. However, the cause-and effect chain has not been explored systematically yet.

[3] NGUYEN, Trinh. *Digitale Transformation. Digitale Wertschöpfungsketten und Geschäftsmodelle in der deutschen Industrie.* Berlin: Bitkom Research, 2022.

[4] GOSCHY, Wilhelm. *Unternehmen im Wandel. Deutscher Change Readiness Index 2022.* Eine Studie der Staufen AG. Köngen: Staufen AG, 2022.

[5] NGUYEN, Trinh. *Digitale Transformation. Digitale Wertschöpfungsketten und Geschäftsmodelle in der deutschen Industrie.* Berlin: Bitkom Research, 2022 p39.

Key Terms

The key terms inherited are digital process maturity and efficiency, which are discussed in detail in Chapter 1. Initially, the terms can be defined as follows:

- *Digital process maturity* defines, if a process works well and fulfills the functions it is designed for.[6] Maturity models are therefore instruments designed to measure and assess objects based on an ordinary scale of degrees of maturity. Maturity in the digital product development process is a reliable measure for the level of digital technology application.[7] Maturity models are proven for technical and econometric performance assessment and provide standardized measures for the progress of a development process towards an ideal standard. Maturity models illustrate the progress made towards an objective and allow to develop guidelines for further development activity to approach this target. Maturity models like SPICE, CMM or CMMI-DEV have established in business practice since the early 1980ies and have gained particular attention with the progress of electronic technologies in the recent decade.[8]
- *Efficiency* will be distinguished later in technical and financial efficiency. Commonly, efficiency involves a comparison of observed inputs (or resources) and outputs (or products) with what is optimal. Efficiency refers to the technical productivity or economic performance of a process or an operation.[9] Key figures comparing outcome to effort or input, e.g. produced amount to used resources, or yield to cost are apt to describe efficiency.[10]

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[6] BURNSTEIN, Ilene, Tarantip SUWANASSART, and Robert. CARLSON. Developing a Testing Maturity Model for software test process evaluation and improvement. *Proceedings International Test Conference 1996. Test and Design Validity*, 1996, pp. 581-589.

[7] RANDERMANN, Marcel, Till BLÜHER, Roland JOCHEM, and Rainer STARK. Reifegradmodelle in der Produktentwicklung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, **114**(4). 2019, pp. 184-186, p184.

[8] NIKOLAENKO, Valentin and Anatoly SIDOROV. Assessment of Project Management Maturity Models Strengths and Weaknesses. *Journal of Risk and Financial Management*, **16**(2). 2023, pp. 1-19, p2.

[9] LASSLOP, Ingo. *Effektivität und Effizienz von Marketing-Events : wirkungstheoretische Analyse und empirische Befunde.* Wiesbaden: Gabler, 2003, p9.

[10] BENKENSTEIN, Martin. Die Gestaltung der Fertigungstiefe als wettbewerbsstrategisches Entscheidungsproblem: eine Analyse aus transaktions- und produktionskostentheoretischer Sicht. *Schmalenbachs Zeitschrift für betriebswirtschaftliche Forschung*, **46**(6). 1994, p486.

Starting with these key definitions, in the course of the thesis a profound structural equation model will be derived. Based on the corresponding theories and extensive literature research an initial model is formed and refined with expert's input, transferred to empirical research and finally results and recommendations are derived.

Research Aim

With the topicality stated, this dissertation intends to derive a model to close this research gap and to connect the effect of digital technology application in the product development process with the efficiency of product development.

The research aim is to develop a structural equation model, based on dependent and independent variables to connect digital process maturity with efficiency with empirical research and then derive results, conclusions, and concrete actions for management. With this model the aim is to find out the relationship between digital process maturity and efficiency in product development. Therefor the following, concrete tasks where conducted, aligned with the corresponding chapters.

Tasks

- To study the core concepts and theories of the work model. They are referred to organizational and technical systems theory, maturity modeling and efficiency concepts in product development. The result is a conceptual work model.
- To conduct a systematic review of previous empirical studies on the impact of digital process maturity on efficiency in engineering. The conceptual model is verified and detailed by earlier empirical results.
- To develop the empirical research design for a study in the German mechanical engineering sector. Concretization of the general model developed in the review section based on practitioners' studies in mechanical engineering sector. A mixed method approach combining interviews and a quantitative survey has to be planned. The interview-based pre study has to be evaluated to adjust the work model.
- To implement and evaluate the quantitative study and testing of the hypotheses using statistic methodology. The work model then is reliability tested and refined.
- To conclude and summarize the results, classify the study in the context of earlier research and derive concrete suggestions for engineering and management practice.

Main Research Question

Is a high maturity in the digital product development process increasing the efficiency of product development?

Research Object

German and Austrian companies in field of mechanical engineering.

Research Subject

Product development process efficiency and the dependence on digitalization.

Hypothesis

Increased maturity in the digital product development process increases the efficiency of product development.

The impact of the progress of the digital development process on the efficiency of product development has been the subject of a series of empirical studies. For the German machinery industry however, no comparable analysis is available. This study is based on a systematic review of previous empirical research and applies retrieved categories and assumption for an own empirical analysis in the German mechanical engineering sector. It explores the influence of digital process maturity on the efficiency of the product development based on the categories of maturity measurement and efficiency assessment retrieved from previous comparable empirical analyses. Effect size and particularly the way this efficiency effect is achieved are evaluated. Conclusions on relevance and success factors of process digitalization in the product development process in the German mechanical engineering industry are drawn.

Theses for defense

1. Businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models.
2. Digital process maturity significantly enhances technical efficiency.
3. Digital process maturity significantly enhances financial efficiency.
4. Technical efficiency increases financial efficiency.

Research Methods

1. <u>Theoretical studies</u> of previous research are conducted and scientific publications are analyzed regarding the subject and the object of the research.

2. Secondary data were analyzed in respect to the impact of digital process maturity on efficiency in engineering, to determine how digital process maturity and efficiency is defined and connected, as well as frequency of use.
3. Qualitative data: experts were asked on the application of process maturity models in their company and mediators of their application. They are asked to assess the level of their company's digital maturity and its impact on product development efficiency.
4. Primary research has been conducted by using a quantitative method incorporating exogenous variables regarding the subject and endogenous variables regarding the object of the study. Empirical data has been collected through a survey.

- Finally, findings from theoretical part, the secondary data research as well as from both empirical researches have been triangulated in order to formulate holistic conclusions and suggestions, answering the underlying research question

The empirical section of the study works on these research gaps and assesses the impact of digital process maturity on the efficiency of product development in the German mechanical engineering industry. The empirical study combines a qualitative and a quantitative part in the form of a mixed methods approach. The qualitative section validates and possibly extends the research model. It comprises 4 semi-structured interviews with executives for digital engineering in different small and medium-sized Germany-based mechanical engineering companies. These are surveyed on the application of process maturity models in their company and mediators of their application. They are asked to assess the level of their company's digital maturity and its impact on product development efficiency. Paths of efficiency development and moderating factors to the relationship are explored. The interviews are evaluated comparatively using Mayring's method of content analysis.[11] Based on the retrieved insights the maturity model specialized for the German mechanical engineering sector is accomplished and the categories of the work model are adjusted and detailed for the second quantitative research step.

A quantitative survey in the German automotive sector is cast to examine the statistical reliability of the model based on a larger dataset. The survey addresses medium-sized

[11] MAYRING, Philipp, and Eva BRUNNER. Qualitative Inhaltsanalyse. In: Renate Buber and Hartmut H. Holzmüller, eds. *Qualitative Marktforschung.* Wiesbaden: Gabler, 2009, pp. 669-680.

mechanical engineering businesses and assesses the causal impact of digital process maturity on product development performance. Mediators and moderators are retrieved from review and interview pretest. They are equally tested for significance. The analysis is based on statistical hypotheses, derived from the review and resulting work model, which are tested by means of a regression model or if the final data set is large enough (n =140), structural equation modeling. The quantitative model explains the relative importance of digital process maturity and other determinants on product development efficiency in German mechanical engineering.

Preliminary research model and key questions

All evaluated studies agree that digital process maturity contributes to enhance efficiency factors and particularly the efficiency of product development. Several moderators can take effect on this relationship and equally mediators, influencing the degree of digital process maturity are of interest. To assess this potential relationship for German mechanical engineering, an adequate maturity model for this industry has to be developed. Apt measures of product development performance have to be considered and all relevant moderators and mediators to this key relationship have to be included in the analysis. Four central research questions summarize these requirements for the empirical section:

1. How can a digital process maturity model for mechanical engineering be designed?
2. Which mediators determine digital process maturity?
3. How can product development efficiency in German mechanical engineering be measured comprehensively?
4. Which moderators take influence on the relationship of digital process maturity and product development efficiency in German mechanical engineering?

Novelty

Mechanical engineering in Germany and Austria is a classic and historically rooted domain, and it makes a significant contribution to the gross national product of both countries. Despite these historical roots, the demand for innovation is still very high, especially in this specific industry. As a result, new products, optimizations or improvements to existing machines must be implemented in ever shorter periods of time. It is obvious that shorter product development cycles can be achieved through a high degree of digitization.

There are three components that must be scientifically combined with one another: Assessment of the degree of digitization, the degree of digitization itself and the efficiency of product development. There is scientific work to be done in all mentioned sub-areas, but the linking and investigation of the impact using a structured model with empirical data as a basis is novel and the main part of this work.

The novelty can be defined as follows:

Scientific:

1. This thesis has developed a structural equation model for the first time, connecting digital process maturity with efficiency in product development.
2. It is novel on the systematic identification regarding relevant mediators of digital process maturity and moderators of the core relationship.
3. This thesis has shown an empirical impact of digitalization on product development in German and Austrian mechanical engineering for the first time.

Practical:

4. This thesis gives guideline for future corporate success within product development.

Executives need arguments, especially about the costs that a high degree of digitization in product development causes, consider license costs or infrastructure costs and the like. The results of this work and the insights gained from it can provide such arguments and serve as a starting point for improvement. Therefore, it is considered a novelty.

Business practice benefits from a comprehensive model specified for mechanical engineering. It advises how to effectively design digital processes in order to maximize product development efficiency. Factors moderating the impact of process digitalization are systematized which enables business to track so far unexplained problems in digitalization processes and optimize their design.

Limitations and further research requirements

Previous research in the effect of digital process maturity on performance refers to a broad range of categories, maturity models and moderators/mediators. It is however little homogenous concerning the applied categories, and the research outcomes are only partly comparable for that reason. The evaluated business processes differ in reach and partly refer to internal processes, partly include the supply chain and partly extend to the customer level. Few studies refer to digital process maturity.

Performance measures are chosen with regard to the research field and equally differ widely. While some studies focus on the shareholder perspective (costs, timing and profitability), others are interested in the technical results and knowledge development. Finally, previous studies are incomprehensive as to the moderating and mediating factors.

No study focusing on digital engineering processes and particularly, no publication in the mechanical engineering business is available.

The empirical survey was conducted in the German and Austrian mechanical engineering sector. These companies have a strong focus on product development. However, it can be assumed that the results obtained could be transferable to other economic sectors where product development is carried out, under critical consideration.

Approbation of research results

The main parts of the thesis were developed in a dialogue with the scientific community. The results and the process of the research were presented in nine international scientific conferences. The results have been reported in six publications.

<u>Author's presentations in scientific conferences</u>

1. Schüssler, F. (2020), *How a positive organizational climate contributes to increased product innovation.* International Academic Institute, Education and Social Sciences Business and Economics Conference, virtual, April 2020
2. Schüssler, F. (2020), *Digital process maturity and the impact on efficiency in product development - a finding from specialists.* International Academic Institute, Education and Social Sciences Business and Economics Conference, virtual, June 2020
3. Schüssler, F. (2020), *Design oriented simulation.* Siemens Digital Industries, Conference on Vehicle Development, virtual, July 2020
4. Schüssler, F., Strummer, M. (2020), *Effiziente und strukturierte Bewertung von allgemeinen Gewindeverbindungen mittels FEM auf Basis des örtlichen Konzepts*. NAFEMS20 DACH Conference, virtual, October 13th 2020
5. Mantler, J., Schüssler, F., Trenker, M. (2020), *Numerical and experimental evaluation.* NAFEMS20 UK Conference, virtual, November 9th 2020
6. Niederauer, E., Schüssler, F. (2020), *Simulation and test, synergies in product development.* PLM Benutzergruppe, CAE Fall Conference, virtual, November 2020

7. Schüssler, F. (2021), *Specialist opinions on digital process maturity and the effects on efficiency of product development*. University of Latvia, 79th International Scientific Conference, virtual, January 28th 2021
8. Schüssler, F. (2022), *The effect of digital process maturity on efficiency in product development – a review based structural equation model.* International Academic Institute, Rome Academic Conference, Rome, March 30th 2022

Publications

1. Schüssler, F. "How a positive organizational climate contributes to increased product innovation". *IAI April 2020 conference proceedings*, 2020, p. 34; ISSN2671-3179
2. Schüssler, F. "Digital process maturity and the impact on efficiency in product development - a finding from specialists". *IAI June 2020 conference proceedings*, 2020, p. 41; ISBN 978-608-4881-11-7
3. Schüssler, F., Strummer, M. "Effiziente und strukturierte Bewertung von allgemeinen Gewindeverbindungen mittels FEM auf Basis des örtlichen Konzepts". *NAFEMS Online Magazin*, Nr. 4/20, 56. Ausgabe, 2020 p. 45-53; ISSN2311-522X
4. Mantler, J., Schüssler, F., Trenker, M. "Numerical and experimental evaluation". *NAFEMS UK Conference Proceedings*, 2020, p. 60-66
5. Schüssler, F. "The effect of digital process maturity on efficiency in product development – a review based structural equation model". *IAI Rome conference proceedings*, 2022

1. THEORIES AND CORE CONCEPTS

Chapter 1 develops the theories and core concepts of the research and the basic model. It starts from an analysis of basic models to assess the impact of a technological device or strategy on business performance and refers to organizational systems theory, the knowledge-based view of the firm, the dynamic capabilities approach and the agile development framework.

The remaining sections of chapter 1 are involved with strategies to measure and assess the value-creation advancement in the value-added cycle. Section 1.2 introduces to maturity modeling, to assess value creation excellence and 1.3 discusses performance and efficiency measures to assess value outputs which are the constituents of the theoretically founded work model.

1.1 Modelling the entrepreneurial value creation cycle

Organizations are social and technical systems designed to generate economic value. Resources are compiled to products which meet market requirements i.e. customer needs and contain a higher economic value than the separate unprocessed input factors. The economic value generated in the process of business operation off costs of operation and taxes corresponds to the financial surplus (shareholder value) of the business owners (shareholders). The perspective of realizing a financial benefit drives people to establish and run businesses in spite of risks and necessary efforts.[12]

The black box of value generation by processing the input resources to superior output goods and services deserves more detailed consideration:

- Organizational systems theory sees businesses as social entities of people who are working together and create added value by cooperation.[13]

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[12] FJELDSTAD, Øystein D. and Charles C. SNOW. Business models and organization design. *Long Range Planning*, **51**(1). 2018, pp. 32-39, p33-37.

[13] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p37-38.

- The knowledge-based view of the firm trace value creation back to the utilization and production of knowledge resources. [14]
- The dynamic capabilities framework applies this understanding to software and other immaterial engineering processes and explains the creation of added value due to the frictionless integration of mental and knowledge resources in a well-defined interaction process of the members of the organization. [15]
- The agile development framework demands the flexible and gradual adaptation of technological developments to end-user requirements and dynamic market conditions.[16]

These four perspectives on entrepreneurial value creation are detailed to generate a first work model plot:

Organizational Systems Theory

Organizational systems theory sees organizations above all as social entities in which two or more people work together to better serve a particular purpose. A social entity can be, for example, a company, a university, or a hospital. Cooperation is advantageous because it allows for specialization. Various activities of the participants influence the result. Coordination is needed to align these activities with regard to a joint organizational goal. [17] The product development and production process in particular requires enormous technical and organizational skills. The embedding of such processes in an organizational framework is effective.

According to Scott[18] there are three different perspectives on organizations: Organizations can be understood as rational, natural, and open systems. The term of "perspective" in this

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[14] GRANT, Robert M. Reflections on knowledge-based approaches to the organization of production. *Journal of Management & Governance*, **17**(3). 2013, pp. 541-558.

[15] FERREIRA, Jorge, Arnaldo COELHO, and Luiz MOUTINHO. Dynamic capabilities, creativity and innovation capability and their impact on competitive advantage and firm performance: The moderating role of entrepreneurial orientation. *Technovation*, **92-93.** 2020, p2-4.

[16] BLOMKVIST, Stefan. Towards a Model for Bridging Agile Development and User-Centered Design. In: Ahmed Seffah, Jan Gulliksen, and Michel C. Desmarais, eds. *Human-Centered Software Engineering — Integrating Usability in the Software Development Lifecycle.* Dordrecht: Springer Netherlands, 2005, pp. 219-244., p219-220.

[17] BAMBERG, Günter, Adolf Gerhard COENENBERG, and Michael KRAPP. *Betriebswirtschaftliche Entscheidungslehre.* 16., überarbeitete Auflage. München: Verlag Franz Vahlen, 2019, p15-22.

[18] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p37-41.

sense must be chosen with caution, since a uniform model cannot be used, but different approaches are pursued that have a strong similarity. Perspectives are essentially different schools of thought which classify historical systems and individual circumstances in their historical significance.

Rational Systems

The rational systems perspective describes organizational behavior as purposeful and coordinated. For example, according to Scott, characteristic terms are information, efficiency, and optimization. Equally, contrary concepts such as authority, control, coordination, rules, and guidelines define this system. Accordingly, there are cognitive and motivational restrictions of action for participants within the organizations. These clearly specified limitations are the main reason for stakeholders to act rationally. Goal definition and formalization are the most important properties that define a rational system.[19]

Goals are conceptions of desired states that should occur. Criteria to evaluate different alternatives to achieve this specific objective must be defined. Economists and decision theorists translate these into an order of preference and utility functions that represent the value of alternative consequences. This so-called preference order is required for rational decisions. Clearly defined, specific goals not only provide evaluation criteria but also define the organization's appearance, the tasks to be performed, the number and qualifications of the required participants, and the required resources. If targets are blurred, it is difficult to form a corresponding structure. The most accurate writing in which certain goals support rational behavior in organizations is by Simon and Barnard, whose ideas provide one of the most important contributions to the rational system perspective.[20] Modern organizational theory is gradually supplanting bureaucratic organizations. Nevertheless, we maintain the perspective that classical and neo-classical theories continue to hold significance and cannot be entirely discarded, as they still offer highly pertinent solutions to specific challenges.[21]

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[19] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p46-47.

[20] SIMON, Herbert A. *Administrative Behavior, 4th Edition.* 4th ed. New York: Free Press, 1997.

[21] OYIBO, Constance and Justin GABRIEL. Evolution of Organization Theory: A Snapshot. *International Journal of Innovation and Economic Development*, **9**(9). 2020, pp. 221-227, p226.

According to Scott,[22] system theorists recognize the importance of formalized structures. Formalization abstracts but is sufficiently precise and complete to provide directions for action. In this regard, Stinchcombe[23] specifies that valuable instructions should be transparent, transferable to the user and include an improvement path that allows temporal corrections. Formalization enables participants and observers to document and design social structures and work processes. In result, participants can exchange views, change responsibilities, or redesign the flow of materials and information. Organizational structure is essential to improve performance.

Natural Systems

The natural systems perspective extends the rational approach. According to Scott,[24] natural system theorists recognize the attributes of rational system theory, target specificity and formalization, but add elements common to any social group. Analysts of natural systems pay great attention to complex behavioral structures and the normative aspects of systems theory and see discrepancies between the declared official and actual, operational goals in organizations. Stakeholders usually pursue side objectives at odds with official organizational objectives. Organizations are more than instruments to achieve these goals, but social groups that seek to adapt and survive under particular circumstances.

Formal structures serving the achievement of goals are strongly influenced, supplemented or eroded by the formation of informal structures in natural systems. According to natural system perspective, organizations comprise formal and informal structures. Individual activities and attitudes define task behavior and are empirically relevant for understanding organizational behavior. Individual participation can lead to organizational malfunctions, which implies that people “matter”, i.e. have to be involved and cared for.

[22] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p47-49.

[23] STINCHCOMBE, Arthur L. Bureaucratic and craft administration of production: A comparative study. *The Sociology of Economic Life:* Routledge, 2018, pp. 326-339., p327-329.

[24] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p38-39.

Open Systems

Open Systems theory was initiated during the intellectual change after World War II.[25] New fields of operations research were then established, which produced a new perspective on organizations.

Ludwig von Bertalanffy[26], initiator of open systems theory, worried about the separation of sciences: “The physicist, the biologist, the psychologist and the social scientist are, so to speak, encapsulated in a private universe, and it is difficult to get word from one cocoon to another and searched for a universal systems theory.”

Bertalanffy aimed to replace a mechanistic worldview with one that views the world as a "great organization." Mulej et al.[27] extend the discussion by arguing that General Systems Theory (GST) should be applied beyond specialized disciplines and take into account a holistic world view. They criticize the prevailing reductionism in scientific thinking and advocate for a "requisite holism," introducing seven groups of "system thinking principles" that include interdependence, complexity, and emergence among others. Their emphasis is on the necessity of a holistic approach to prevent major issues, advocating for both formal and informal systems of thinking. In summary, while Bertalanffy's GST is foundational, there's an ongoing debate on its definition and scope, as well as its philosophical underpinnings. Additionally, there's a call for a more holistic approach in applying GST across various disciplines.[28]

Summative systems model of organizations

Summarizing the above points, organizations can be understood as rational and natural systems to some extent. They are arrangements of structures and processes, but equally are defined by the interaction of the people involved in this framework and value creation process. Open systems theory includes organic and organizational factors and considers the

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[25] SCOTT, W. Richard and Gerald Fredrick DAVIS. *Organizations and organizing. Rational, natural and open systems perspectives.* New York, London: Routledge, 2016, p91.

[26] BERTALANFFY, Ludwig von. *General system theorie. Foundations, development, applications.* Rev. edition 17th pbk. printing. New York, N.Y: Braziller, 2009, p3.

[27] MULEJ, Matjaz, Vojko POTOCAN, Zdenka ZENKO, Stefan KAJZER, Dusko URSIC, Jozica KNEZ-RIEDL, Monty LYNN, and Jozef OVSENIK. How to restore Bertalanffian systems thinking. *Kybernetes*, **33**(1). 2004, pp. 48-61.

[28] DRACK, Manfred and Gregor SCHWARZ. Recent developments in general system theory. *Systems Research and Behavioral Science*, **27**(6). 2010, pp. 601-610.

interaction processes which in the case of business organizations create value for their customers and shareholders. These considerations define a first input-out model of business organizations' value creation process:

Businesses use material and immaterial input factors to more value using organizational structures and processes as well as human resources. The output represents a market value above the value of input factors and the sale of outputs in the market generates higher financial value for business shareholders. From an open systems perspective, businesses are value-creating entities:

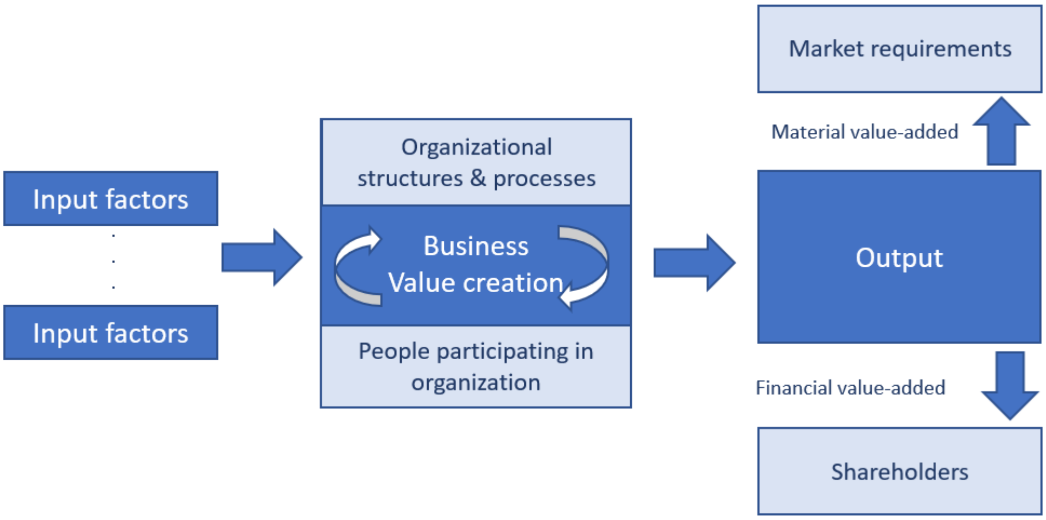

Figure 1.1: **Open systems model of value creation in business organizations**

Own representation.

The center of Figure 1.1 parallels a black magic box in which people and organizational structures and processes come together to generate the decisive additional value resulting in an output of superior financial and market value, which justifies the existence of any business. Several theories have attempted to unbox this process and understand how entrepreneurial value creation in fact takes place:

1.1.1 Knowledge-based view of the firms

The resource and knowledge-based view of the firm analyze the process of value generation symbolized by the white curved arrows in Figure 1.1.

Resource-based view

The resource-based view of the firm is a management theory established by Penrose in 1959. It sets off from the observation that businesses perform differently in the market although they operate under similar conditions and basically can use the same input factors, use the same output channels, and serve similar customers. Obviously, the way in which businesses operate with available input factors due to the resources they dispose of within their organizational black box makes the difference. Penrose[29] explains that companies are not just "administrative units" combining the inputs in a standardized way. Successful companies understand to integrate the input factors in an effective way, which results a marketable output and produces financial additional value to the shareholders. According to Penrose, people involved in the organization define effectiveness and efficiency of the value-creation process by engagement and proactivity. People codetermine organizational structures and processes, which makes human resources the key to excellence and this is still valid.[30]

Businesses differentiate from others due the unique, effective, and efficient combination of input factors. Previous literature differs on extent to which the available input factors, e.g. raw materials are seen as entrepreneurial resources themselves or to which generally available resources are transformed into unique resources by utilization and processing in the businesses' value creation process. Resources are essential to business excellence if they are unique, are used in a unique way by combining them with others in the value-creation process or, if the way the business uses them is unique.[31] Penrose repeatedly points out the relevance of human resources and the integration of human resources to produce competitive and innovative products in an efficient way. Human resources are of particular value, since every human being is unique and the combination of diverse human competencies and can produce unique outputs which enable businesses to differentiate form competitors in the market. [32]

Knowledge-based view

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[29] PENROSE, Edith. *The theory of the growth of the firm.* 4th edition, reprinted. Oxford: Oxford University Press, 2013, p9-27.

[30] KOR, Yasemin Y., Joseph T. MAHONEY, Enno SIEMSEN, and Danchi TAN. Penrose's The Theory of the Growth of the Firm: An Exemplar of Engaged Scholarship. *Production and Operations Management,* **25**(10). 2016, pp. 1727-1744.

[31] MARTELO LANDROGUEZ, Silvia, Carmen BARROSO CASTRO, and Gabriel CEPEDA-CARRIÓN. Creating dynamic capabilities to increase customer value. *Management Decision*, **49**(7). 2011, pp. 1141-1159, p1143-1145.

[32] PENROSE, Edith. *The theory of the growth of the firm.* 4th edition, reprinted. Oxford: Oxford University Press, 2013, p118-120.

The knowledge-based view of the firm builds on Penrose's resource-based concept. Human uniqueness broadly crystallizes in knowledge and experiences. The knowledge-based view has emerged as an accomplishment of the resource-based view in the 1990ies and knowledge as the key entrepreneurial resource has been explored empirically throughout the first two decades of the 2000s.[33]

Knowledge disposes of particular characteristics which makes it one of the most powerful entrepreneurial resources:[34]

- Knowledge cannot be imitated easily and has the potential to unfold economies of scale.[35]
- Knowledge is flexible, can be used in several contexts and for the development and production of several goods or services. Knowledge thus has the potential to unfold economies of scope.[36]
- Knowledge can be proliferated, shared, and augmented by teamwork. Businesses can use knowledge resources to develop form within and multiply their knowledge by sharing it among their staff.[37]
- Finally, knowledge does not loose in value or disappears when used, but rather augments, develops and grows. Businesses knowing to retain competent employees and to document and archive their knowledge enjoy the potential to use and build up knowledge continuously.[38]

According to the knowledge-based view, businesses achieve competitive advantages in markets due to unique combinations of knowledge resources and their effective and

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[33] KAUR, Vaneet. *Knowledge-Based Dynamic Capabilities. The Road Ahead in Gaining Organizational Competitiveness.* 1st ed. 2019. Cham: Springer International Publishing; Imprint: Springer, 2019. Innovation, Technology, and Knowledge Management, p29.

[34] BARNEY, Jay B. Resource-based theories of competitive advantage: A ten-year retrospective on the resource-based view. *Journal of Management*, **27**(6). 2001, pp. 643-650, p643.

[35] GRANT, Robert M. Reflections on knowledge-based approaches to the organization of production. *Journal of Management & Governance*, **17**(3). 2013, pp. 541-558, p542.

[36] SARJANA, Sri. Dynamic capabilities in manufacturing. *Journal of Entrepreneurship, Business and Economics*, **3**(2). 2015, pp. 41-64, p45.

[37] TSANG, Eric W. K. Choice of international technology transfer mode: A resource-based view. *MIR: Management International Review.* 1997, pp. 151-168, p152.

[38] HOLSAPPLE, Clyde W. and Kshiti D. JOSHI. Organizational knowledge resources. *Decision support systems*, **31**(1). 2001, pp. 39-54, p40-42.

efficient implementation in marketable products, which again is a matter of knowledge utilization. Knowledge building and sharing could thus result the magic formula driving the value-added cycle symbolized by the white curved arrows in the model sketched in Figure 1.1.

1.1.2 Dynamic capabilities

The dynamic capabilities perspective is closely intertwined with the knowledge-based view in literature.[39] In the understanding of the underlying cognitive theory of the firm, businesses' main function is the alignment of entrepreneurial insights and development with the requirements of the market in order to bring technologies to consumers and to the market.[40]

Dynamic capabilities represent the entrepreneurial competence to flexibly apply resources and above all knowledge in the right place and right time to develop in line with market demands and changing environments.[41] Dynamic capabilities are the competence to integrate adequate external and internal resources to optimal output configurations.[42]

Dynamic capabilities theory has gained in importance for knowledge management with the access of digital technologies to businesses' value-added cycle. New IT resources have to be matched with human knowledge resources so that output, i.e. customer market value and financial probability are maximized. IT resource management has become an essential element of corporate strategy planning.[43] Dynamic capabilities theory integrates the knowledge-based perspective and strategic enterprise planning to a comprehensive model:

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[39] SARJANA, Sri. Dynamic capabilities in manufacturing. *Journal of Entrepreneurship, Business and Economics*, **3**(2). 2015, pp. 41-64, p45.

[40] NOOTEBOOM, Bart. *A cognitive theory of the firm. Learning, governance and dynamic capabilities.* Cheltenham, Northampton, Mass: Edward Elgar, 2009, p1.

[41] AUGIER, Mie and David J. TEECE. Dynamic capabilities and multinational enterprise: Penrosean insights and omissions. *Management International Review*, **47**(2). 2007, pp. 175-192, p175.

[42] HELFAT, Constance E. and Margaret A. PETERAF. Understanding dynamic capabilities: progress along a developmental path. *Strategic Organization*, **7**(1). 2009, pp. 91-102, p92.

[43] WHEELER, Bradley C. NEBIC: A dynamic capabilities theory for assessing net-enablement. *Information systems research*, **13**(2). 2002, pp. 125-146, p125.

accordingly, the match of technological knowledge management and its application in a dynamic market environment intertwine to make businesses successful.[44]

According to Teece – one of the founders of dynamic capability theory –in a technology dominated environment, dynamic capabilities determine to what extent businesses excel in international growth, product identity and market entry timing.[45] The dynamic capabilities framework sees the key competency of the firm in the linking of entrepreneurial capabilities and technological advancements.[46]

Including entrepreneurial strategy, the dynamic capabilities add an essential factor to the process of knowledge management, which drives the black box of entrepreneurial value creation in the open systems model of the firm sketched in Figure 1.1.

1.1.3 Agile development

The "agile development model" accomplishes the dynamic capability approach by another building block: the management of uncertainty by flexibility concerning the organization of knowledge resources.[47] Uncertainty, i.e. the ignorance of potential future states of environment and their occurrence probability, is a common phenomenon in innovation processes, i.e. in all processes that involve the development of new knowledge resources.[48] Although the "dynamic capabilities concept" and – in essence equally the "knowledge-based view" -implicitly entail the existence of uncertainty, neither theory explicitly addresses this issue. The Agile Development Framework closes this void:

Agile development methods originate in software industry and frequently have substituted so called "waterfall" methods. While for waterfall methods the development process is planned in advance and one development step follows the other strictly observing this scheme, agile development establishes a more tentative trial and error planning cycle based

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[44] JONES, Geoffrey and R. Daniel WADHWANI. Entrepreneurial theory and the history of globalization. *Business History Conference. Business and economic history on-line: Papers presented at the BHC annual meeting*, (5). 2007, p7.

[45] TEECE, David. A dynamic capabilities-based entrepreneurial theory of the multinational enterprise. *Journal of international business studies*, **45.** 2014, pp. 8-37, p9-10.

[46] ARAMAND, Majid and Dave VALLIERE. Dynamic capabilities in entrepreneurial firms: A case study approach. *Journal of International Entrepreneurship,* **10.** 2012, pp. 142-157, p142.

[47] TEECE, David, Margaret PETERAF, and Sohvi LEIH. Dynamic capabilities and organizational agility: Risk, uncertainty and strategy in the innovation economy. *California management review*, **58**(4). 2016, pp. 13-35, p13.

[48] TVERSKY, Amos and Craig R. FOX. Weighing risk and uncertainty. *Psychological review*, **102**(2). 1995, pp. 269-283, p270.

on user stories- i.e. the requirements of the market.[49] Incremental development steps are done in close cooperation with end users and tested repeatedly in order to gradually approximate customer needs. This process is more flexible and safer than a hierarchically prescheduled comprehensive development. It allows to continuously adapt to changing user requirements.[50] Agile planning has proven successful in many knowledge-oriented business domains beyond IT development.[51] Customers' early and continuous involvement in new product and services design enhances end-user acceptance and the adaptation of end products to changing environment conditions.[52]

Empirical studies show that in an environment dominated by major technological advancements, operational agility has gained in importance to adapt businesses technology orientation and strategic planning to continuously changing technological requirements. According to a survey among involved businesses, the use of the internet of things and dynamic data information processing, for instance, require operational agility at an internal and external level.[53] In dynamic environments agile project portfolio management reduces the impact of growing uncertainty on business strategy planning among Canadian companies.[54] This reduction of uncertainty is a great benefit.

1.1.4 A summative model of value-creation excellence

Integrating the three perspectives sketched in sections 1.1.1 to 1.1.3 a comprehensive model of business value creation processes emerges.

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[49] BLOMKVIST, Stefan. Towards a Model for Bridging Agile Development and User-Centered Design. In: Ahmed Seffah, Jan Gulliksen, and Michel C. Desmarais, eds. *Human-Centered Software Engineering — Integrating Usability in the Software Development Lifecycle.* Dordrecht: Springer Netherlands, 2005, pp. 219-244., p219-220.

[50] HUO, Ming, Jane. VERNER, Liming ZHU, and Muhammad Ali BABAR. Software quality and agile methods. *Proceedings of the 28th Annual International Computer Software and Applications Conference, 2004. COMPSAC 2004,* 2004,pp. 520-525.

[51] RIGBY, Darell K., Jeff SUTHERLAND, and Hirotaka TAKEUCHI. The secret history of agile innovation. *Harvard Business Review*, **4.** 2016.

[52] ABRAHAMSSON, Pekka, Kieran CONBOY, and Xiaofeng WANG. Lots done, more to do': the current state of agile systems development research. *European Journal of Information Systems*, **18**(4). 2009, pp. 281-284.

[53] AKHTAR, Pervaiz, Zaheer KHAN, Shlomo TARBA, and Uchitha JAYAWICKRAMA. The Internet of Things, dynamic data and information processing capabilities, and operational agility. *Technological Forecasting and Social Change*, **136.** 2018, pp. 307-316, p308.

[54] PETIT, Yvan. Project portfolios in dynamic environments: Organizing for uncertainty. *International Journal of Project Management*, **30**(5). 2012, pp. 539-553, p539.

According to the knowledge-based perspective, value creation implies the integration of knowledge resources and the synthesis of new knowledge which drives the value-creation process. This process is based on the integration of human and technological resources.

According to the "dynamic capabilities framework", knowledge resources become marketable products due to entrepreneurial engagement and foresight, which implements knowledge into products fitting with market requirements.

According to the agile development framework, the management of uncertainty is essential in an increasingly dynamic environment. The marketability of knowledge and entrepreneurial resources is improved by early integration of customers in entrepreneurial development processes and incremental development steps.

Integrating these three perspectives and new inside view on the black box of business value creation results:

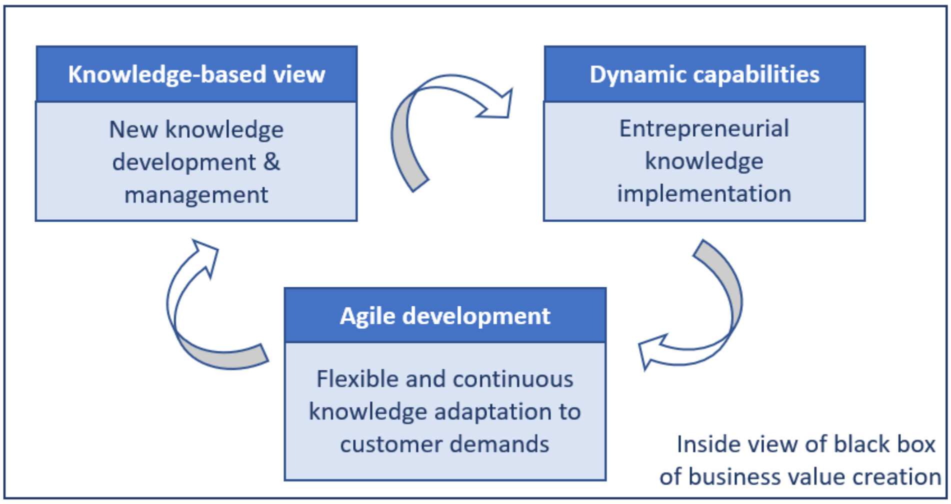

Figure 1.2: **Inside view of black box of business value creation excellence**

Own representation

Value creation excellence unfolds in the development of new knowledge resources by integrating manpower and technology, the implementation of products based on entrepreneurial proactivity and the continuous adaptation of development cycles to market requirements. The remaining sections of chapter 1 are involved with strategies to measure and assess the stage of value-creation advancement in the value-added cycle sketched in

Figure 1.2. Section 1.2, identifies and classifies maturity models as adequate tools to assess value creation excellence. Section 1.3 develops methods of output value assessment referring to theories of performance and efficiency measurement.

1.2 Maturity modeling

Maturity models measure value creation excellence. The following paragraphs discuss history and basic concept of maturity modeling, compare maturity models applied in engineering practice and provide a comprehensive overview on the diverse concepts to later extract an own comprehensive maturity model in the empirical section of the study.

1.2.1 Origins and concept of maturity modeling in quality management

Term of maturity modeling

Maturity generally is classified as a "state of completeness, perfection or readiness".[55] Maturity is addressed in several reference systems:

- Process maturity means that a process works well and fulfills the functions it is designed for.[56]
- Object maturity refers to a technically perfect consumer product or software, which usually meets all quality requirements.[57]
- People capability can be understood as maturity, when employees manage their jobs and are knowledgeable and experienced.[58]

Maturity can refer to organizational, human and technical systems or all three system types accordingly: In the perspective of the knowledge-based view (compare section 1.1.1) maturity refers to the integration and comprehensive availability of businesses knowledge

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[55] METTLER, Tobias. Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, **3**(1-2). 2011, pp. 81-98, p83.

[56] BURNSTEIN, Ilene, Tarantip SUWANASSART, and Robert. CARLSON. Developing a Testing Maturity Model for software test process evaluation and improvement. *Proceedings International Test Conference 1996. Test and Design Validity,* 1996, pp. 581-589.

[57] METTLER, Tobias. Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, **3**(1-2). 2011, pp. 81-98, p81.

[58] CURTIS, Bill, William E. HEFLEY, and Sally MILLER. *People capability maturity model:* Carnegie Mellon University, Software Engineering Institute, 1995, p25.

resources.[59] The dynamic capabilities framework in mind, maturity refers to the integration of knowledge and entrepreneurial competencies in a corporation.[60] Maturity analysis is common practice to evaluate and practise agility in IT-related developments.[61]

Maturity models are instruments designed to measure and assess objects based on an ordinary scale of degrees of maturity. Maturity models "help an individual or entity to reach a more sophisticated maturity level (i.e., ability) in people/culture, processes/structures and/or objects/technologies following a step-by-step continuous improvement process."[62] The maturity scale usually describes a desired progress in maturity concerning the object.[63] The term of maturity management, however, is more comprehensive and refers to the degree to which a project is continuously developed, supervised, improved, revised, and amended.[64]

Quality management and continuous improvement processes

Maturity model application ideally establishes a continuous improvement process: Present status are measured and based on this stage new progressive targets concerning the performance of the target object are defined. After a consecutive development cycle goal achievement is measured based on the maturity scale and new adapted development objectives are defined.[65] The resulting continuous improvement cycle corresponds to concepts applied in quality management, probably since the first maturity models originated there (see consecutive paragraphs).[66]

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[59] KHATIBIAN, Neda, Tahmoores HASAN GHOLOI POUR, and Hasan ABEDI JAFARI. Measurement of knowledge management maturity level within organizations. *Business strategy series*, **11**(1). 2010, pp. 54-70.

[60] COSIC, Ranko, Graeme SHANKS, and Sean MAYNARD. Towards a business analytics capability maturity model. *23rd Australasian Conference on Information Systems Proceedings.* 2012, (14)., p1.

[61] COHAN, Sean and Hillel GLAZER. An agile development team's quest for CMMI® maturity level 5. *2009 Agile Conference.* 2009, pp. 201-206.

[62] METTLER, Tobias. Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, **3**(1-2). 2011, pp. 81-98.

[63] RANDERMANN, Marcel, Till BLÜHER, Roland JOCHEM, and Rainer STARK. Reifegradmodelle in der Produktentwicklung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, **114**(4). 2019, pp. 184-186, p184.

[64] DOOLEY, Kevin, Anand SUBRA, and John ANDERSON. Maturity and its impact on new product development project performance. *Research in Engineering Design*, **13**(1). 2001, pp. 23-29, p23.

[65] KERZNER, Harold R. *Strategic Planning for Project Management Using a Project Management Maturity Model.* Hoboken: Wiley, 2002, p110.

[66] CHEN, Chung-Yang and Jung-Chieh LEE. Comparative effects of knowledge-based antecedents in different realms of CMMI-based software process improvement success. *Computer Standards & Interfaces*, **81.** 2022, pp. 1-14.

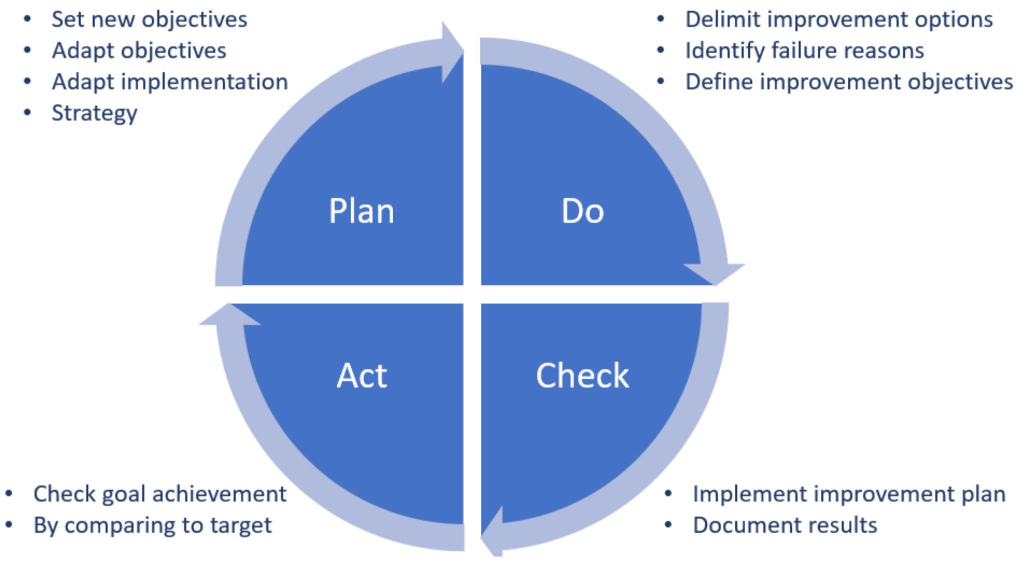

Figure 1.3: **PDCA Cycle of quality management as foundation to maturity modeling**

own representation adapted from Ahrens[67]

Continuous improvement processes have been modeled graphically in various forms. The Plan-Do-Check-Act (PDCA) Cycle is among the most general and most established cycle models in industrial engineering.[68]

- The planning stage involves the delimitation of improvement potentials, the identification of failure causes, the definition of an improvement goal, and the planning of the implementation of the improvement.
- At the stage of "doing" improvement steps are implemented and results are documented and visualized.
- At the checking stage, the achieved level of problem solution and improvement is examined by comparing realized improvements to the initially set targets.
- At the acting stage new improvements are made in order to better achieve the target or the target is adjusted to available options. If the initial target has been achieved new

[67] AHRENS, Volker. *Interpretation des PDCA-Zyklus nach DIN EN ISO 9001: 2015 als Meta-Vorgehensmodell.* Elmshorn: Nordakademie, Hochschule der Wirtschaft, 2016.

[68] AHRENS, Volker. *Interpretation des PDCA-Zyklus nach DIN EN ISO 9001: 2015 als Meta-Vorgehensmodell.* Elmshorn: Nordakademie, Hochschule der Wirtschaft, 2016, p5-11.

improvement objectives are defined and the PDCA cycle closes up into a new optimization round.[69]

Quality management models of the PDCA type have been adapted from Japanese engineering practice in the 1970ies and 80ies. They are based on the understanding that manufacturing efficiency increases when processes are continuously monitored and controlled by all participants in the value-creation chain, not just planned by top management. The implementation of quality consciousness at all levels of the company contributes to increased resource efficiency, smoother workflows and higher employee engagement.[70]

QMMG – a first quality centered maturity model

Maturity models originate in quality management. They are based on the understanding that businesses can self-reliantly assess their quality status without the help of consultants by applying easy-to use tools.[71] Maturity models provide a roadmap for improvement.

The earliest type of maturity model was devised for quality management and referred to as QMMG (Quality Management Maturity Grid). It was suggested by P.B. Crosby[72] in 1979 and is in operation until today for quality management issues.[73] It is briefly presented here as a representative concept providing an initiation understanding of the technical functioning Maturity Models.

The QMMG, alike later maturity models, uses a questionnaire type form to assess maturity in several dimensions. The items are checked on a Likert-scale describing maturity per item in the form of not achieved, partly achieved, fully achieved….[74]

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[69] URBAN, Frank K. and Anett BRAUNE. PDCA als Methode der qualitäts-und zielorientierten Fabrikplanung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, **104**(1-2). 2009, pp. 60-63, p60-63.

[70] MURRAY, Peter and Ross CHAPMAN. From continuous improvement to organisational learning: developmental theory. *The learning organization*, **10**(5). 2003, pp. 272-282, p274.

[71] ALBLIWI, Saja Ahmed, Antony JIJU, and Norin ARSHED. Critical literature review on maturity models for business process excellence. *2014 IEEE International Conference on Industrial Engineering and Engineering Management*, 2014, pp. 79-83.

[72] CROSBY, Philip B. *Quality is free. The art of making quality certain*. New York: McGraw-Hill Book, 1979.

[73] GIOVANNI, Pietro de and Georges ZACCOUR. A survey of dynamic models of product quality. *European Journal of Operational Research*, **307**(3). 2023, pp. 991-1007.

[74] FRASER, Peter, James MOULTRIE, and Mike GREGORY. The use of maturity models/grids as a tool in assessing product development capability. *IEEE International Engineering Management Conference*, 2002, 244-249., p244.

The QMMG differentiates 5 stages of maturity as follows:

Table 1.1: **Measurement concept of the QMMG Model**

Stage	Term	Description
1	Uncertainty	"We don't know why we have problems with quality"
2	Awakening	"Is it absolutely necessary to always have problems with quality?"
3	Enlightenment	"Through management commitment and quality improvement we are identifying and resolving our problems"
4	Wisdom	"Defect prevention is a routine part of our operation"
5	Certainty	"We know why we do not have problems with quality"

Adapted from Fraser[75]

These maturity stages are assessed in six measurement categories, which are management understanding and attitude, quality organization status, problem handling, cost of quality as % of sales, quality improvement actions, summation of company quality posture. The QMMG is thus a grid-based approach comprising two assessment axes in the form of a matrix.[76] It focusses on quality and is little flexible for other domains of analysis.

A range of maturity models for different applications has been added to the repertory since. Maturity models have been proposed for a series of applications among them quality management, software development, supply chain management, innovation and product development and design.[77]

Quality Management Models today- represented by EFQM

The QMMG framework has been fundamental to the development of comprehensive quality management tools which are frequently applied in today's business practice and are counted

[75] FRASER, Peter, James MOULTRIE, and Mike GREGORY. The use of maturity models/grids as a tool in assessing product development capability. *IEEE International Engineering Management Conference*, 2002,pp. 244-249.

[76] MAIER, Anja M., James MOULTRIE, and P. John CLARKSON. Assessing organizational capabilities: reviewing and guiding the development of maturity grids. *IEEE transactions on engineering management*, **59**(1). 2011, pp. 138-159, p140.

[77] FRASER, Peter, James MOULTRIE, and Mike GREGORY. The use of maturity models/grids as a tool in assessing product development capability. *IEEE International Engineering Management Conference*, 2002, 244-249., p244.

among maturity models by Hausner[78] and Bensiek.[79] The best-known quality management models are TQM (Total Quality management), EFQM (European Foundation for Quality Management) and ISO 9001. All three standards are based on the understanding that quality does not only concerns the final output or product but concretizes at all levels of the value-added chain, i.e. is above all process quality. The definition of quality in the quality guideline of DIN ISO 9000 is representative for this understanding:

> "Quality is the capacity of the complete feature set of a product system or process to conform to the demands of clients and other parties involved."

This inclusive understanding of quality is exemplified by the EFQM model here: The EFQM was developed in 1988 by the European Foundation for Quality Management based on the approaches of DIN ISO 9001 and the TQM model and is intended to serve the continuous evaluation and improvement of quality management in institutions.[80] Optimal results are achieved when employees at all levels are integrated into a holistic improvement process. It is important to bring shareholders, employees, customers and external partners together to pursue one common goal.[81] The management is challenged to develop a vision that serves as motivation and inspiration for all parties involved. Creativity and new ideas should be promoted and introduced at all company levels.[82]

The performance appraisal system of EFQM sees the company as a holistic system based on the interaction of the pillars, leadership, strategy, employees, partnerships/resources,

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78 HAUSNER, Marcus. *EFQM | Chancen und Grenzen des Einsatzes von Reifegrad-Modellen.* Heidelberg: Institut für Bildungswissenschaft, 2017., p1.

79 BENSIEK, Tobias. *Systematik zur reifegradbasierten Leistungsbewertung und-steigerung von Geschäftsprozessen im Mittelstand:* Universität Paderborn Heinz Nixdorf Inst, 2013, p44.

80 CALATRAVA MORENO, MARÍA DEL CARMEN. Towards a flexible assessment of higher education with 360-degree feedback. *2013 12th International Conference on Information Technology Based Higher Education and Training (ITHET),* 2013, pp. 1-7., p1.

81 SAIZARBITORIA IÑAKI, Heras, German ARANA LANDÍN, and Martí CASADESÚS FA. A Delphi study on motivation for ISO 9000 and EFQM. *International Journal of Quality & Reliability Management,* **23**(7). 2006, pp. 807-827, p807.

82 GÓMEZ, Joaquín Gómez, Micaela MARTINEZ COSTA, and Angel R. MARTINEZ LORENTE. EFQM Excellence Model and TQM: an empirical comparison. *Total Quality Management & Business Excellence,* **28**(1-2). 2017, pp. 88-103, p88.

processes, products and services. Each category contributes 10 % as enabler of quality. The remaining 50% of quality appraisal is based on results at the level of customers (15%), employees (10%), society (10%) and financial performance (15%). A well-known chart of the EFQM illustrates the interaction of the model building blocks (following page).

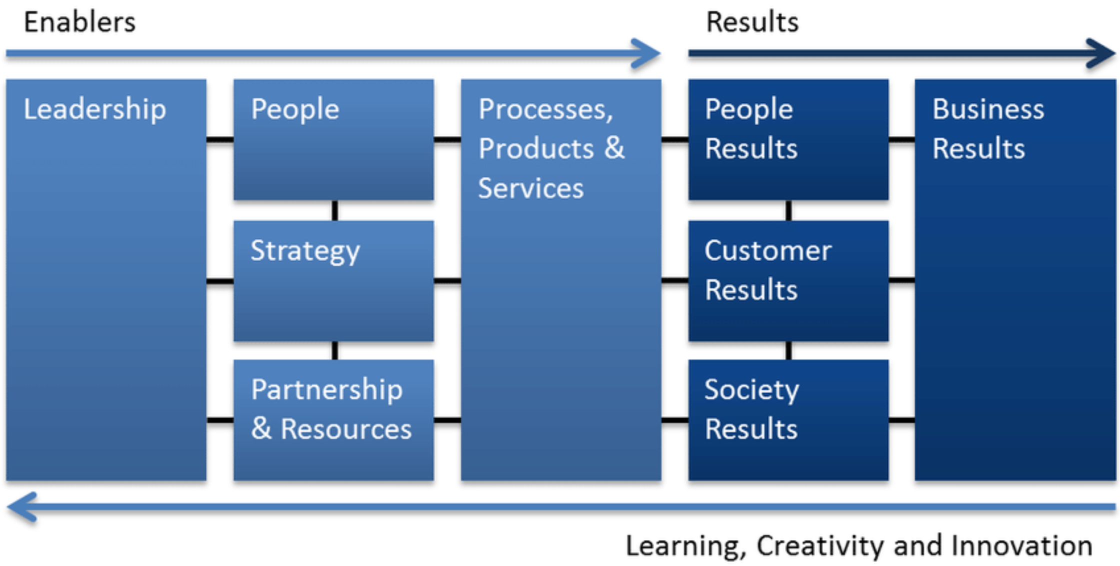

Figure 1.4: **EFQM Modell**

Source: Calatrava Moreno[83]

To assess process quality the EFQM model refers to value drivers which are optimized continuously in the PDCA Cycle. As part of their implementation, the strategic adequacy of the processes and their implementation is continuously questioned, and new objectives are gained due to the re-prioritization of value drivers. Performance contributions are allocated to small organizational units that further specify, analyze and improve these sub-processes. Financial and operational value drivers are relevant in that process: Financial value drivers correspond to the balance sheet values and the key figures. Operative value drivers are the technical fundamentals bringing forth these financial results and are located “upstream” These are for example, product quality, employee motivation, market conditions.

[83] CALATRAVA MORENO, MARÍA DEL CARMEN. Towards a flexible assessment of higher education with 360-degree feedback. *2013 12th International Conference on Information Technology Based Higher Education and Training (ITHET)*, 2013, pp. 1-7.

1.2.2 Maturity models for engineering

With focus on engineering the following modelling approaches can be described and some limitations are stated.

Delimitation of quality and maturity modeling

Quality management models have inspired maturity models for business and more specifically engineering applications.

Other than Hausner [84] and Bensiek[85], this study distinguishes maturity models from quality management models. Both models equal in their understanding that a continuous evolution cycle (PDCA) should be established to optimize corporate performance. They equally correspond with the definition of the weighted categories which contribute to performance. However, quality management models and maturity models differ in four fundamental points:

- Quality management models usually refer to the whole organization, and are little specified for particular departments or functions, while maturity models are flexible for adaptation to individual project or technology specific requirements.[86]
- Maturity models define and assess competencies (capabilities) rather than quality outputs. They focus on the process of value generation rather than the process of quality management.[87]
- While quality models design a continuous evolution process, maturity models determine levels of maturity measured on an ordinal scale progression from low to high in a linear way.[88]

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[84] HAUSNER, Marcus. *EFQM | Chancen und Grenzen des Einsatzes von Reifegrad-Modellen.* Heidelberg: Institut für Bildungswissenschaft, 2017, p1.

[85] BENSIEK, Tobias. *Systematik zur reifegradbasierten Leistungsbewertung und-steigerung von Geschäftsprozessen im Mittelstand:* Universität Paderborn Heinz Nixdorf Inst, 2013, p44.

[86] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017., p55-56.

[87] SCHMUTTE, Andre M., and Peter F.-J. NIERMANN. Der „Stresstest" für die Wettbewerbsfähigkeit: Systematische Potenzialanalyse mit Reifegradmodellen. *Managemententscheidungen:* Springer Gabler, Wiesbaden, 2017, pp. 57-72., p57.

[88] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017, p55-56.

- While today's quality models are structural in design, i.e. aim at analyzing the interaction processes among model elements, maturity models are hierarchical and designed to appraise systems.

The following sections introduce to and systematically compare maturity models which are common practice in software and mechanical engineering and innovation for later reference in the empirical section of this study. The model selection is based on a systematic review of previous empirical studies in engineering, citing or developing maturity models for the industry. The review includes the databases Scholar Google, ScienceDirect, Ebsco Host and WISO and relies on a uniform keyword combination, which is "maturity model AND engineering AND theory".[89] Regarding the technical focus, the type of systematic review can be confirmed and refined.[90]

The number of existing maturity models and their development is very dynamic; there is a plethora of different models that are modified based on specific industry requirements. For further consideration, the most common models in the field of mechanical engineering, developed until 2020, will be described.[91] Various maturity models outline the evolution of Business Process Management within organizations, ranging from initial, less developed practices to highly advanced and effective methods. These models have different focuses: some assess the current status of Business Process Management practices, others look at the state of processes, and some consider both aspects. Both basic and descriptive principles are adequately covered in these models.[92] Maier's[93] more comprehensive and compact overview on 25 different types of maturity models in several context provides additional orientation on available models.

CMMI (Capability Maturity Model Integration)

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[89] CLARKE, Mike. The QUORUM statement. *Lancet (London, England)*, **355**(9205). 2000, pp. 756-757.

[90] PHILLIPS, Margaret, Jason B. REED, Dave ZWICKY, and Amy S. VAN EPPS. A scoping review of engineering education systematic reviews. *Journal of Engineering Education.* 2023, pp. 1-20.

[91] TARHAN, Ayca, Oktay TURETKEN, and Hajo A. REIJERS. Business process maturity models: A systematic literature review. *Information and software technology*, **75.** 2016, pp. 122-134.

[92] FRYT, Maciej. Process Maturity Models – Applicability and Usability Review [online]. *World Scientific News.* 2016. Available from: http://www.worldscientificnews.com/wp-content/uploads/2019/04/WSN-129-2019-51-71.pdf.

[93] MAIER, Anja M., James MOULTRIE, and P. John CLARKSON. Assessing organizational capabilities: reviewing and guiding the development of maturity grids. *IEEE transactions on engineering management,* **59**(1). 2011, pp. 138-159 p141-143.

The CMMI is an early adaptation of the QMMG for Software engineering and originates in 1986. The CMMI was originally designed to assess the efficiency of software development processes and to improve them based on best practice standards. The model has increasingly been applied in other contexts, involving but not restricted to IT, e.g. systems engineering and integrated product development. In 2000, a comprehensive version of the CMMI model was published to enable its application across specific domains. The topical version 1.3 of CMMI comprises three modules- CMMI for development (CMMI-DEV), for acquisition and for services. For inhouse engineering mainly the development module is relevant: The CMMI-DEV is designed for performance assessment and improvement in organizations software and hardware engineering.[94] The CMMI is structured hierarchically in the form of a tree as follows:

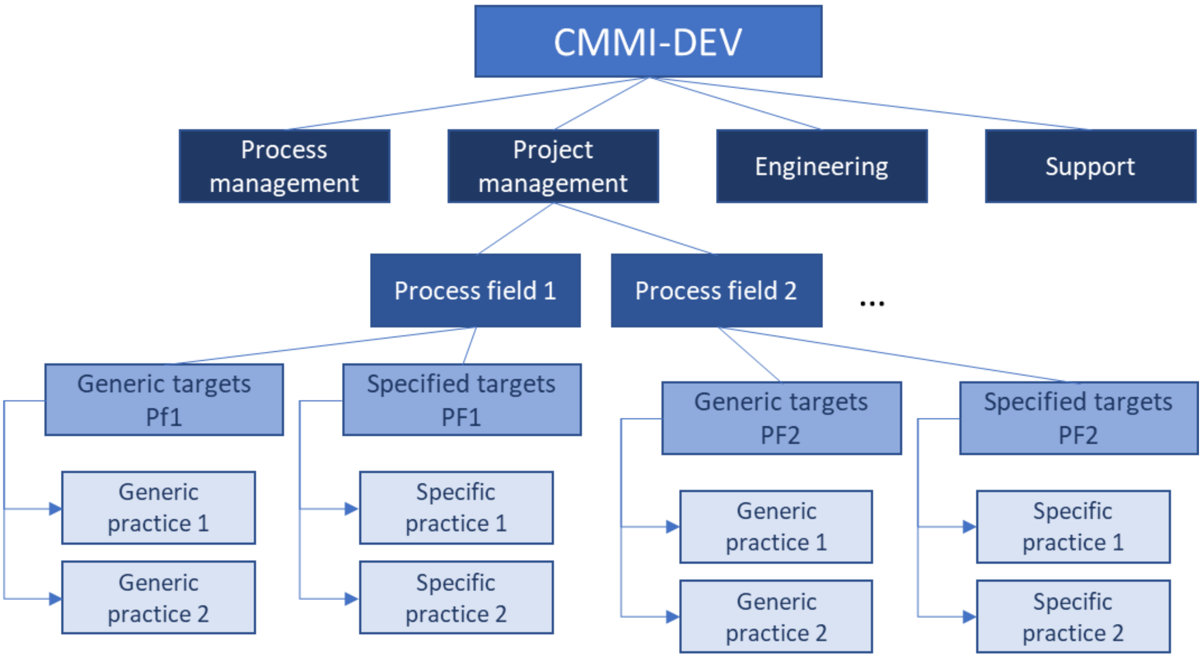

Figure 1.5: **Prototypical design of CMMI-DEV**

Own representation on Bensiek [95]

[94] TEAM, SCAMPI Upgrade. Appraisal Requirements for CMMI, Version 1.2 (ARC, V1. 2). *Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University.* 2011, p5-7.

[95] BENSIEK, Tobias. *Systematik zur reifegradbasierten Leistungsbewertung und-steigerung von Geschäftsprozessen im Mittelstand:* Universität Paderborn Heinz Nixdorf Inst, 2013.

CMMI-DEV addresses altogether 22 process levels which are classified in four categories: process management, project management, engineering, and support. Each process level is assigned targets. A target is checked as accomplished if the predefined practices are applied. Practices comprise specific and generic practices. Specific practices are used to attain specific targets, e.g. the implementation of cost estimates or the appraisal of particular products. Generic practices are directed to the accomplishment of generic targets, which are the definition, management, and implementation of the CMMI processes themselves. To assess project performance on that basis, capability or maturity levels are applied.[96]

Maturity levels describe the total maturity of the company as a whole on the stage initial (1), managed (2), defined (3), quantitatively managed (4) and optimized (5). Using capability levels each process field is classified based on four capability levels form 0 (no capability) to 3 (full capability). The "Software Engineering Institute", license owner of CMMI-DEV, provides a detailed description of the performance elements necessary to attain a certain capability or maturity level. Enterprises are free to determine own development targets, i.e. the desired maturity or capability levels.[97]

The CMMI contains a detailed evaluation software and topical documentation. Bensiek, however, criticizes the complexity and high effort to implement CMMI.[98]

PEMM (Process & Enterprise Maturity Model)

The Process and Enterprise Maturity Model is a simple and pragmatic maturity model, which was designed by Hammer & Company Consultants. Like the CMMI-DEV it is based on a hierarchy of assessment levels. Maturity analysis is done in two surveys which are filled in by the stakeholders during interviews, workshops or discussions. The results are used to sketch businesses level of maturity and outline fields of potential improvement.[99]

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[96] PINO, Francisco J., Maria Teresa BALDASSARRE, Mario PIATTINI, and Giuseppe VISAGGIO. Harmonizing maturity levels from CMMI-DEV and ISO/IEC 15504. *Journal of Software Maintenance and Evolution: Research and Practice*, **22**(4). 2010, pp. 279-296, p280.

[97] TEAM, SCAMPI Upgrade. Appraisal Requirements for CMMI, Version 1.2 (ARC, V1. 2). *Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University*. 2011, p5-7.

[98] BENSIEK, Tobias. *Systematik zur reifegradbasierten Leistungsbewertung und-steigerung von Geschäftsprozessen im Mittelstand:* Universität Paderborn Heinz Nixdorf Inst, 2013, p41.

[99] ROHLOFF, Michael. Case Study and Maturity Model for Business Process Management Implementation. In: Umeshwar Dayal, Johann Eder, Jana Koehler, and Hajo A. Reijers, eds. *Business Process Management.* Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 128-142., p128-129.

Generic and specific targets of the CMMI-DEV are classified as process determiners and business competencies here. The model differentiates five categories of process determiners, which are process design, employees, responsibility, infrastructure and key figures. Business competencies comprise leadership, business culture, experience and governance. Each research field comprises several subcategories for appraisal in the survey.

To assess performance in both fields several hierarchical levels in the corporation should be involved. The maturity levels reach from 0 = no process, random principle, to 4 = "processes are lived and continuously optimized at the internal level and in cooperation with suppliers" categories. Traffic-light color designs for each category visualize to what extent each category has achieved a satisfactory level. Category appraisals are weighted and added up to achieve a maturity assessment for the whole corporation.[100]

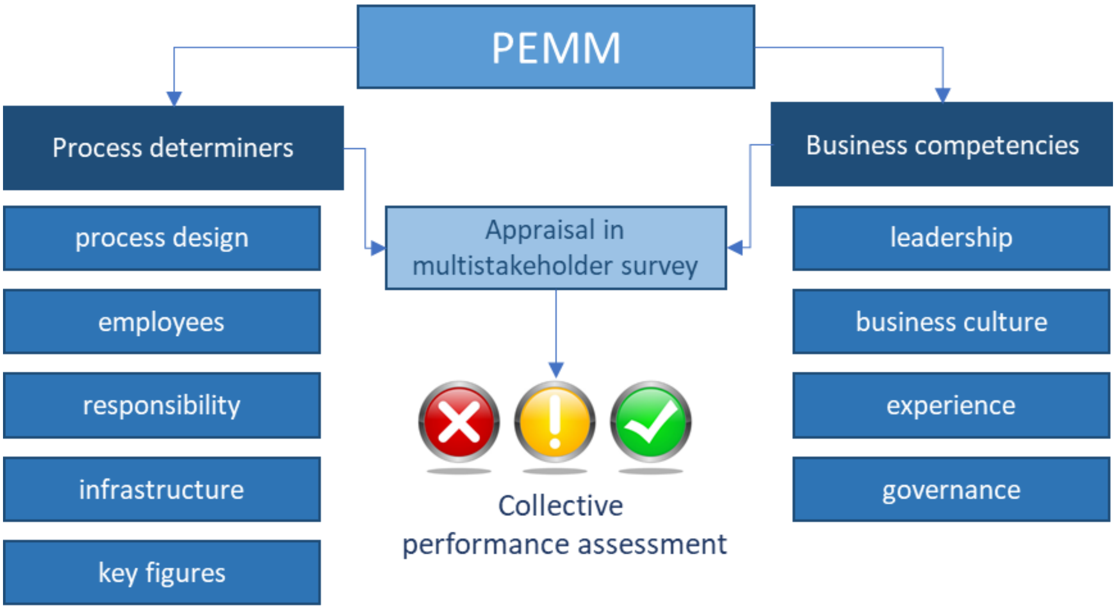

Figure 1.6: **PEMM maturity model – design**

Own representation on information retrieved from Hammer[101]

The model illustrates that malfunctions in any subunit of the firm impair the result for the total company. The PEMM is easy to apply and can be implemented by companies self-reliantly without the help of a consultants. However, PEMM is comparatively subjective.

[100] HAMMER, Michael. Der große Prozess-Check. *Harvard Business Manager*, **29**(5). 2007, pp. 34-52, p48-49.

[101] HAMMER, Michael. Der große Prozess-Check. *Harvard Business Manager*, **29**(5). 2007, pp. 34-52.

Classifications result from discussion rounds rather than from on detailed assessment standards. The PEMM appraisal corresponds to a comprehensive estimate of the status of the firm from the perspective of its stakeholders. Concrete technical capabilities of the firm are not explicitly included in the model.[102]

Maturity models for specific engineering applications

Based on the design of PEMM and CMMI several fully engineering specific maturity models have been suggested, particularly in the field of cyber-physical systems, i.e. systems that integrate physical processes and IT.[103] Already in the 1990ies, computer-integrated manufacturing systems have been assessed using specific maturity models.[104]

Pérez Hernández & Reiff-Marganiec suggest a CMMI model to classify the maturity of smart object. Their model differentiates five maturity levels to classify the performance of smart objects. These are essential =1, networked =2, enhanced = 3, aware, = 4, "Internet of Things" complete = 5.[105] Grades are assigned for core capabilities and extended capabilities. Core capabilities are necessary for digital objects and comprise digital identification, data retention, communication and energy harvesting. Extended (i.e. optional) capabilities are information processing, networking, sensing and actuating. Altogether 17 competencies of smart objects are identified and classified on the mentioned five-level scale.[106]

Geisberger & Broy classify maturity levels of cyber-physical systems based on five maturity stages which describe systems progress at the levels of openness, complexity and intelligence. The study differentiates five maturity levels, where level 1 describes systems integrating real and virtual world, level 2 refers to systems with flexible outward boundaries, level 3 are context-adaptive or partly autonomous systems. Level 4 comprise cooperative

[102] POWER, Brad. Michael Hammer's process and enterprise maturity model. *Business Process Trends.* 2007, pp. 1-4.

[103] LEE, Edward A. Cyber Physical Systems: Design Challenges. *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, 2008, pp. 363-369., p363.

[104] MEUDT, Tobias, Malte POHL, and Joachim METTERNICH. *Modelle und Strategien zur Einführung des Computer Integrated Manufacturing (CIM)-Ein Literaturüberblick:* Universitäts-und Landesbibliothek Darmstadt, 2017, p26.

[105] PÉREZ HERNÁNDEZ, Marco E., and Stephan REIFF-MARGANIEC. Classifying Smart Objects using capabilities. *2014 International Conference on Smart Computing*, 2014, pp. 309-316., p309.

[106] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017, p60.

systems with shared or changing control and level five refers to comprehensive man-machine interaction.[107]

5 C architectures have repeatedly been applied to describe the maturity of IT[108] and cyber-physical applications. 5-C Architecture is a maturity model comprising five stages, which are:

Table 1.2: **5 C Architecture Classification**

Stage	Term	Description
1	Smart Connection	System is Plug & Play, Sensor network, tether free communication.
2	Conversion	System processes data and aggregates information.
3	Cyber	System compares information in time e.g. clustering
4	Cognition	System analyses and visualizes information to describe its own state.
5	Configuration	System optimizes itself and adapts to changing environments

Own representation drawing on Klein[109]

Klein et al. (2019) assess the design and performance of digital twins on that basis. [110] Westermann evaluates a cyber-physical system for mechanical and plant engineering using a variation of the 5 C model.[111] Lee et al. refer to 5C for the appraisal of Industry 4.0 architectures.[112] This description can easily be used for maturity modeling.

[107] GEISBERGER, Eva and Manfred BROY. *agendaCPS: integrierte forschungsagenda cyber-physical systems.* 1st ed. Heidelberg: Springer-Verlag Berlin, 2012, p64-65.

[108] WENDELSTORF, Jens. Beiträge der Wissenschaft zur Industrie 4.0!? [online]. 2016. Available from: https://dokumente.ub.tu-clausthal.de/receive/clausthal_mods_00000334., p11.

[109] KLEIN, Matthias, Benjamin MASCHLER, Andreas ZELLER, Behrang ASHTARI, Nasser JAZDI, Michael WEYRICH, and Roland ROSEN. Architektur und Technologiekomponenten eines digitalen Zwillings. *Automation 2019:* VDI Verlag, 2019, pp. 89-102.

[110] KLEIN, Matthias, Benjamin MASCHLER, Andreas ZELLER, Behrang ASHTARI, Nasser JAZDI, Michael WEYRICH, and Roland ROSEN. Architektur und Technologiekomponenten eines digitalen Zwillings. *Automation 2019:* VDI Verlag, 2019, pp. 89-102.

[111] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017, p94-95.

[112] LEE, Jay, Behrad BAGHERI, and Hung-An KAO. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing letters*, **3.** 2015, pp. 18-23, p18.

1.2.3 Comparative overview on maturity models

Table 1.3 provides a comprehensive overview on the quality and maturity models presented in section 1.2. The overview is structured according to model type, classification levels, predominant application, advantages, and limitations.

Table 1.3: **Comparative overview on maturity models** (own representation following page)

Model type	**Quality maturity**	**Quality management**	**Capability Maturity Model – Development Integration**	**Process & Enterprise Maturity Model**	**Engineering specific maturity**
Exemplified by	**QMMG**	**EFQM**	**CMMI-DEV**	**PEMM**	**5C architecture**
Structure	hierarchical	object-oriented	hierarchical – object-oriented	hierarchical	hierarchical
Categories	• Organization status • Problem handling, • Cost of quality • Improvement actions	Enablers • Leadership • People • Strategy • Partnerships • Processes • Products/services • Results	Levels • Process management • Project management • Engineering • Support Generic/ specific targets Generic/ specific practices	Process determiners: • Process design, • Employees • Responsibility, infrastructure, • Key figures Business competencies • Leadership • Business culture • Experience • Governance	Process determiners • At technical level only • Specific
Maturity levels	(1) Uncertainty (2) Awakening (3) Enlightenment (4) Wisdom (5) Certainty		(1) Initial (2) Defined (3) Managed (4) Quant. Managed (5) Optimized	(0) No Process (1) Initially managed (2) Partly managed (3) Mainly managed (4) Fully managed	(0) Smart connection (1) Conversion (2) Cyber (3) Cognition (4) Configuration
Application	Quality assessment Whole business	Quality improvement Whole business	Performance and interaction analysis Whole business or projects	Business development and process analysis	Cyber-physical systems IT applications Computer integrated manufacturing
Advantages	Comprehensive general	Comprehensive quality improvement in PDCA cycle	Adequate for performance appraisal and process improvement	Easy to use	Technically concrete Easy to apply
Limitations	Abstract Little concrete	No concrete appraisal scheme	Complex difficult to evaluate	Little concrete from a technical perspective	No integration of whole business

The hierarchically structured QMMG model has been fundamental to quality management and later maturity models. While quality management models like the presented EFQM have adopted an object-oriented structure, a hierarchical structure dominates in the maturity models.

Obviously, the CMMI-DEV utilizes the most complex categorization grid and rates institutions and subordinate entities based on sets of targets and practices. The PEMM relies on a more compact institutional structure and on target ratings only. Both the CMMI-DEV and PEMM include the analysis of the management and engineering level. Engineering specific maturity models like the 5 C architecture refer to the technical engineering level only, which results a clearer and simplified rating system, which however focusses on select business fields or projects.

Maturity models have thus developed from the compact but rather abstract QMMG model towards technically refined solutions. Available models compromise between application width and technological refinement. Models with a technical focus have been drafted for IT applications and cyber physical systems mainly. So far, no maturity model specified in mechanical engineering is available which contextualizes engineering performance in the context of the whole business at the same time.

1.3 Efficiency and performance measurement

Efficiency versus effectiveness

The Cambridge dictionary defines efficiency as capability to "work in a quick and organized way" and distinguishes effectiveness as "the ability of producing the desired results, even if the way this is achieved is not efficient."[113] While effectiveness means doing the right things, efficiency is doing things right.

Laitinen et al. draft a four-sector matrix of low versus high efficiency and low versus high effectiveness, which makes this distinction clearer:[114] A generalized version is presented here:

[113] HEACOCK, Paul, ed. *Cambridge academic content dictionary.* 1st ed. New York: Cambridge University Press, 2009.

[114] LAITINEN, Ilpo, Tony KINDER, and Jari STENVALL. Local public service productivity and performance measurement. *International Journal of Knowledge-Based Development*, **9**(1). 2018, pp. 49-75, p51.

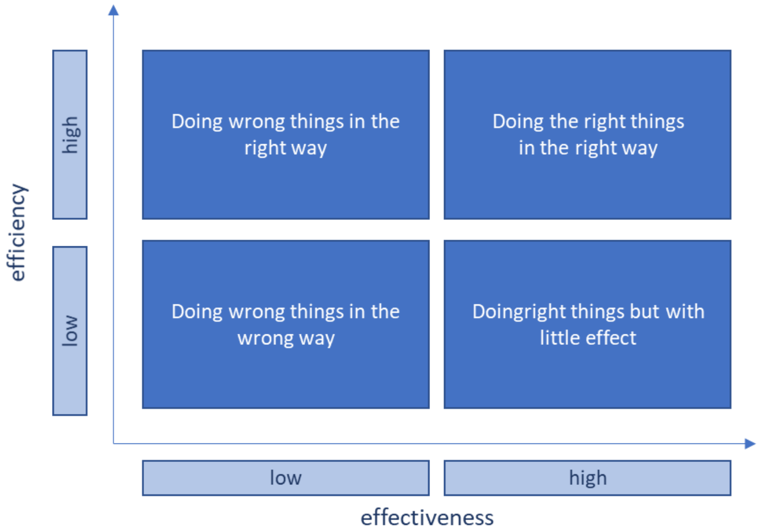

Figure 1.7: **Efficiency versus effectiveness**

own representation

Figure 1.7 illustrates that efficiency refers to the way things are done, while effectiveness refers to the things themselves. Given a right solution however, efficiency measures to what extent this solution is implemented correctly. To succeed, effectiveness and efficiency are inseparable.

In a management slogan low effectiveness and low efficiency combined mean the quick death of a system, while high effectiveness and efficiency result in optimal development of the system. Effectiveness alone enables survival. Efficiency alone means "slow death", since the solution is inadequate but implemented carefully.[115]

According to Aparicio's theoretical definition, efficiency involves a comparison of observed inputs (or resources) and outputs (or products) with what is optimal.

The efficiency construct offers itself to compare different levels of implementation of a proven solution in different systems and has found extensive application in engineering and economic studies. There is a technical as well as an economic meaning of efficiency.[116]

The following paragraphs provide an overview of efficiency measures and illustrate that the efficiency construct is closely related to performance.

[115] DRUCKER, Peter. *The effective executive:* Routledge, 2018, p1-5.

[116] APARICIO, Juan, Ca LOVELL, Jesus T. PASTOR, and Joe ZHU. *Advances in Efficiency and Productivity II*, 2020, p4.

Engineering efficiency and performance

In an engineering context efficiency, according to Usubamatov refers as the ability to accomplish a job with minimum expenditure of time and effort,[117] applications of the term efficiency in engineering however go beyond this energetic perspective:

In engineering efficiency finds different applications depending on the technological field in consideration: Howell refers to irrigation efficiency in the context of agricultural engineering to "characterize irrigation performance" concerning the uniformity of water application across the whole irrigated surface and the extent to which the crop reacts by growth to the irrigation.[118] Solar cell efficiency refers to the extent to which solar cells absorb the available light and transform it into electricity i.e. efficiency is the electric power output per time unit.[119] Energy efficiency in buildings refers to the extent to which buildings keep the heath inflowing from solar radiation or heating energy. The level of annual energy consumption is an inverse measure of energetic performance. Energy efficient buildings safe heat energy and thus show a high economic and ecological performance.[120]

This example illustrates that technical performance is inseparable from economic performance. Engineering attempts to design technical systems so that they run economically, (e.g. vehicles consuming little energy) or so that they deliver a maximum output at a certain energy input (e.g. vehicles with a maximum power output or speed).[121]

In software engineering the term efficiency can refer to a series of features: hard and software applications are partly assessed concerning their energy efficiency, i.e. the amount of energy consumed for certain functions, where low energy consumption is desirable.[122] However there are further perspectives: Software engineering project efficiency can be

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[117] USUBAMATOV, Ryspek. *Productivity theory for industrial engineering:* CRC Press, 2018, p3.

[118] HOWELL, Terry A. Irrigation efficiency. *Encyclopedia of water science*, **467.** 2003, p. 500.

[119] GREEN, Martin, Ewan DUNLOP, Jochen HOHL-EBINGER, Masahiro YOSHITA, Nikos KOPIDAKIS, and Xiaojing HAO. Solar cell efficiency tables (version 57). *Progress in photovoltaics: research and applications*, **29**(1). 2021, pp. 3-15.

[120] JANDA, Kathryn Bess. *Building change: Effects of professional culture and organizational context on energy efficiency adoption in buildings:* University of California, Berkeley, 1998, p1.

[121] GILBERT, Thomas F. *Human competence: Engineering worthy performance:* John Wiley & Sons, 2013, p13.

[122] JOHANN, Timo, Markus DICK, Stefan NAUMANN, and Eva KERN. How to measure energy-efficiency of software: Metrics and measurement results. *2012 First International Workshop on Green and Sustainable Software (GREENS),* 2012, pp. 51-54..

measured as the ratio of produced code amount and consumed time.[123] This measure does not consider quality, which is coded in further efficiency ratios: Fault removal efficiency refers to the ratio of discovered errors from total errors in a program.[124] Software-test efficiency refers to the time and effort of testing procedures until program release.[125]

These measures of efficiency in software engineering again illustrate the proximity of technical efficiency standards and economic efficiency: Time and quality improvements reduce development costs; energy efficiency reduces the cost of operation. Technical efficiency usually contributes to economic efficiency.

Economic efficiency and performance

Accordingly, efficiency refers to the effective operation as measured by a comparison of production with cost (as in energy, time, and money). According to the economic principle efficiency can be reached in two ways:

Either the output of a process is maximized by using a defined set of resources (profit maximization) or, the resource input required to attain a certain target is minimized (cost minimization).[126]

Efficiency according to the minimum principle means the minimization of waste, expense or effort in the production of a certain output.[127] To assess efficiency different measures are available depending on the perspective and value-creation stage. At the production level, economic efficiency is frequently calculated according to the minimum principle referring to the cost of production by unit, the costs per labor or machine hour or the costs of input resources per unit.[128] In brief, economic efficiency as measured by the minimum principle can be measured as a ratio of output versus input, which equals the productivity of the unit

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[123] CHINUBHAI, Aneesh. Efficiency in software development projects. *International Journal of Software Engineering and Its Applications*, **5**(4). 2011, pp. 171-180, p171.

[124] ZHANG, Xuemei, Xiaolin TENG, and Hoang PHAM. Considering fault removal efficiency in software reliability assessment. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, **33**(1). 2003, pp. 114-120, p114.

[125] HUANG, Chin-Yu and Michael R. LYU. Optimal release time for software systems considering cost, testing-effort, and test efficiency. *IEEE transactions on Reliability*, **54**(4). 2005, pp. 583-591, p583-585.

[126] USUBAMATOV, Ryspek. *Productivity theory for industrial engineering:* CRC Press, 2018, p2-5.

[127] WIREMAN, Terry. *Developing performance indicators for managing maintenance:* Industrial Press Inc, 2005., p140.

[128] SMITH, Malcolm. *Performance measurement and management. A Strategic Approach to Management Accounting:* Sage Publications Ltd., 2005, p226-227.

in consideration. Although related to monetary results the input factors are usually not monetary but technical, which again underlines the close interrelationship between technical and financial factors in efficiency assessment.[129]

The problem about measuring efficiency based on the minimum principle is that measured input factors do not directly influence the output or success of a company. Rather many factors at the input level interact and are interdependent.[130] Financial performance measures accomplish efficiency assessment at the level of the maximum principle, which intends to realize a maximum output at a given input. Major financial performance indicators are profits from total assets or from employed capital, return on equity or revenues from turnover. Businesses attempt to maximize these output related performance indicators to maximize cashflows to their owners, the shareholders.[131]

A comprehensive framework for efficiency assessment

Summarizing the results of section 1.3, efficiency describes the fulfillment of a defined objective in “the right way”. Performance measures are applied for efficiency assessment. Efficiency assessment is common in engineering and finance.

In both disciplines, efficiency is measured based on the minimum or maximum principle. Both are complementary. Businesses either attempt to minimize inputs to reach a certain output or to maximize outputs from a certain input. Input and output factors commonly used in engineering and finance differ but are interrelated. Technical efficiency increases financial efficiency.

In engineering, efficiency refers to the resource-input to product-output ratio of a technical system, which usually has got economic implications. In finance, efficiency refers to the relationship of costs and benefits, which usually are founded in production technology and processes.

These insights on efficiency assessment are condensed in a comprehensive model:

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[129] BEST, David, Julie MCLEOD, and Philip A. JONES. *Performance management for BS ISO 15489-1:* BSI British Standards Institution, 2002, p11.

[130] WIREMAN, Terry. *Developing performance indicators for managing maintenance:* Industrial Press Inc, 2005, p140.

[131] SICHIGEA, Dan Florentin, Mirela GANEA, and Lorena TUPANGIU. Financial Performance Indicators–Instruments in Lending Decision Making. *Finante-provocarile viitorului (Finance-Challenges of the Future)*, **1**(13). 2011, pp. 168-174, p172.

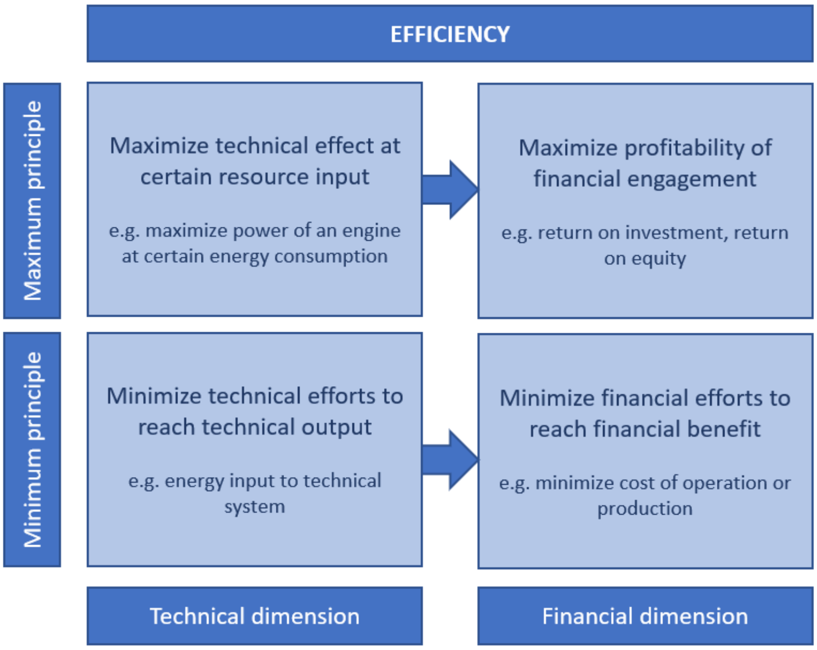

Figure 1.8: **Principles of efficiency**

own representation

Chapter 1 has thus introduced to process maturity and efficiency and has systematized measures of maturity and efficiency assessment. Based on a systematic review the following paragraphs will illustrate that process maturity, and particularly digital process maturity in development usually enhances technical and financial efficiency.

2. Review of previous empirical research on the impact of digital maturity on efficiency

Extensive empirical research on the effect of digital process maturity on efficiency has been done to assess how and to what extent development maturity improves the efficiency of products or whole businesses.

Review method and overview of empirical studies

To gain an overview on previous research on the effects of digital maturity on development efficiency and relevant characteristics of maturity and efficiency, a preliminary systematic review of empirical academic publications is conducted. The academic database Scopus (TU Wien) as well as further databases are consulted and recent peer-reviewed publications (published between 2001 and 2019) are extracted using the key word combinations: *("Information technology" OR "IT" OR "software") AND (maturity model OR "SPICE" OR "CMM" OR "CMMI-DEV") AND ("product development" OR "engineering") AND efficiency AND empirical*

The focus is on publications in engineering and production, but equally comparable other sectors. Apart from computer aided engineering related publications equally studies focusing on other innovative software technologies (e.g. industry 4.0, cloud computing, etc.) are considered. The retrieved studies are classified in a tabular overview using the categories publication year, authors, concerned IT technology, method of research, measures of digital process maturity, moderators of maturity impact and efficiency targets of maturity development to identify major structuring categories. Using the method suggested by Webster & Watson,[132] and in terms of engineering,[133] first an author-centric overview table is drafted, which classifies the above contents by the author. Condensing the columns "IT technology" and "efficiency effects", concept charts of relevant categories concerning input and output factors are drafted, which allow to quantify the relevant issues. 20 studies are found eligible for further evaluation according to these criteria and are displayed in Appendix A.

[132] WEBSTER, Jane, and Richard T. WATSON. Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly Vol 26.* 2002, xiii-xxiii.

[133] PHILLIPS, Margaret, Jason B. REED, Dave ZWICKY, and Amy S. VAN EPPS. A scoping review of engineering education systematic reviews. *Journal of Engineering Education.* 2023, pp. 1-20.

2.1 Quantitative overview on review results

All evaluated studies assess the effect of process maturity in digital technologies on performance factors, they differ concerning their context and assessed technologies, however. While some studies evaluate internal business processes and IT systems, others refer to the supply-chain. Some studies refer to non-commercial entities, e.g. university or government projects.

From 20 evaluated studies only three are qualitative, the rest is based on expert surveys or business data analysis and uses statistical methods e.g. regression or structural equation modeling.

Most of the studies refer to particular established process maturity models. Mainly CMMI is addressed repeatedly, in 10 studies altogether. Six studies compare several maturity models or generally refer to process or development maturity. Figure 2.1 illustrates the frequency distribution of applied maturity models.

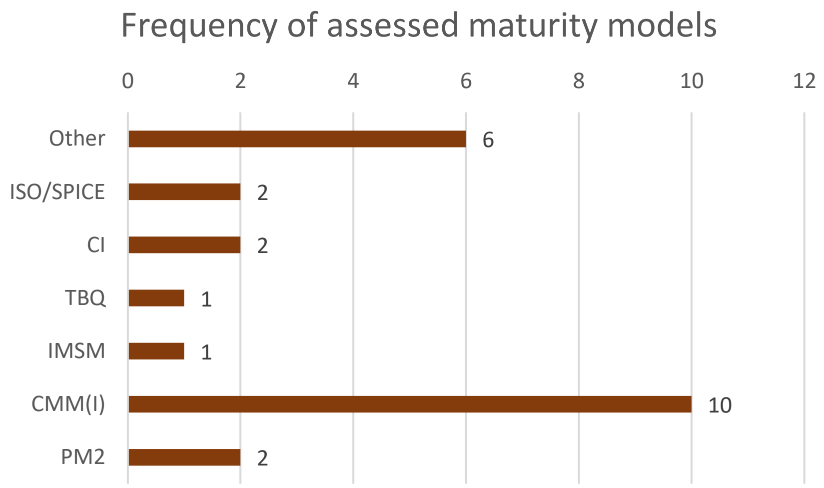

Figure 2.1: **Type of maturity models and their frequency used in earlier studies,** own representation on eligible studies, published between 2001 and 2019

The efficiency effects expected from and usually observed due to the evolution of digital process maturity comprise essentially six levels of efficiency in two contexts – financial and technical efficiency:

Technical efficiency concerns:

a) Knowledge/ knowledge transfer effects

b) Software/ product performance
c) Supply chain performance
d) Project process performance/project outcome

Financial efficiency concerns

e) Cost control
f) Time schedule performance
g) Project risk control
h) Economic business performance

Considering that some studies use several performance targets, the following frequency distribution of applied performance measures results for the review of the eligible 20 empirical studies:

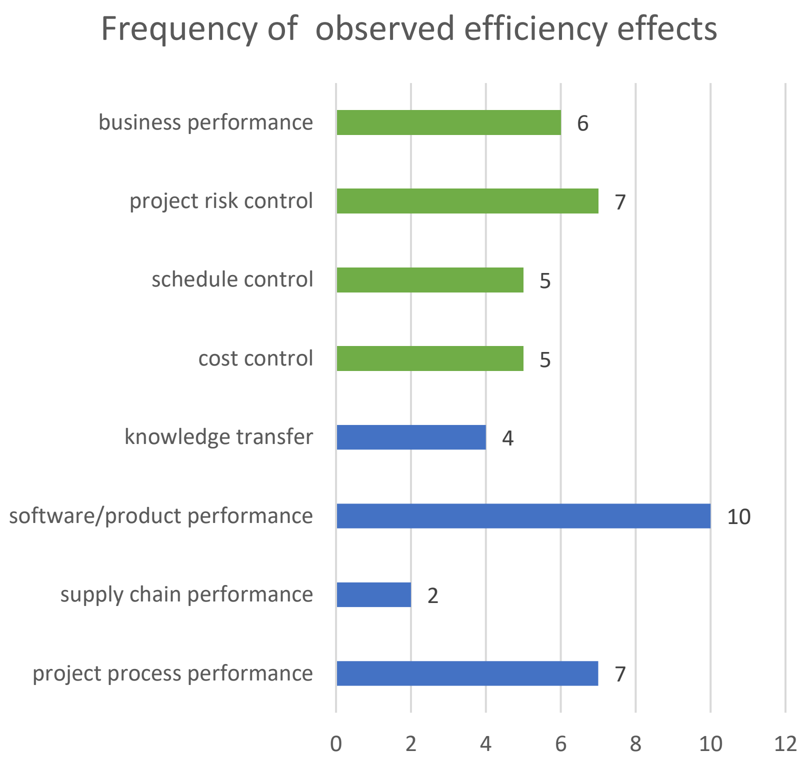

Figure 2.2: **Type and frequency of performance targets applied in earlier empirical studies**,

own representation on eligible studies, published between 2001 and 2019

Figure 2.2 illustrates that project and product performance are the most frequently evaluated performance targets in studies using digital process maturity models. Most studies (14 from 20) additionally include factors moderating the impact of digital process maturity on efficiency. The following list summarizes moderators found relevant to the impact of maturity modeling on business efficiency:

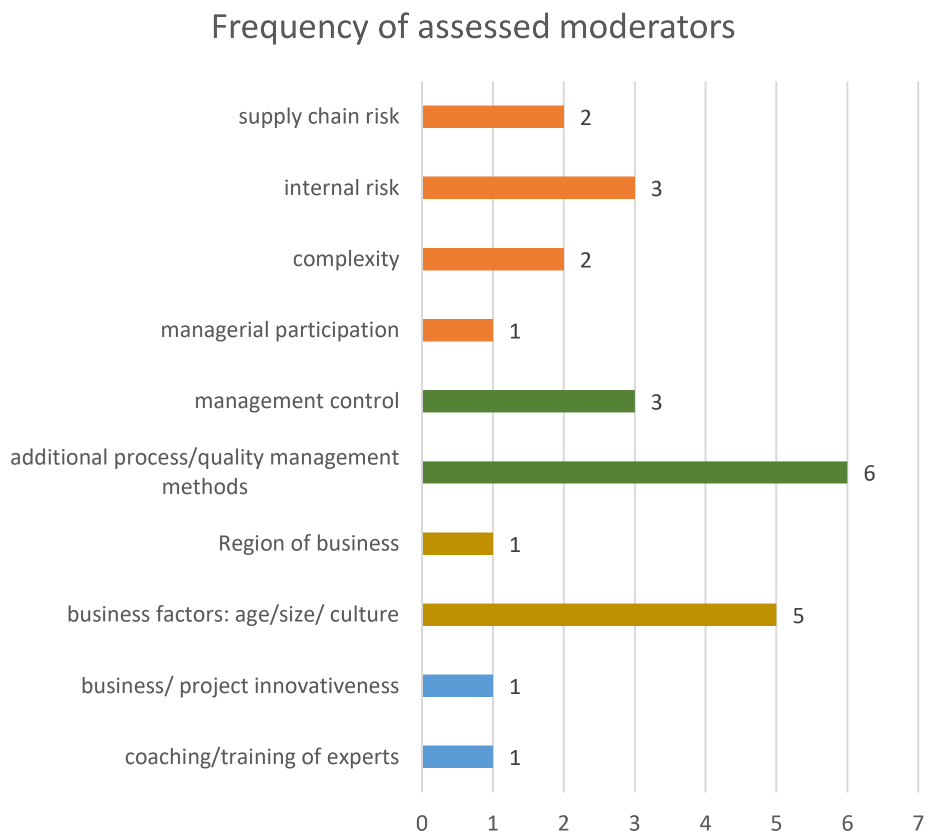

Figure 2.3: **Type and frequency of considered mediators in earlier empirical studies** own representation on eligible studies, published between 2001 and 2019

Moderators of the impact of maturity modeling on efficiency can be classified into 4 categories risk related moderators (orange), control related factors (green), business related factors (brown) and knowledge related factors (blue). Control and risk are most frequently addressed.

The following section 2.2 and 2.3 contain the textual evaluation of results following the above retrieved categories of analysis. Section 2.2 is classified by efficiency effects and section 2.3 explains retrieved moderators of efficiency.

2.2 Efficiency effects of digital process maturity

The efficiency effects retrieved in Figure 2.2 are classified according to the systematics derived in the theoretical section (Figure 1.8) into a technical and a financial dimension is achieved. The items retrieved in Figure 2.2 are assigned to the dimensions as follows:

Table 2.1: **Classification of review items into efficiency categories**

Technical efficiency	**Financial efficiency**
• Project process performance	• Schedule control
• Supply chain performance	• Cost control
• Software/ Product performance	• Project risk control
• Knowledge transfer	• Business performance

Project process performance

As Jiang et al find for the application of CMM among 154 international software developers, the application of maturity models and progress on the maturity scale has a positive effect on the performance and progress of software development projects.[134] Over time, the Capability Maturity Model (CMM) and Capability Maturity Model Integrated (CMMI) have emerged as the two most commonly applied maturity models in the software industry.[135]

Reliability assessment and tracking systems enhance businesses` capability to manage and plan complex development processes. Tiku et al. explore this effect in a case study in the electronics industry and find: Failure tracking routines gain in validity due to maturity model application, which enhances the reliability of development outcomes. The continuous evaluation of outcomes in the development process enhances process flows.[136]

The implementation of CMM models and their continued update to new standards has reduced the variability of productivity and has increased productivity in an Italian software company.[137] The same effect has been found for a sample of international software

[134] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

[135] DAHLIN, Gunnar. What can we learn from process maturity models – A literature review of models addressing process maturity. *International Journal of Process Management and Benchmarking*, **10**(4). 2020, pp. 495-519, p496.

[136] TIKU, Sanjay, Michael AZARIAN, and Michael PECHT. Using a reliability capability maturity model to benchmark electronics companies. *International Journal of Quality & Reliability Management*, **24**(5). 2007, pp. 547-563.

[137] BELLINI, Emilio and Corrado LO STORTO. The impact of software capability maturity model on knowledge management and organisational learning: empirical findings and useful insights. *International Journal of Information Systems and Change Management*, **1**(4). 2006, pp. 339-373.

development businesses. By enhancing software process maturity, the performance of software projects concerning processes and product output is improved.[138]

Software development process improvement projects in 722 small software companies which at the beginning of the study were mostly not certified, benefit most, when the implementation of agile development principles is followed by maturity models which control and monitor the efficiency of development outcomes.[139] With CI model implementation businesses' process performance improves towards increased relationship, speed, cost and organizational performance.[140]

Supply chain performance

In software supply chain management, the application of maturity models improves collaboration by reducing complexity and enhances the transparency of cooperation.[141] The quality of supply chain management depends on the extent to which processes are defined, managed, measured and controlled i.e. the extent to which maturity models are applied and continuously improved. Lockamy et al. point out that in software development the application of maturity models can significantly contribute to reduce development uncertainty. Supply chain performance is improved if maturity processes are applied consistently.[142] Companies dispensing with supply chain maturity models underperform concerning costs and cooperation in the value creation chain.[143] Similarly the CI maturity is found to enhance development processes in supply chains. Jorgensen et al. however explain

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[138] DI TULLIO, Dany and Bouchaib BAHLI. The impact of software process maturity and software development risk on the performance of software development projects. *ICIS 2006 Proceedings. 90.* 2006, p1482.

[139] RÖNKKÖ, Mikko, Juhana PELTONEN, and Christian FRÜHWIRTH. Examining the Effects of Agile Methods and Process Maturity on Software Product Development Performance. In: Björn Regnell, Inge van de Weerd, and Olga de Troyer, eds. *Software Business: Second International Conference, ICSOB 2011, Brussels, Belgium, June 8-10, 2011. Proceedings.* Berlin, Heidelberg: Scholars Portal, 2011, pp. 85-97.

[140] JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p331.

[141] TIKU, Sanjay, Michael AZARIAN, and Michael PECHT. Using a reliability capability maturity model to benchmark electronics companies. *International Journal of Quality & Reliability Management*, **24**(5). 2007, pp. 547-563.

[142] LOCKAMY III, Archie, Paul CHILDERHOUSE, Stephen M. DISNEY, Denis R. TOWILL, and Kevin MCCORMACK. The impact of process maturity and uncertainty on supply chain performance: an empirical study. *International Journal of Manufacturing Technology and Management*, **15**(1). 2008, pp. 12-27, p24.

[143] TARHAN, Ayca, Oktay TURETKEN, and Hajo A. REIJERS. Do mature business processes lead to improved performance? : a review of literature for empirical evidence. *Proceedings of the 23rd European Conference on Information Systems (ECIS 2015), 26-29 May 2015, Munster, Germany.* 2015, pp. 1-16, p5.

that improvement processes do not always evolve linearly.[144] Not all advances in maturity come down to strategic CI application, but partly companies equally evolve on a natural improvement path. With progression on the path to CI capability however, maturity model implementation is systematized and integrated into goal-oriented and strategic planning processes.[145]

Software/ Product performance

Software process improvement practices have been found to enhance software performance and customer satisfaction in a survey among 67 software developers in New England. Software process improvement enhances correctness and verifiability of software products, which enhances software reliability and testability above all. The majority of surveyed developers agree that software expandability and flexibility greatly contribute to customer quality perception.[146] Equally, Jiang et al.confirm that software performance is higher when maturity analyses are performed and high maturity levels are reached. New technologies are then managed more easily, tests are implemented more reliably, and errors are avoided.[147] Titov et al. emphasize the high impact of maturity model application on product quality in Russian engineering businesses. A survey finds that progression in maturity level reduces defects by manhour, which contributes to reduce costs for error correction and amendments.[148]

According to Ashrafi, the quality outcome of the application of maturity models depends on the chosen maturity modeling solution. Integrating ISO and CMM standards enhances the performance quality outcomes at the level of efficiency, integrity, reliability and testability as compared to the application of ISO or CMM alone. Equally, the quality of adaptation at the customer level enhances by the combined application of ISO and CMM,

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144 JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p328.

145 JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p330.

146 KUILBOER, Jean-Pierre and Noushin ASHRAFI. Software process and product improvement: an empirical assessment. *Information and software technology*, **42**(1). 2000, pp. 27-34, p31-32.

147 JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

148 TITOV, Sergei, Gregory BUBNOV, Maria GUSEVA, Alexei LYALIN, and Irina BRIKOSHINA. Capability maturity models in engineering companies: case study analysis. *ITM Web of Conferences*, **6.** 2016, p3.

while particularly ISO standards alone frequently result insufficient applicability of outcomes.[149]

Dooley et al. generalize the analysis of maturity model impact from software development to new product engineering in general and assess a sample of 39 new product development programs. They find that maturity enhances output quality significantly.[150]

Knowledge transfer

Software capability maturity modeling supports organizational knowledge management and learning processes in software development companies. A survey in the Italian subsidiary of an international software company comes to the conclusion that the application of the CMM maturity model supports organizational learning. The systematic structuring and control of software engineering processes enhances knowledge flow inside of and in-between departments. Knowledge interchanging paths are a solid infrastructure for knowledge organization and interchange which are preconditional to organizational learning processes.[151] Technological transfer offices implementing academic innovation in business practice in development countries operate more effectively when maturity approaches are applied. Knowledge and practical development fields can be structured systematically by implementing the maturity model approach which leads to higher consistency of intervention and technology application.[152] In engineering businesses in Germany and Switzerland, maturity model application is associated with high levels of organizational learning, which promotes high organizational efficiency and effectiveness.[153]

Schedule and cost control

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[149] ASHRAFI, Noushin. The impact of software process improvement on quality: in theory and practice. *Information & Management*, **40**(7). 2003, pp. 677-690, p684-685.

[150] DOOLEY, Kevin, Anand SUBRA, and John ANDERSON. Maturity and its impact on new product development project performance. *Research in Engineering Design*, **13**(1). 2001, pp. 23-29, p23.

[151] BELLINI, Emilio and Corrado LO STORTO. The impact of software capability maturity model on knowledge management and organisational learning: empirical findings and useful insights. *International Journal of Information Systems and Change Management*, **1**(4). 2006, pp. 339-373, p349.

[152] SECUNDO, Giustina, Christle de BEER, and Giuseppina PASSIANTE. Measuring university technology transfer efficiency: a maturity level approach. *Measuring Business Excellence*, **20**(3). 2016, pp. 42-54.

[153] BITITCI, Umit, Patrizia GARENGO, Viktor DÖRFLER, and Sai NUDURUPATI. Performance measurement: challenges for tomorrow. *International journal of management reviews*, **14**(3). 2012, pp. 305-327.

Functional development risks contribute to economic risks in software development, particularly in external and distant supply chains:[154] Development schedule achievement benefits from maturity modeling in software development according to a developers' survey in New England, since maturity planning enhances software reliability and reduces iteration cycles in development. CI application enhances timeliness and in result cost performance:[155]

According to a survey among software developers, quality enhancements achieved by increased process maturity do not necessarily increase the cost of implementation and maintenance, but results cost reductions of the total process due to reduced quality problems and higher customer satisfaction.[156] The application of maturity models in new product development reduces development costs and time schedule overrun, according to an empirical study of 39 product innovation programs.[157]

Project risk control

The U.S. Federal Government has successfully applied maturity models to reduce the implementation risk and cost of project implementation. Maturity models have reduced complexity and contract-related risks since they establish clear standards for workflow implementation and collaboration across departments.

A time series of risks and costs of 82 government projects indicates that uncontrolled contraction and execution risks exert negative performance effects which are reduced by the introduction of CMMI standards.[158]

Business performance

Business process maturity models in software engineering improve the performance of project flows and in result the performance of the business as a whole. A survey among

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[154] NA, Kwan-Sik, James T. SIMPSON, Xiaotong LI, Tushar SINGH, and Ki-Yoon KIM. Software development risk and project performance measurement: Evidence in Korea. *Journal of Systems and Software*, **80**(4). 2007, pp. 596-605, p603.

[155] JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p331.

[156] KUILBOER, Jean-Pierre and Noushin ASHRAFI. Software process and product improvement: an empirical assessment. *Information and software technology*, **42**(1). 2000, pp. 27-34, p34.

[157] DOOLEY, Kevin, Anand SUBRA, and John ANDERSON. Maturity and its impact on new product development project performance. *Research in Engineering Design*, **13**(1). 2001, pp. 23-29, p23.

[158] MISHRA, Anant, Sidhartha R. DAS, and James J. MURRAY. Risk, process maturity, and project performance: An empirical analysis of US federal government technology projects. *Production and Operations Management*, **25**(2). 2016, pp. 210-232, p223.

software developers from several nations and in different companies confirms the positive effect of maturity model application on business performance up to a certain point, since several moderators have to be taken into account (compare section 3.4).[159] High organizational process performance improves business performance according to a representative review of 62 studies.[160]

Maturity models can be designed to integrate the development and management level, which then operate on a common performance assessment system. This integration enhances the understanding across departments and establishes a common standard of performance evaluation, which in the long run contributes to enhance performance outcome for the business as a whole.[161]

The improvement of technology development processes and product performance in software development due to the application of maturity models improves customer satisfaction with the delivered product, which increases customer demand. A solid demand base enables the company to implement financial objectives.[162] Maturity models in software engineering positively impact project and business performance by streamlining processes and integrating management and development levels, thereby improving customer satisfaction and financial outcomes, although the effectiveness is moderated by various factors.

2.3 Moderators of digital product development efficiency

Figure 2.3 classifies moderators of the impact of maturity model application on efficiency. Several studies deal with with a single moderating factor. To structure the classification, the following major categories shine up:

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[159] DIJKMAN, Remco, Sander Vincent LAMMERS, and Ad de JONG. Properties that influence business process management maturity and its effect on organizational performance. *Information Systems Frontiers*, **18.** 2016, pp. 717-734, p726.

[160] TARHAN, Ayca, Oktay TURETKEN, and Hajo A. REIJERS. Do mature business processes lead to improved performance? : a review of literature for empirical evidence. *Proceedings of the 23rd European Conference on Information Systems (ECIS 2015), 26-29 May 2015, Munster, Germany.* 2015, pp. 1-16, p13.

[161] DOMINGUES, Pedro, Paulo SAMPAIO, and Pedro M. AREZES. Integrated management systems assessment: a maturity model proposal. *Journal of Cleaner Production*, **124.** 2016, pp. 164-174, p171.

[162] KUILBOER, Jean-Pierre and Noushin ASHRAFI. Software process and product improvement: an empirical assessment. *Information and software technology*, **42**(1). 2000, pp. 27-34, p34.

Table 2.2: **Overview on moderators of the impact of maturity modelling on efficiency**

Knowledge related moderators	Business related moderators	Control related moderators	Risk related moderators
• Experts coaching/training	• Business region	• Additional maturity or quality measures	• Supply chain risk
• Business/ project innovativeness	• Business age	• Managerial participation	• Internal risk
	• Shared culture/ vision	• Managerial control	• Complexity

Knowledge related moderators

Assessing the impact of project management processes on product and process quality Jiang et al. use factor analysis to identify a category of knowledge related factors moderating this relationship. Developers' and review leaders' training on maturity management systems is essential to ensure their effective application. [163]

The impact of business model maturity on the performance of software SME in Germany and the Netherlands significantly depends on the moderator of corporate innovativeness, which positively impacts the effect of maturity model application on business performance.[164] The degree of expertise project participants bring in software development positively moderates development risks and accordingly improves project processes and outputs.[165]

Business related moderators

Dijkman's multi-company survey additionally shows that the area the business is located impacts its responsiveness to maturity model application. Localization in innovative urban agglomerations positively moderate the effect of maturity models on performance. The

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[163] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

[164] DIJKMAN, Remco, Sander Vincent LAMMERS, and Ad de JONG. Properties that influence business process management maturity and its effect on organizational performance. *Information Systems Frontiers*, **18.** 2016, pp. 717-734, p727.

[165] DI TULLIO, Dany and Bouchaib BAHLI. The impact of software process maturity and software development risk on the performance of software development projects. *ICIS 2006 Proceedings. 90.* 2006, p1486.

additional factors size and age however are not significant in the respective structural equation model.[166] According to Berghaus & Back, the application and performance impact of maturity modeling is related to business size and strategic orientation. Larger companies disposing of a clear strategy and maturity mode implementation concept excel on smaller and less organized firms.[167]

In correspondence, Dominguez et al. find business culture and vision an important moderator to maturity model effectiveness. According to a survey among maturity model managers in Portugal an open but clearly structured business culture supports maturity model implementation and acceptance. Developers usually adjust to the concise processes of maturity models in a better way when they have been accustomed to similar routines before and when the business culture and management support documentation and systematic improvement processes.[168]

Control related moderators

According to Jiang's empirical study among international software developers, controlling maturity model standards is another important aspect to ensure that maturity model application, in fact they enhance process and product quality. Maturity models require the development and systematic application of the necessary standards of documentation. Managers are advised to review these standards and ensure compliance. Regular reviews of design processes and codes are necessary to keep the maturity model going.[169] Managerial cooperation in maturity model implementation and supervision has repeatedly been found an important factor in expert interviews in 12 European manufacturing companies. Bititci points out the high impact of informal behavioral factors, e.g. managerial openness to

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[166] DIJKMAN, Remco, Sander Vincent LAMMERS, and Ad de JONG. Properties that influence business process management maturity and its effect on organizational performance. *Information Systems Frontiers*, **18.** 2016, pp. 717-734, p727.

[167] BERGHAUS, Sabine and Andrea BACK. Stages in digital business transformation: Results of an empirical maturity study. *MCIS 2016 Proceedings. 22.* 2016, p7.

[168] DOMINGUES, Pedro, Paulo SAMPAIO, and Pedro M. AREZES. Integrated management systems assessment: a maturity model proposal. *Journal of Cleaner Production*, **124.** 2016, pp. 164-174.

[169] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

change and the establishment of an organizational culture directed towards maturity development.[170]

Managerial support of maturity modeling processes is desirable to gain acceptance with line employees and supervise the regular application of maturity standards. The efficiency outcome of maturity model application depends on regular monitoring and control.[171]

Equally, a survey among 212 project managers in China confirms that managerial control is important to lead maturity projects to success. Control activities during the software development phase enhance software flexibility, consecutive project success and later product performance. Beyond control activity, software development projects require managerial participation and identification. If managers review development processes regularly and follow established guidelines themselves, these find higher acceptance with employees, which again contributes to enhance project and product performance.[172] Maturity models improve the control in software development processes themselves, since they demand discipline in application and structure the development process.[173]

Several studies find the application of more than one maturity model or supplementary quality management systems beyond maturity models useful to enhance efficiency in software development processes: According to Mishra the cost performance index of software projects benefits from the application of CMMI 4 partly but is enhanced significantly by a transition to CMMI 5.[174] Bellini et al. compare the effect of CMM Version 1, 2 and 3 on productivity and the relative deviation of productivity. Younger CMM models are more reliable enhancers of productivity but do not systematically reduce the relative

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[170] BITITCI, Umit, Patrizia GARENGO, Viktor DÖRFLER, and Sai NUDURUPATI. Performance measurement: challenges for tomorrow. *International journal of management reviews,* **14**(3). 2012, pp. 305-327.

[171] DOMINGUES, Pedro, Paulo SAMPAIO, and Pedro M. AREZES. Integrated management systems assessment: a maturity model proposal. *Journal of Cleaner Production,* **124.** 2016, pp. 164-174.

[172] WANG, Eric T. G., Pei-Hung JU, James J. JIANG, and Gary KLEIN. The effects of change control and management review on software flexibility and project performance. *Information & Management*, **45**(7). 2008, pp. 438-443.

[173] BELLINI, Emilio and Corrado LO STORTO. The impact of software capability maturity model on knowledge management and organisational learning: empirical findings and useful insights. *International Journal of Information Systems and Change Management*, **1**(4). 2006, pp. 339-373, p339.

[174] MISHRA, Anant, Sidhartha R. DAS, and James J. MURRAY. Risk, process maturity, and project performance: An empirical analysis of US federal government technology projects. *Production and Operations Management*, **25**(2). 2016, pp. 210-232, p223.

deviation of productivity outcomes.[175] According to Ashrafi, integrating ISO 9000 ff standards and CMM enhances most efficiency parameters in software engineering, particularly verifiability and correctness of the software application.[176]

The combination of agile and maturity models in software development is optimal to improve development efficiency and innovativeness, there are positive cross-relationships between agile concepts and maturity model application.[177]

Risk related moderators

Three studies address the impact of maturity modeling on risk control in development processes. Reduced risk promotes the efficiency of processes and outcomes:

In a survey among US IT companies which outsource development processes in Korea, Na et al. show that schedule and consecutive cost overrun is a major risk of outsourcing development projects. Project complexity and distance of the supplier contribute to increase these risk factors. The reduction of functional development risk is essential to enhance process and product performance and avoid schedule and cost overrun.[178] CMMI application moderates the impact of complexity, contracting and execution risk in software supply chains: CMMI provides suppliers with clear standards, makes processes transparent and encourages all stakeholders to control the productivity of their development process regularly.[179] Lockamy et al. come to the same conclusions based on the statistical analysis of 20 supply chains. Supply chains applying maturity models are in better control of information flow and processes than supply chains doing without maturity assessment,

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[175] BELLINI, Emilio and Corrado LO STORTO. The impact of software capability maturity model on knowledge management and organisational learning: empirical findings and useful insights. *International Journal of Information Systems and Change Management*, **1**(4). 2006, pp. 339-373, p352.

[176] ASHRAFI, Noushin. The impact of software process improvement on quality: in theory and practice. *Information & Management*, **40**(7). 2003, pp. 677-690, p678.

[177] ASHRAFI, Noushin. The impact of software process improvement on quality: in theory and practice. *Information & Management*, **40**(7). 2003, pp. 677-690, p683.

[178] NA, Kwan-Sik, James T. SIMPSON, Xiaotong LI, Tushar SINGH, and Ki-Yoon KIM. Software development risk and project performance measurement: Evidence in Korea. *Journal of Systems and Software*, **80**(4). 2007, pp. 596-605, p600.

[179] MISHRA, Anant, Sidhartha R. DAS, and James J. MURRAY. Risk, process maturity, and project performance: An empirical analysis of US federal government technology projects. *Production and Operations Management*, **25**(2). 2016, pp. 210-232, p223.

which reduces the risk of project failure.[180] Software development companies implementing CMM realized improved software project performance due to reduced development risks.[181]

2.4 Review-founded research model

Section 2.4 summarizes the results of the review and derives a research model for further analysis in the empirical part of the study.

Summary of review results

Impact of maturity on efficiency

All retrieved studies agree that digital process maturity contributes to enhance efficiency. The application of maturity models eases development towards process maturity. Although businesses follow a natural path to process maturity, progress on this path usually entails the transgression to systematic maturity planning and analysis in a continuous improvement process.[182]

Section 2.2 has found that the identified efficiency effects comprise financial and technical dimensions and essentially seven categories of efficiency have been identified. Technical efficiency refers to project process performance, supply chain performance, the performance of the final software or product and to knowledge development and transfer. Financial efficiency concerns schedule and cost control, project risk control and enhanced (financial) business performance (compare

Table 2.1).

The analysis of technical efficiency effects has equally shown that individual effects are intercorrelated. The following correlations have been found:

- Process performance in IT projects is essential to supply chain performance. The strategic organization of project process flows motivates supply chain partners to

[180] LOCKAMY III, Archie, Paul CHILDERHOUSE, Stephen M. DISNEY, Denis R. TOWILL, and Kevin MCCORMACK. The impact of process maturity and uncertainty on supply chain performance: an empirical study. *International Journal of Manufacturing Technology and Management*, **15**(1). 2008, pp. 12-27, p24-25.

[181] DI TULLIO, Dany and Bouchaib BAHLI. The impact of software process maturity and software development risk on the performance of software development projects. *ICIS 2006 Proceedings. 90.* 2006, p90.

[182] JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p328.

adopt these structures and process patterns.[183] If internal process flows are ill-organized, on the other hand, supply chain partners dispense with orientation on product and process concepts and result disorganized themselves.

- Process performance of software development projects enhances the performance of the final software product.[184]
- Supply chain performance equally contributes to enhanced product or process performance, since the product outcome depends on the smooth interaction of all interlinks in the supply chain.[185]
- The efficiency of knowledge transfer depends on the effective interaction in the supply chain[186] and process flow efficiency in the organization. [187]

The analysis of financial efficiency effects has shown that equally these are closely interrelated:

- Cost and schedule efficiency are inseparable.[188] Unless timelines are met, costs overrun targets due to longer manpower and machinery engagement.[189]
- The avoidance of project implementation risk, contributes to the control of costs and timelines.[190]

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[183] TITOV, Sergei, Gregory BUBNOV, Maria GUSEVA, Alexei LYALIN, and Irina BRIKOSHINA. Capability maturity models in engineering companies: case study analysis. *ITM Web of Conferences*, **6.** 2016, p3.

[184] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

[185] JØRGENSEN, Frances, Harry BOER, and Bjørge LAUGEN. CI Implementation: An Empirical Test of the CI Maturity Model. *Creativity and Innovation Management*, **15.** 2006, p328.

[186] BITITCI, Umit, Patrizia GARENGO, Viktor DÖRFLER, and Sai NUDURUPATI. Performance measurement: challenges for tomorrow. *International journal of management reviews*, **14**(3). 2012, pp. 305-327

[187] BELLINI, Emilio and Corrado LO STORTO. The impact of software capability maturity model on knowledge management and organisational learning: empirical findings and useful insights. *International Journal of Information Systems and Change Management*, **1**(4). 2006, pp. 339-373, p349.

[188] DOOLEY, Kevin, Anand SUBRA, and John ANDERSON. Maturity and its impact on new product development project performance. *Research in Engineering Design*, **13**(1). 2001, pp. 23-29, p23.

[189] NA, Kwan-Sik, James T. SIMPSON, Xiaotong LI, Tushar SINGH, and Ki-Yoon KIM. Software development risk and project performance measurement: Evidence in Korea. *Journal of Systems and Software*, **80**(4). 2007, pp. 596-605, p603.

[190] MISHRA, Anant, Sidhartha R. DAS, and James J. MURRAY. Risk, process maturity, and project performance: An empirical analysis of US federal government technology projects. *Production and Operations Management*, **25**(2). 2016, pp. 210-232, p223.

- Economic business performance requires that cost targets and schedules are met. Project risks endanger development success and financial targets.

Technical and financial dimensions of efficiency have been found interrelated in the theoretical sections and this understanding is confirmed in the review of empirical studies. High process and product performance contribute to businesses' economic performance.[191] Satisfied customers return to the company and ensure profitability in the long run.[192]

Moderators of the impact of maturity on efficiency

Section 2.3 of the review has identified four categories of moderators which take effect on the (positive) impact of maturity on technical and financial efficiency.

Effective knowledge management[193] and high levels of innovativeness in corporations strengthen the effect of maturity model application on technical efficiency.

Business related moderators, particularly high business size,[194] location in an innovative area[195] and an open business culture[196] have been found to support efficiency increased on maturity model implementation.

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[191] TARHAN, Ayca, Oktay TURETKEN, and Hajo A. REIJERS. Do mature business processes lead to improved performance? : a review of literature for empirical evidence. *Proceedings of the 23rd European Conference on Information Systems (ECIS 2015), 26-29 May 2015, Munster, Germany.* 2015, pp. 1-16, p13.

[192] KUILBOER, Jean-Pierre and Noushin ASHRAFI. Software process and product improvement: an empirical assessment. *Information and software technology*, **42**(1). 2000, pp. 27-34, p34.

[193] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

[194] DIJKMAN, Remco, Sander Vincent LAMMERS, and Ad de JONG. Properties that influence business process management maturity and its effect on organizational performance. *Information Systems Frontiers*, **18.** 2016, pp. 717-734.

[195] DOMINGUES, Pedro, Paulo SAMPAIO, and Pedro M. AREZES. Integrated management systems assessment: a maturity model proposal. *Journal of Cleaner Production*, **124.** 2016, pp. 164-174.

[196] BERGHAUS, Sabine and Andrea BACK. Stages in digital business transformation: Results of an empirical maturity study. *MCIS 2016 Proceedings. 22.* 2016, p7.

Control of the progress of the maturity process is essential to realize efficiency effects. Control measures comprise monitoring[197] but equally the proactive participation and engagement of the management in the implementation process.[198]

Although maturity development has been found to reduce project risks and thus enhance financial efficiency, project risk-factors are equally a major moderator of the successful application of maturity principles. Complex projects with uncertain outcomes[199] respond worse to maturity assessment processes than clearly defined and well-structured projects.[200]

Model summary and research hypotheses

The chart on the following page (Figure 2.4) summarizes the cause-and-effect chains retrieved from the review of 20 previous empirical studies in maturity model application.

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[197] JIANG, James J., Gary KLEIN, Hsin-Ginn HWANG, Jack HUANG, and Shin-Yuan HUNG. An exploration of the relationship between software development process maturity and project performance. *Information & Management*, **41**(3). 2004, pp. 279-288, p283.

[198] BITITCI, Umit, Patrizia GARENGO, Viktor DÖRFLER, and Sai NUDURUPATI. Performance measurement: challenges for tomorrow. *International journal of management reviews*, **14**(3). 2012, pp. 305-327

[199] NA, Kwan-Sik, James T. SIMPSON, Xiaotong LI, Tushar SINGH, and Ki-Yoon KIM. Software development risk and project performance measurement: Evidence in Korea. *Journal of Systems and Software*, **80**(4). 2007, pp. 596-605, p603.

[200] MISHRA, Anant, Sidhartha R. DAS, and James J. MURRAY. Risk, process maturity, and project performance: An empirical analysis of US federal government technology projects. *Production and Operations Management*, **25**(2). 2016, pp. 210-232, p223.

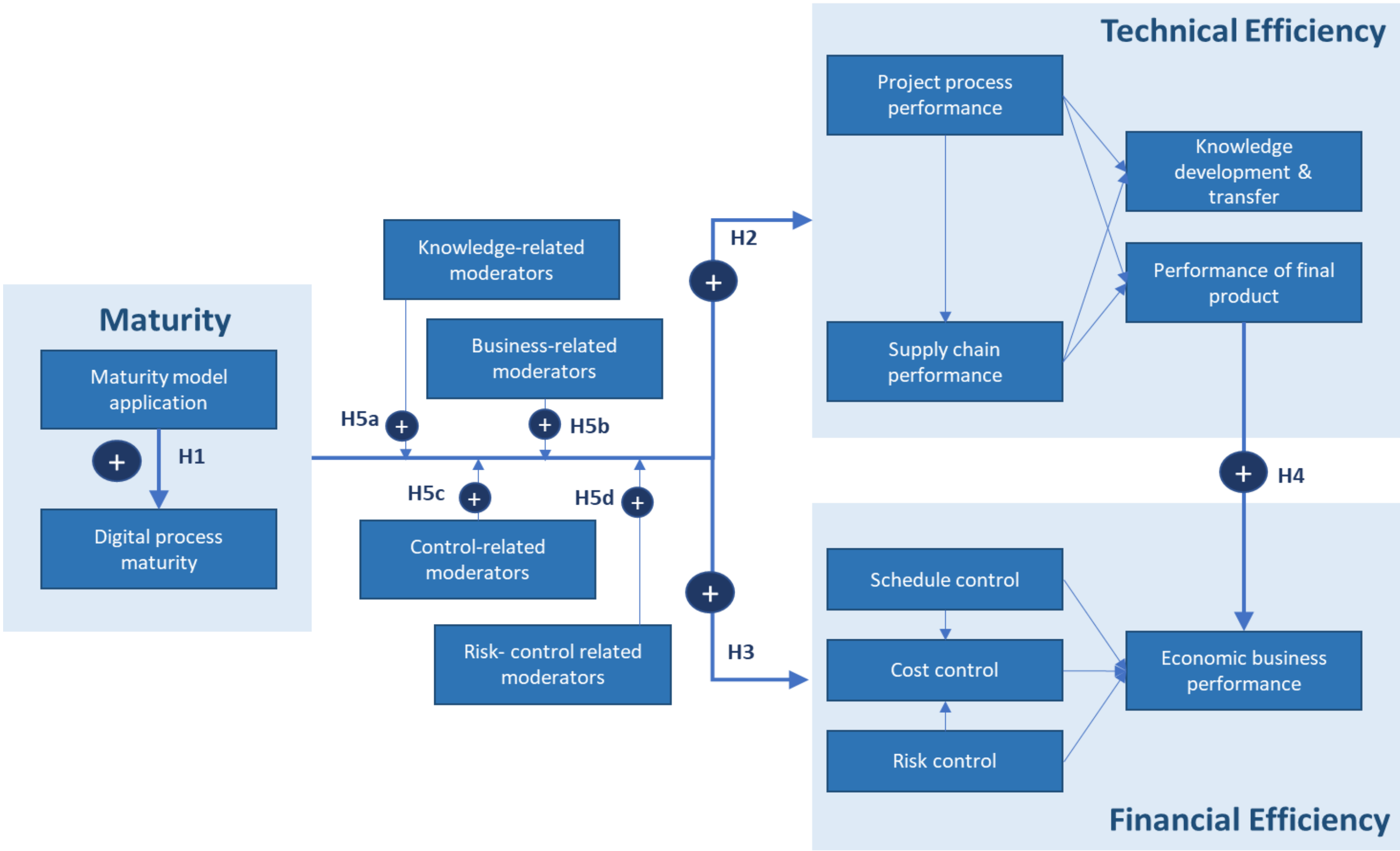

Figure 2.4: **Review-based causal work-model**

Own representation

Altogether the review has found three essential causal chains, which are summarized in the form of propositions and equally are included in Figure 2.4:

H1) Maturity model application enhances digital process maturity.

H2) Digital process maturity significantly enhances technical efficiency.

H3) Digital process maturity significantly enhances financial efficiency.

H4) Technical efficiency enhances financial efficiency

H5 Moderators, particularly H5a) knowledge-related, H5b) business-related, H5c) control-related and H5d) risk-control related factors, positively moderate this relationship.

Research gaps

Although the review has delivered concrete hypotheses on the effect of digital process maturity on efficiency and has detailed categories of efficiency, several points remain open.

Most previous studies address only particular efficiency effects but do not refer to the whole cause and effect chain as described in Figure 2.4. The comparative effect sizes of efficiency characteristics have not been evaluated yet.

Most studies refer to one or two moderators only. The neglection of important moderators however can disturb observed effect sizes and lead to the assumption of spurious correlations. The above research model integrates all so far identified moderating parameters but has not yet been quantified.

The majority of previous empirical studies consider only one or two process maturity models but does not include a comparison of the models concerning their efficiency effects. Bitici et al. refer to expert interviews in 12 manufacturing organizations to conclude that model characteristics are probably relevant to efficiency outputs. [201] Tarhan et al. come to similar conclusions based on a systematic review.[202] Both qualitative studies however are not representative and do not provide quantitative results.

[201] BITITCI, Umit, Patrizia GARENGO, Viktor DÖRFLER, and Sai NUDURUPATI. Performance measurement: challenges for tomorrow. *International journal of management reviews*, **14**(3). 2012, pp. 305-327

[202] TARHAN, Ayca, Oktay TURETKEN, and Hajo A. REIJERS. Do mature business processes lead to improved performance? : a review of literature for empirical evidence. *Proceedings of the 23rd European Conference on Information Systems (ECIS 2015), 26-29 May 2015, Munster, Germany.* 2015, pp. 1-16, p13.

Only two studies partly refer to German companies. Berghaus & Back differentiate maturity stages for Swiss and German companies.[203] Dijkman et al. assess the innovation impact of maturity for German and Dutch organizations.[204] Neither study however differentiates national particularities, although the business culture and enterprise location have been recognized as moderators of maturity impact on efficiency.[205] No study elaborates business field specific particularities. No study addressing a particular business branch or companies in Germany in particular has been available so far.

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[203] BERGHAUS, Sabine and Andrea BACK. Stages in digital business transformation: Results of an empirical maturity study. *MCIS 2016 Proceedings. 22.* 2016, p7.

[204] DIJKMAN, Remco, Sander Vincent LAMMERS, and Ad de JONG. Properties that influence business process management maturity and its effect on organizational performance. *Information Systems Frontiers*, **18.** 2016, pp. 717-734, p727.

[205] DOMINGUES, Pedro, Paulo SAMPAIO, and Pedro M. AREZES. Integrated management systems assessment: a maturity model proposal. *Journal of Cleaner Production*, **124.** 2016, pp. 164-174.

3. EMPIRICAL RESEARCH DESIGN AND PRETEST

Chapter 3 develops an empirical research approach to close the above identified research gaps. Section 3.1 explains the choice of a mixed method research design comprising interviews and a multiple-choice survey. Section 3.2 develops the design of the qualitative research part. Section 3.3 introduces to the German mechanical engineering business. Section 3.4 develops the implementation concept for the qualitative study and section 3.5 presents the interview results and, based on the insights section 3.6 adjusts the research model concretizes the hypotheses.

3.1 Empirical Research design

Research objectives

Previous elaboration has shown that the causal relationship between digital process maturity and development efficiency has not yet been assessed comprehensively in an empirical study. No study specified for the German mechanical engineering sector is available.

The empirical section of this dissertation closes these research gaps, i.e. assesses the impact of process maturity on the efficiency of product development in German mechanical engineering. Based on a systematic review chapter 2 has drafted a preliminary model, explaining the cause- and effect chain leading form digital process maturity to product development efficiency. So far however, there is no comprehensive validation of the suggested model-which has been patched from diverse partial insights of several earlier studies in related contexts.

The preliminary research model which has been deducted from previous empirical research using a deductive approach accordingly requires further validation and reliability testing:

Validation means to assess the extent to which the measurement instrument i.e. the model in fact measures what it is intended for. Reliability testing implies that the causal relationships suggested by the model (which are plausible due to the positive validity test) are in fact observed and statistically proven.[206] Based on closer examination, it can be

[206] WEIBER, Rolf and D. Strukturgleichungsmodellierung MÜHLHAUS. Eine anwendungsorientierte Einführung in die Kausalanalyse mit Hilfe von AMOS, SmartPLS und SPSS. *Structural equation modeling. An application-oriented introduction to causal analysis using AMOS, SmartPLS and SPSS]. 2nd ed. Berlin: Springer Gabler.* 2014, p103.

concluded that the Cronbach Alpha reliability results are consistent regardless of whether the analysis is composite-based or factor-based. Furthermore, there is little to no difference between the respective algorithms and the coefficients for Dijkstra's PLSc and True Composite Reliability estimates.[207]

To analyze the impacts of digital process maturity on product development efficiency in German mechanical engineering this study draws on the assumptions of the suggested research model and seeks to validate and ideally expand them based on qualitative business-specific empirical insights. Finally, this study tests the whole model for reliability using statistical methods.

Based on a validated and reliability tested model, the study offers reliable insights to what extent and through which paths digital process maturity impacts the efficiency of product development in German mechanical engineering and develops detailed suggestions how respective businesses realize efficiency gains by developing IT process maturity.

Mixed-method approach

This research objective of model validation and reliability testing calls for a two staged mixed method research design, which combines qualitative and quantitative methods.[208]

The combination of qualitative and quantitative research methods has various advantages over a single method concept:[209] Purely quantitative studies examine the causal relationships derived from theory reliably but cannot take into account new insights deviating from the initial model.[210] Quantitative research cannot check for validity.[211] Qualitative research provides insights beyond the range of existing models, since in-depth analyses discovering new categories are possible. Purely qualitative studies however usually rely on small samples which are assessed in large detail but usually lack representativeness

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[207] CANATAY, Arman, Tochukwu EMEGWA, Liza M. LYBOLT, and Karen D. LOCH. Reliability assessment in SEM models with composites and factors: A modern perspective. *Data Analysis Perspectives Journal*, **3**(1). 2022, pp. 1-6.

[208] VENKATESH, Viswanath, Susan A. BROWN, and Hillol BALA. Bridging the qualitative-quantitative divide: Guidelines for conducting mixed methods research in information systems. *MIS quarterly.* 2013, pp. 21-54, p22.

[209] KEPPER, Gaby. Methoden der qualitativen Marktforschung. *Gabler Marktforschung*, **3.** 2008, pp. 175-212

[210] HOLLWECK, Trista. Robert K. Yin. (2014). Case Study Research Design and Methods (5th ed.). Thousand Oaks, CA: Sage. 282 pages. *The Canadian Journal of Program Evaluation*, **30.** 2016, p36.

[211] WEIBER, Rolf and D. Strukturgleichungsmodellierung MÜHLHAUS. Eine anwendungsorientierte Einführung in die Kausalanalyse mit Hilfe von AMOS, SmartPLS und SPSS. *Structural equation modeling. An application-oriented introduction to causal analysis using AMOS, SmartPLS and SPSS]. 2nd ed. Berlin: Springer Gabler.* 2014, p104.

and quantitative reliability. By integrating both – qualitative and quantitative methods, both problems are solved.[212]

First, the working model is validated on the basis of qualitative in-depth analysis in the business field and, if necessary, extended by relevant factors and relationships. Then, the empirically founded parameters are quantitatively tested for reliability using statistical methods in a large-scale quantitative study.[213] A mixed-method approach is thus particularly suitable for research areas, for which empirically validated categories are still scarce, e.g. the impact of digital process maturity on product development efficiency in German mechanical engineering.

Comprehensive research plan

The following comprehensive model (Figure 3.1, following page) illustrates the work plan for the empirical two-stages, mixed-method study.

The review-based work model is validated in an empirical pre-study (chapter 3), and the validated model forms the basis of a quantitative representative survey which is evaluated statistically to test the hypotheses (chapter 4), to come to a reliable and reproducible explanation of the impact of digital process maturity on development efficiency in the German mechanical engineering sector.

The study uses data triangulation to integrate the qualitative and quantitative empirical results and deducts conclusions to academic research and business practice on that basis. Data-triangulation interconnects qualitative and quantitative results to validate and explain the outcomes of both research parts. The quantitative study builds on tentative theories derived in the qualitative section and tests the causalities for reliability. Quantitative results are then linked back to the insights gained from qualitative research to found the causal backgrounds. By iterative interconnection of qualitative and quantitative methods a dialogue is established, and the potentials of qualitative and quantitative approaches are multiplied.[214]

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212 COLLINS, Hilary. *Creative research: the theory and practice of research for the creative industries:* Bloomsbury Publishing, 2018, p169.

213 WYNN JR, Donald E. and Clay K. WILLIAMS. Recent advances and opportunities for improving critical realism-based case study research in IS. *Journal of the Association for Information Systems*, **21**(1). 2020, p. 8.

214 WILSON, Virginia. Research Methods: Triangulation. *Evidence Based Library and Information Practice*, **9**(1). 2014, pp. 74-75.

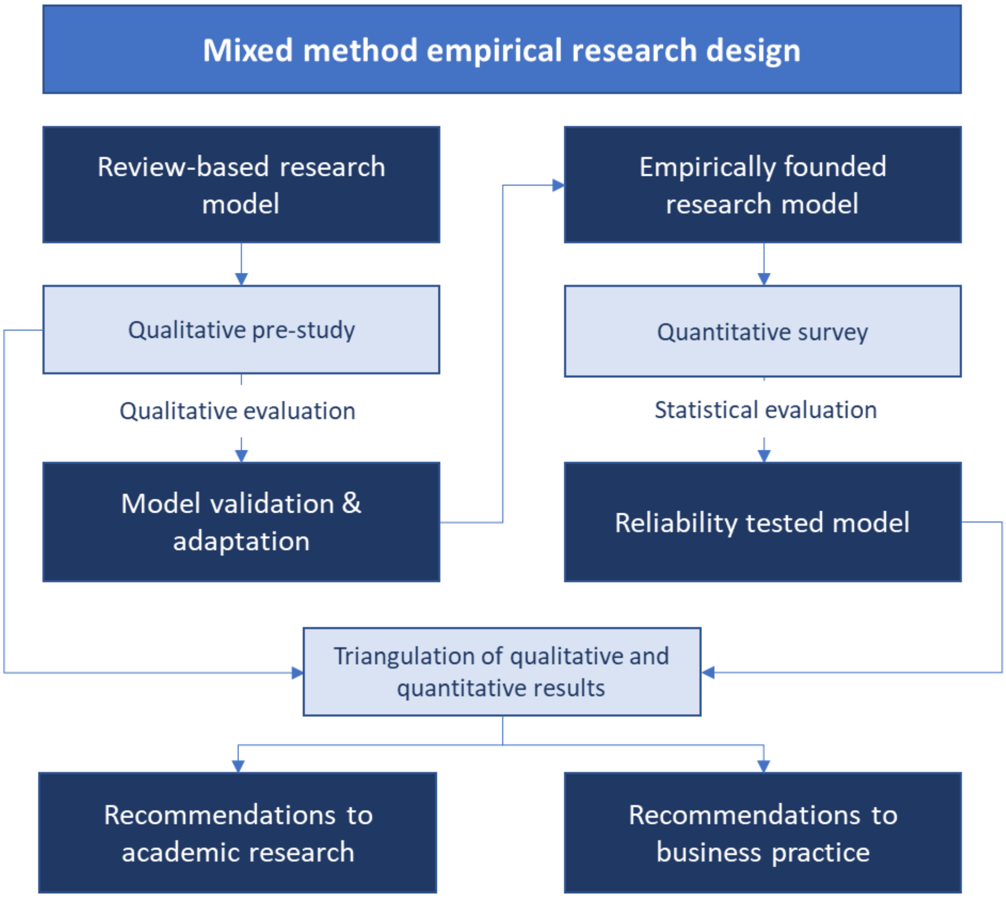

Figure 3.1: **Summative empirical research model**, own representation

3.2 Choice of qualitative research design for the pretest

Academic research offers diverse qualitative research methods, and the research design has to be chosen carefully to realize the intended insights.

Choice of qualitative research method

Document analysis evaluates and interprets publicly available sources concerning an empirical study object.[215] However, document analysis alone is insufficient for a

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[215] BOWEN, Glenn A. Document analysis as a qualitative research method. *Qualitative research journal*, **9**(2). 2009, pp. 27-40.

comprehensive assessment, as it can be biased and often lacks access to all relevant data.[216] It serves as a preparatory step for more in-depth research methods. [217]

Action research involves the researcher's active participation in the daily activities of the target company and follows a spiraling process of planning, participation, and analysis. However, this method can risk the researcher losing objectivity due to close involvement with the subject. Despite its practical relevance, action research is not suitable for this study due to time constraints.[218]

Interview-based field research is more practical. Here the researcher is an external observer, i.e. the interviewer. In contrast to document analysis, the field researcher observes the study object in the context of its environment and time[219] and comes to document the individual properties and development of the examination object through intensive observation.[220] Correspondingly, Yin[221] sees interviews as "an empirical inquiry that investigates a contemporary phenomenon in its real-life context; when the boundary between phenomenon and context are not clear; and in which multiple sources of evidence are used". The accessibility of information about the object of study for an external researcher limits the scope of interviews.[222] Despite these limitations, the interview approach represents a viable research strategy for this thesis.

Number of cases for qualitative study

The necessary or desirable number of study cases has been discussed to extent in previous literature. Single-case studies comprehensively analyze one study object in its historical or environmental context,[223] providing a profound understanding of the research subject and

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[216] PRIOR, Lindsay. *Using documents in social research:* Sage, 2003, p26.

[217] BOWEN, Glenn A. Document analysis as a qualitative research method. *Qualitative research journal*, **9**(2). 2009, pp. 27-40.

[218] MCNIFF, Jean and Jack WHITEHEAD. *All you need to know about action research:* Sage Publications, 2011, p87-94.

[219] FLYVBJERG, Bent. Five misunderstandings about case-study research. *Qualitative inquiry*, **12**(2). 2006, pp. 219-245.

[220] CRESWELL, John W. and Cheryl N. POTH. *Qualitative inquiry and research design: Choosing among five approaches:* Sage Publications, 2016, p81-90.

[221] HOLLWECK, Trista. Robert K. Yin. (2014). Case Study Research Design and Methods (5th ed.). Thousand Oaks, CA: Sage. 282 pages. *The Canadian Journal of Program Evaluation*, **30.** 2016, p23.

[222] CRESWELL, John W. and Cheryl N. POTH. *Qualitative inquiry and research design: Choosing among five approaches:* Sage Publications, 2016, p81-90.

[223] LAMNEK, Siegfried and Claudia KRELL. *Qualitative Sozialforschung: mit Online-Material:* Beltz, 2016, p28-29.

incorporating various strategies, although a comparison with other study subjects is not possible. This limitation impairs the validity of results. Comparing multiple cases located in a common context grants a higher degree of generalizability. Several cases avoid biases resulting from the choice of particular companies and individual interview participants.[224]

Opinions about the minimum number of required cases to validate research vary: On the one hand, case study validity increases with rising numbers and diversity of cases, while, on the other hand, the selection of few cases provides a deeper understanding of the structures and effects of complex phenomena.[225] By means of comparative case study analysis, various comparable situations and diverse interviewee perspectives in several entities can be analyzed efficiently. Yin finds three to seven cases an ideal compromise, and this suggestion is adopted for this study.[226]

Choice of interview method

In methodological literature, various forms of interviewing are systematized and discussed with regard to their suitability for different study objects. Narrative and structured interview styles are compared to semi-structured interviews in the following:

In narrative interviews, the interviewee independently reports on a topic without responding to concrete key questions. Thus, the researcher receives a comprehensive presentation of the overall context from the perspective of the interviewee. Frequently, narrative interview results are hard to compare for several interviewees, due to diverging presentation structures and divergences in interview topics. [227]

So-called "problem-centered interviews", a term coined by Witzel,[228] avoid this difficulty and provide a comprehensive and obligatory set of questions to be answered (structured interview) or a set of open questions that can be modified and amended by the interviewee (semi-structured interview). Problem centered interviews expect statements on specific

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[224] EISENHARDT, Kathleen M. and Melissa E. GRAEBNER. Theory building from cases: Opportunities and challenges. *Academy of management journal*, **50**(1). 2007, pp. 25-32.

[225] SAUNDERS, Mark and Philip LEWIS. *Doing research in business and management:* Pearson, 2017,p104-178.

[226] HOLLWECK, Trista. Robert K. Yin. (2014). Case Study Research Design and Methods (5th ed.). Thousand Oaks, CA: Sage. 282 pages. *The Canadian Journal of Program Evaluation*, **30.** 2016.

[227] LIAMPUTTONG, Pranee. *Qualitative research methods.* Fifth edition. Australia: Oxford University Press, 2020.

[228] WITZEL, Andreas. Das problemzentrierte Interview. S. 227-255 in: G. Jüttemann (Hrsg.): Qualitative Forschung in der Psychologie. 1985.

issues and the results are comparable. In semi-structured interviews, interviewees still have room for their own representations[229] and these are particularly suitable for the analysis of diverse understandings of individuals at different levels and in different contexts: they invite participants to classify themselves as actors on the scene of the research object.[230]

Semi-structured interviews appear adequate for this study since they invite different perspectives on the issue of the impact of IT maturity on development efficiency. The inclusion of several participants in the interview study, reduces interviewees' individual perception and reporting biases.[231] In methodological literature, various interviewing techniques like narrative, structured, and semi-structured interviews are discussed for their appropriateness in studying different subjects; narrative interviews offer a holistic but potentially incomparable view from interviewees, while problem-centered interviews, including structured and semi-structured types, provide more targeted and comparable results, with semi-structured interviews being particularly suitable for exploring diverse perspectives, such as the impact of IT maturity on development efficiency, while mitigating individual biases through the inclusion of multiple participants.

3.3 Digital processes in the German mechanical engineering industry

To select a representative sample for the qualitative and quantitative part of the study, a profound understanding of the conditions in the target industry – the German mechanical engineering sector - is essential. Document analysis is applied to gather basic structural data on the industry and its development in the recent decade and assess the impact and changes digitalization has brought to German mechanical engineering businesses.

Development, status and prospects of German mechanical engineering

Historically, the mechanical engineering industry originates in the 18th century with the invention of the steam engine by James Watt. The mechanical engineering business made important advances with the development of serial production in the early 20th century.

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[229] CRESWELL, John W. and Cheryl N. POTH. *Qualitative inquiry and research design: Choosing among five approaches:* Sage Publications, 2016, p81-90.

[230] WIKGREN, Marianne. Critical realism as a philosophy and social theory in information science? *Journal of documentation*, **61**(1). 2005, pp. 11-22.

[231] EASTON, Geoff. Critical realism in case study research. *Industrial marketing management*, **39**(1). 2010, pp. 118-128.

Since then, this economic sector, which in its early days comprised craft enterprises mainly, has industrialized to a large extent.

Today, mechanical engineering is among Germany's most important economic sectors and comprises about 6,600 companies. Most of them are located in the federal states of Baden-Württemberg, Bavaria and Nordrhein-Westfalen. 95% of these businesses employ less than 500 people (average: 179.5 people). Accordingly, mechanical engineering is a branch of engineering with a strong medium-sized character.[232]

In 2021, Germany's mechanical engineering sector employed more than 1,007 million people and showed an employment reduction of 1,2 % on 2020.[233]

During the 1990ies, the number of employees fell from 1.4 million to 900,000 people due to rationalizations of production and the decline of the steel industry. After a period of stagnation in the early 2000s, the industry gained in drive in 2005 to 2008 but experienced a significant cutback in the aftermath of the global financial crisis of 2008. Since 2011 German mechanical engineering has been growing mainly due to increasing export and foreign demand.

Employment figures mirror the development of turnovers and profits. In 2018, (most recent data), the German mechanical engineering business realized turnovers of 232.5 billion euros (up 2.8% on 2017). Goods worth 177.8 billion Euros were exported (up 5.3% on 2017), which corresponds to an export quota of 79.3 % (2017: 78.6%). Capacity utilization in 2018 was 90.5 %, which accounts for the strong boom in the sector.

The German mechanical engineering business is highly innovative. The share of completely new products per year is between 5.5 % (2008) and 8 % (2012). Process innovations result in annual cost decreases of 2.6 % (2016) to 4.5 % (2010 and 2012).[234]

Digitalization in product development in German mechanical engineering

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[232] KLINKUSCH, Julia. *Branchenprofil Maschinenbau in Deutschland: Stirbt der Klassiker aus?* [online] [viewed 6 September 2023]. Available from: https://www.ingenieur.de/karriere/branchenprofile/maschinen-und-anlagenbau/.

[233] WIECHERS, Ralph, Annette MEYERHOFF, and Holger PAUL. Maschinenbau in Zahl und Bild 2022. *Frankfurt am Main: Verein Deutscher Maschinen-und Anlagenbauer (VDMA)(Hrsg.).* 2022, p15.

[234] WIECHERS, Ralph, Annette MEYERHOFF, and Holger PAUL. Maschinenbau in Zahl und Bild 2019. *Frankfurt am Main: Verein Deutscher Maschinen-und Anlagenbauer (VDMA)(Hrsg.).* 2019, p16.

Digitalization has greatly advanced the German mechanical engineering sector in the recent two decades as a survey of Porsche Consulting among 50 German, Italian, and Swiss mechanical engineering companies shows. New products employing digital technologies have been developed and digitalization has changed customer relationships, which today usually communicate and order online. VDMA sees three important development trends which are about to change the mechanical engineering sector: the switch from hardware to software and services, digital changes in the investment goods business and the growing need for collaboration with competitors and customers.[235]

Many production processes today use digital technologies to operate robotic production equipment. Digital technologies interconnect production, distribution and entrepreneurial planning. The businesses perceive that digitalization contributes to efficiency gains and growth.[236] Businesses in the mechanical engineering sector are more open to digital technologies like cloud computing, big data management, robotics and artificial intelligence than other industrial sectors in Germany.[237]

Digitalization impacts the whole mechanical engineering value cycle, but particularly R&D. Here, digitalization stands for product and service innovation and contributes to operational excellence.[238] New products are designed using 3D CAD technologies. They are computed and detailed using high end digital calculation programs. Simulations support the process of new product testing and are indispensable to assess and accomplish test bench data. Large scale product innovation in mechanical engineering would be unthinkable without digital technologies. Digitalization enables new business concepts which interconnect digital technologies and classical mechanical applications e.g. in the fields of robotics and self-driving machinery. In the field of industry 4.0, German mechanical engineering is among the most innovative and open sectors globally. Nine out of ten companies are intensely

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[235] VDMA & MCKINSEY. *How to succeed: Strategic options for European machinery. Shifting growth patterns, increasing pace of digitization, and organizational change,* 2016.

[236] ZIEGLER, Marc and Sven ROSSMANN. *Digital Machinery Decoded:* Porsche Consulting, 2020.

[237] PFITZER, Dirk, Wolfgang FREIBICHLER, and Claudia WALDVOGEL. *Wertschöpfungskrise im Maschinen- und Anlagenbau:* Porsche Consulting, 2019.

[238] ZIEGLER, Marc and Sven ROSSMANN. *Digital Machinery Decoded:* Porsche Consulting, 2020, p4-6.

involved with industry 4.0 technologies to enhance their production and development processes and outputs.[239]

The German mechanical engineering sector however is equally criticized for its reluctance in advancing digitalization. Increasingly, emerging markets, like China, outstep classical German mechanical engineering suppliers in the integration of digital and mechanical technologies. Particularly small and medium sized German companies frequently do not feel competent to change from classical machinery development to products driven by digital technologies. The German mechanical engineering industry has to develop higher openness for change and equally think about partnerships with electronic equipment providers to keep pace in the global race towards digitalization.[240] Digitalization profoundly influences the entire mechanical engineering value cycle, especially in R&D, enabling innovation, operational excellence, and new business models such as robotics and self-driving machinery; however, the German sector faces criticism for its slow adoption, risking being outpaced by emerging markets like China, thereby necessitating a greater openness to change and partnerships with electronic equipment providers.

3.4 Interview implementation

Considering the insights on the mechanical engineering industry in Germany in general now the interviews with representatives of such businesses are prepared. Interview implementation comprises the selection of interview participants, the draft of the questionnaire and the conception of the interview evaluation strategy.

Selection of interview partners

The selection of study participants determines to what extent the results are representative, i. e. provide a comprehensive picture of the underlying reality. Uncritical participant selection can produce misleading insights, when the interviewees are themselves biased or do not have comprehensive knowledge concerning the points inquired about.[241]

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239 DISPAN, Jürgen and Martin SCHWARZ-KOCHER. *Digitalisierung im Maschinenbau. Entwicklungstrends, Herausforderungen, Beschäftigungswirkungen, Gestaltungsfelder im Maschinen-und Anlagenbau,* 2018, p11.

240 HACKSTEIN, Sascha. Maschinenbau und Digitalisierung: Eine Branche im Zwiespalt. *Produktion Online*, 2018. Available from: https://www.produktion.de/wirtschaft/maschinenbau-und-digitalisierung-eine-branche-im-zwiespalt-388.html.

241 SAYER, Andrew. Who’s afraid of critical social science? *Current sociology*, **57**(6). 2009, pp. 767-786.

Organizations are complex entities and comprise multiple levels of activity, but only some are potentially relevant to analysis.[242] Research neglecting the comprehensive analysis of all major levels relevant to a topic is necessarily incomprehensive and biased by the perspective of the selected interviewees.[243]

To obtain representative information on the impact of digital process maturity on the efficiency of product development in German mechanical engineering, people involved with digital processes and active in product development in a German mechanical engineering company are selected. The sector overview has shown that the majority of businesses in the target sector are SME. Correspondingly, this study focusses on such companies and intends to include participants from SME of different sizes and orientations.

The selected companies are anonymized but comprise one company focusing on mechanical engineering in aviation, and one company developing film-stretching and protrusion systems. The latter has got less than 500 employees, but more than 250. The mechanical engineering aviation company employs more than 1,000 people.

Both companies are highly innovative: the film-stretching business develops innovative stretching equipment to realize higher process efficiency and reduce the environmental impact of their products. The aviation company develops new small aircraft particularly turboprop machines.

The participants are anonymized and represented by their initials in the evaluation. Altogether four participants (two from each company) have been acquired as interview partners. They are all experts from technical departments in the positions of electric project leader (BG) and head of business development (MS) at the film-stretching company and head of structural engineering (TB) as well as head of development, aviation physics and concept development in the aviation company (TK). As such they are well informed on the relevance of digital processes in the R&D department and beyond.

The following Table 3.1 provides an overview on participants, companies and innovative products and processes of these companies:

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[242] DU GAY, Paul and Signe VIKKELSØ. *For formal organization: The past in the present and future of organization theory.* Oxford: Oxford University Press, 2017, p32.

[243] MILLER, Kent D. and Eric W. K. TSANG. Testing management theories: Critical realist philosophy and research methods. *Strategic management journal*, **32**(2). 2011, pp. 139-158.

Table 3.1: **Interview participants and companies**

	Company	**Participants**	**Innovative products and processes**
BG	• Producer of film-stretching systems • Extrusion of plastics and additives to produce foils for packing, industrial and consumer goods	• Electric project leader • Responsible for electric components and software	• Innovate film-stretching systems to enhance speed, output, process efficiency and increased use of regenerative resources • Business process innovation
MS	• Modernization of film-stretching systems after warrantee expiry • Service, modernization and after-sales procurement of film-stretching equipment	• Head of department business development	• Internal process optimization • Development and design of new products and services
TB	• Aviation company • > 1,000 employees	• Head of development, aviation physics and concept development	• Innovative small aircrafts and turboprop-aircrafts
TK	• Aviation company • > 1,000 employees	• Head of structural engineering	• Innovative small aircrafts and turboprop-aircrafts

Interview questionnaire

The interviews reflect the derived research model. The participants are not introduced to the model directly, but the research questions are developed from the model categories. The interview questions accordingly refer to the following four major issues:

a) Degree and form of digital process maturity
b) Efficiency of product development
c) Causal relationship between digital process maturity and efficiency of product development

d) Potential moderators of the relationship between digital process maturity and product development efficiency

The interview section thus is designed so that the interview questions are conclusively developed with reference to the research questions and the key elements of analysis. The research questions are based on the four relevant major issues.

This study design corresponds to the strategy of conceptual and instrumental operationalization as suggested by Kaiser.[244]

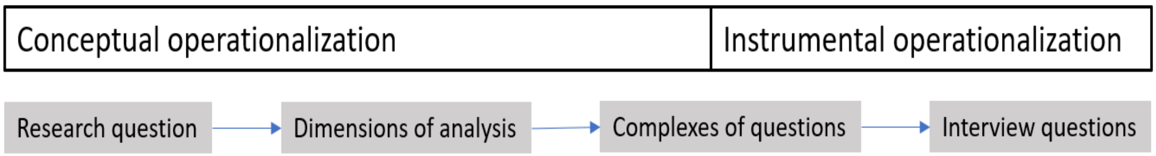

Figure 3.2: **Operationalization of questioning**

Own draft adapted from Kaiser[245]

Since German participants are interviewed, the original questions are in German and are translated here for the purpose of this study as follows:

Table 3.2: **Interview questions**

Issue	**Research questions**
Introduction	1. Could you tell me which products your company produces and what is your function in the company?
	2. Which products or processes have been newly developed in your company?
Digital process maturity	3. What do you personally understand by digital process maturity?
	4. In what respect do digital technologies determine the value creation process in your company?
	5. Is there a consciousness for the meaning of digital process maturity in your company and how is this expressed?
	6. Does your company make efforts to measure digital process maturity and which measures do you apply?

[244] KAISER, Robert. *Qualitative experteninterviews:* Springer, 2014, p52-65.

[245] KAISER, Robert. *Qualitative experteninterviews:* Springer, 2014.

Product development efficiency	7. What makes out efficiency of product development in your company? How is it measured?
	8. How does technical efficiency of product development impact financial efficiency or financial parameters?
Causal relationship between digital process maturity and product development	9. Do you personally think that the level of digitalization (digital process maturity) is related to the efficiency of product development processes? In what regard do you think that digital process maturity is important for the product development process?
	10. In what way could more effective or increased utilization of digital technologies contribute to increase the efficiency of product development in your company?
Moderators of the relationship between digital process maturity and product development	11. Which factors are particularly important for the efficiency of product development apart from digital technologies? a. Are existing knowledge resources important? b. Is the attitude of the management important? c. Is risk management important? Part questions a. to c. are asked only, if the interviewee has not got any own ideas on No 11.
	12. Do you think that every company has got its own important factors determining product development efficiency? Which factors are specific for your company?

Content-analytical evaluation design

Recommendations on how to analyze data are multifaceted.[246] In order to assess the data systematically with respect to the research questions and to reliably recognize consistencies, deviations, patterns, and distinctive features, a qualitative content analysis is conducted as suggested by Gläser & Laudel. Since interview questions are open and rather complex, the range of possible answers is wide. Interview results are evaluated with regard to the research model and arranged so that the research propositions as derived from the systematic review in chapter 2 are answered systematically. To organize this process in a structured way, the

[246] BORCHARDT, Andreas and Stephan E. GÖTHLICH. *Erkenntnisgewinnung durch Fallstudien:* Springer, 2009.

procedural steps of qualitative content analysis as proposed by Gläser & Laudel[247] are followed (see Figure 3.3).

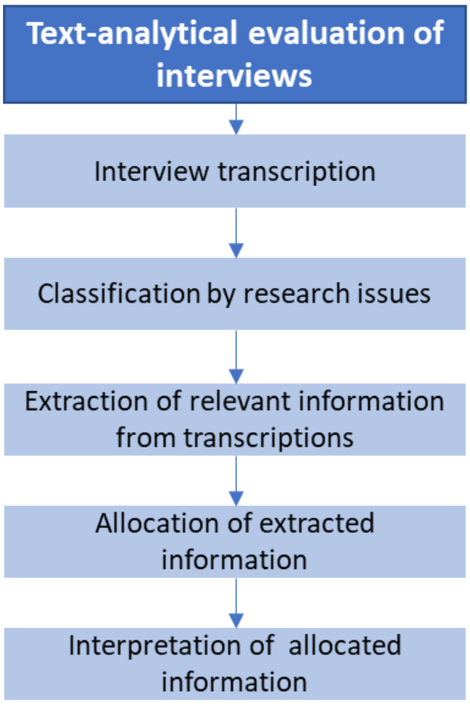

Figure 3.3: **Procedural steps for a Qualitative Content Analysis**

Source: own representation according Gläser[248]

The interview texts are transcribed word by word. The answers are evaluated by research questions and are cross checked for each participant. The results for participant BG and MS (stretching company) and for TB and TK (aviation company) are evaluated in the joint context of the respective companies.

The classification of results by participant and company in the context of the other interviewees' answers allows to critically question and compare the perspectives. The text resulting from the evaluation of the interviews thus can be interpreted reproducibly and is classified in the context of previous research by direct reference to the research questions.

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[247] GLÄSER, Jochen and Grit LAUDEL. *Experteninterviews und qualitative Inhaltsanalyse:* Springer-Verlag, 2010, 201-204.

[248] GLÄSER, Jochen and Grit LAUDEL. *Experteninterviews und qualitative Inhaltsanalyse:* Springer-Verlag, 2010.

3.5 Interview results

Section 3.5 presents the interview results according to the plan developed in section 3.4. Referring to the results the research model is adjusted and concretizes the suggested hypotheses. The full-text interviews are included in appendix 8.1.

Digital process maturity (IQ 3-6)

Interview questions 3 to 6 analyze the participants' understanding and perceived relevance of process maturity.

Film stretching company

According to BG digital process maturity means that all relevant business data are digitalized and that manual transference and conversion is possibly avoided. The business process is available as a digital representation. MS explains that digital processes cope without manual data and frequently even without human intervention.

As BG explains, the whole value creation process at the film-stretching company, i. e. all departments, processes, development and procurement, applies digital technologies. Furthermore, the final product is digitalized. Increasingly, customers servicing relies on digital technologies, too. MS underlines the high relevance of digital customers and internal processes in their company. Digital supply chain management has just been stepped up to establish a fully digital interaction of suppliers, their company and their customers.

According to BG, their film-stretching company is strongly conscious of the relevance of digitalization and attempts to digitalize every new process. MS agrees that digitalization is given high priority in their company, which shines up when the budgets of digitalization projects are analyzed.

Measurements systems for the degree of digitalization however are not available in their company (MS & BG).

Aviation company

According to TK, digital process maturity implies that computer aided processes are fully established. Similarly, TB explains that mature digital processes should reflect the diverse requirements to the development of a complex product. This means that information is made available to different clients based on a joint digital data basis and digital communication.

In the aviation company, digital process maturity is essential in engineering above all. TK thinks that their company has about 50% progressed towards digital process maturity. Employees are partly conscious of the relevance of digitalization. TB agrees that some employees have no more than a basic understanding. While some employees are open towards the implementation of new software tools, others are more reserved (TK). TB sees digital process maturity as key to future development and growth, however. ~~To date~~ Currently, there are no efforts to measure digital process maturity in their company (TK & TB).

Product development efficiency (IQ 7- 8)

Interview questions 7 and 8 explore what participants understand by efficiency in product development and how it is measured.

Film stretching company

The film stretching company measures key performance indicators, customer service reaction times, work hours per service order and number of cases per time unit. The company intends to reduce project specific costs and focusses on key activities, which have resulted in significant cost reductions (MS).

Aviation company

According to TK, efficiency means that there are established processes which are well established in the company and the number of design loops is controlled. The number of design loops could be used as a measure of efficiency. Efficient development searches for the best solution in collaboration with other departments (TB). Efficiency of development is measurable through product performance (TB).

TK does not know to what extent technical efficiency impacts financial efficiency but assumes that there is an important interrelationship at multiple levels, e. g. timing, sustainability, and risk control. TB explains that financial efficiency of product development is realized when development time is controlled, development budgets are met and a marketable product results at low resource usage (low costs).

Causal relationship between digital process maturity and development efficiency (IQ 9 & 10)

According to the results of interview question 9 and 10, all participants see causal interrelations between digital process maturity and product development efficiency:

Film stretching company

According to BG, digital process maturity and development efficiency are directly interdependent. The company increases product development efficiency by avoiding double data structures. Mechanical construction and electrical project development operated on separate development programs and have integrated the data manually until recently. Today, both departments operate on a single system, which avoids redundancies and contradictions and thus has reduced development costs.

MS however does not see that digital maturity automatically increases efficiency. The way digitalization is implemented makes the difference.

BG explains that although digitalization in the film-stretching company is very high, there are still redundant data structures. BG hopes to realize further efficiency gains in this process. Equally, MS sees further potential efficiency gains from digitalization which could result from the reduction of development times, higher transparency and the digital support of operative tasks.

BG however admits that digitalization can compromise flexibility. Digital processes hardly allow deviation from routines and standards. Human intervention should remain possible even in highly automated systems.

Aviation company

According to TB, there is a partial causal relationship between digital process maturity and development efficiency. Data management maturity is one important factor. TK assumes that the level of digitalization impacts the efficiency of product development processes with a time lag. Investments in digital technologies from a certain break-even point on will enhance development efficiency. TK thinks that their company could enhance technical development efficiency by digitalization in the field of tolerance management. This department currently relies on mainly manual documentation.

Moderators of the relationship between digital process maturity and development efficiency (IQ 11 & 12)

As interview questions 11 and 12 reveal, the participants agree that diverse moderators impact on the relationship of digital process maturity and digital product development efficiency:

Film stretching company

Employee competence and decision autonomy are the most important aspects to make digitalization succeed, according to BG. Employees should look beyond their responsibility range and understand what drives efficiency in neighboring departments.

Clear structures and budgets, according to MS, are further moderating factors necessary to enhance development efficiency by digitalization.

Risk management is a second very important aspect to make digitalization successful (BG & MS). Their company assesses the investment risk before high-sophisticated technological equipment is acquired and introduced. New technologies or unexpected environmental circumstances could turn investments obsolete. Risk plans classify risks and prevent mis-investments (BG). Data security in this context is another important aspect (MS).

Business specific factors, e.g. the degree of internationalization or the business sector, codetermine the extent to which digitalization can be effective. In BG's company internationalization and high technological requirements of film stretching require a high degree of digitalization to operate efficiently at all (MS).

Aviation company

The success of complex products, according to TB, depends on diverse factors, e.g. the availability of expert knowledge, interdisciplinary collaboration between departments, effective management of and reduction of interfaces between the departments.

According to TK, diligent problem analysis before starting the development process is essential to utilize the impacts of digitalization. Managerial support is another important moderator of the effect digital maturity can take in the development process.

TK does not think that company specific factors matter for businesses beyond a certain size (of about 150 employees). In his opinion bureaucratic structures are similar for medium-sized as well as large companies. TB agrees that all companies face similar problems while subject issues frequently differ.

3.6 Conclusions from qualitative interview section

3.6.1 Comparative analysis of results

The interview results are summarized in an overview table, to extract the main points and compare the results:

Table 3.3. **Interview results – summary**

Interview results – summary by model parameter		
Issue	**Film-stretching company**	**Aviation company**
Digital process maturity - concept	• Digitalization and transference of business data • Avoid manual data management • Digital appliances in product • Digital customer management • Digital supply chain management	• Establishment of computer aided processes • Comprehensive digital product development process
Digital process maturity - measurement	• Consciousness of relevance of digitalization • Budgeting digitalization • Priority of digitalization issues	• Progress of digitalization • Consciousness of relevance of digitalization • Openness of employees to digitalization
Product development efficiency measurement	• Customer service times reduced • Output per time unit maximized • Project cost reduced • Key performance indicators	• Number of design loops of R&D projects diminished • Product performance improved • R&D timing met • R&D budget met
Impact of digital process maturity on R&D efficiency	Digital data processes directly enhance development efficiency and reduces costs, development time & increases transparency of cost and risk	Digital data processes amongst others impact R&D efficiency with a time lag !!Amortization of IT technology
Moderators of impact of digital process maturity on R&D efficiency	• Employee competence • Employee decision autonomy • Clear organizational structures • Budgets for digitalization • Investment risk management • Data security management	• Expert knowledge • Interdisciplinary collaboration between departments • Effective collaboration management • Managerial support
Business specific controls	• Level of internationalization • Relevance of technology to business	

Comparing the results of the interviews between the film-stretching and the aviation company, similar understandings of the relevance of digital process maturity shine up:

Digital process maturity implies that the vast majority of data is fully digitalized and managed by computer systems. This concerns the development process itself (aviation company). The film stretching company extends this requirement to the digitalization of the final product, digital customer- and supply chain management.

A broad variety of measures for the progress of digital maturity is named. Both companies demand that all members of the organization should have recognized the relevance of digitalization and employees should be open-minded concerning this strategic step. Digitalization issues should be prioritized and sufficiently budgeted.

The film stretching company measures product development efficiency at all organizational levels, e. g. at customer service times, output time, project cost control and financial performance indicators. This accounts for the understanding that R&D efficiency and business efficiency are closely interlinked. The aviation company is not fully certain to what extent a direct impact of R&D efficiency on business efficiency exists. Measurement of R&D efficiency is done at the level of the R&D department mainly. Examples for this assessment are the fulfilment of schedules and budget plans, reduction of design loops, or the performance (improvement) of the final product.

According to the interviewees of the film-stretching company, digital process maturity directly impacts development efficiency e. g. by cost and development time reductions, transparency increase and risk control. The representatives of the aviation company see an indirect relationship between digital process maturity and R&D efficiency and emphasize the high relevance of additional moderators. Digital investments accordingly become effective with a time lag, e.g. after investment cost amortization.

All four participants identify several moderators of the impact of digital maturity on development efficiency. Both companies agree that knowledge management e.g. employee competence and expert knowledge are essential to make digitalization projects succeed. The film-stretching company additionally points out the relevance of clear organizational structures which enable employees to decide autonomously. The aviation company points out the relevance of inter-department collaboration and the effective management of this process. Budgeting, data security and risk assessment of digitalization investments are further important moderators according to the executives of the film-stretching company.

Only the film-stretching company recognizes business specific control factors, e.g the level of internationalization and the degree of technological orientation.

3.6.2 Adaptation of research model and hypotheses for quantitative research

The interview results widely confirm the research model suggested based on the review of previous studies and allow some further concretizations of the model with regard to the quantitative research stage.

The interviews have provided closer insights on what digital process maturity means from the perspective of German mechanical engineering businesses. Digital business data management and transference, digital products, digital customer management and digital supply chain management are the essential parameters of digital process maturity accordingly.

Neither of the interviewed companies in fact applies maturity models. The interviews thus provide no concrete information on hypothesis 1. It seems plausible that businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models. Hypothesis 1 remains to be evaluated in the quantitative section.

Measures of technical and financial efficiency relevant in the mechanical engineering business have been concretized in the course of the interviews.

Technical efficiency concerns the accomplishment of R& D time schedules and control of product design loops, conformity to R& D budgets and finally product performance. These technical efficiency measures concretize the review results based on concrete key figures.

Financial efficiency concerns the reduction of project costs, the maximation of output per time unit and the accomplishment of key performance indicators e.g. profitability. These results correspond to the review-based insights which define financial efficiency as schedule, cost, and risk control resulting in economic performance.

All four participants agree that digital process maturity impacts R&D efficiency but emphasize that several moderators have to be considered. This observation confirms the basic model. While the film stretching company observes impact of digital process maturity on technical as well as financial R&D efficiency, the aviation company is not certain about the impact on financial efficiency. Positive financial impacts seem plausible in the long run when digitalization investments have amortized. These findings from the interviews provide initial empirical support for hypotheses H2 and H3, accordingly.

H2) Digital process maturity significantly enhances technical efficiency.

H3) Digital process maturity significantly enhances financial efficiency.

The participants basically agree that R&D efficiency contributes to financial business performance–since efficient R&D reduces development costs and time and results in superior products which offer advantages in sales markets. These observations preliminarily support:

H4) Technical efficiency enhances financial efficiency.

Hypothesis 5 refers to the moderators of the impact of digital process maturity on development efficiency and essentially four moderators have been derived from the review. These are mainly confirmed concerning their relevance by the interviews and are concretized concerning the relevant items.

The participants agree on the high importance of knowledge related moderators. These concern employee competence and expert knowledge but equally interdisciplinary collaboration within and between the departments.

Business related moderators have partly been confirmed by the film stretching company. Accordingly, the degree of internationalization and relevance of technology to the business are important. The observation of TB and TK that "from a certain size" businesses share the same problems and suggests that business size is another business specific moderator.

Control-related moderators concern the issues of managerial support, employee autonomy budgeting and organizational structures addressed in the interviews.

Both companies find risk control factors highly relevant, and the necessity of managing IT investment risk and data security have been explicitly addressed.

The interview results thus equally confirm hypotheses H5a to H5d and provide adequate measurement items.

Integrating the review and interview results, the work model now is amended by concrete measurement categories and formulated in a quantitatively testable version, shown in Figure 3.4:

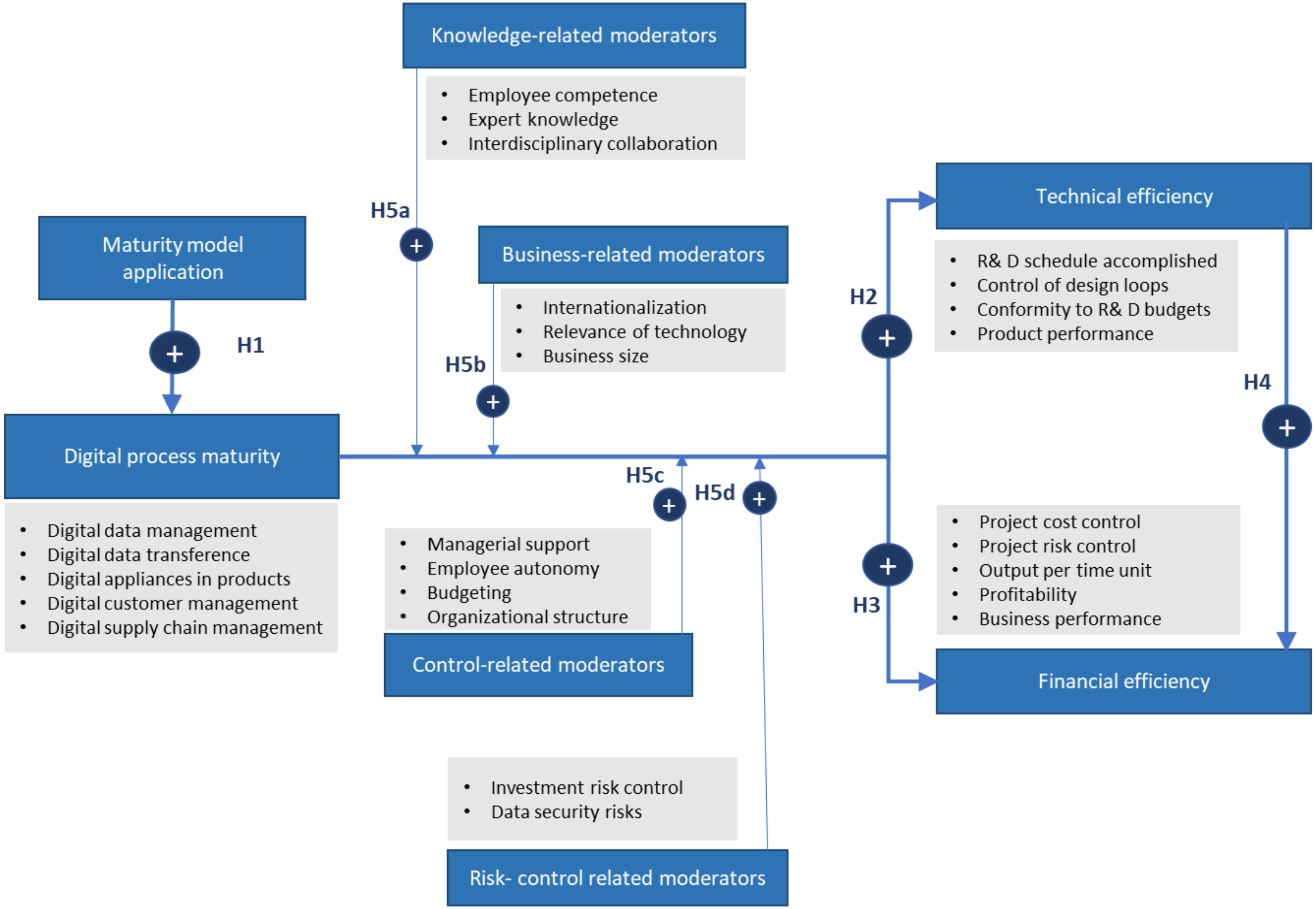

Figure 3.4: **Review- and interview-founded concretized work model**

4. QUANTITATIVE BUSINESS SURVEY

Chapter 4 develops, implements, and evaluates the business survey in order to test the review founded and interview-adjusted work model.

4.1 Objective of quantitative survey

A quantitative survey among German businesses in the mechanical engineering sector is devised to empirically verify and quantitatively found the suggested causal model on the impact of digital process maturity on technical and financial efficiency of product development in mechanical engineering. The empirical results are evaluated using statistical methods in order to quantitatively test the hypotheses of the work model. Based on the survey results the following insights have been gained:

H1) Businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models.

H2) Digital process maturity significantly enhances technical efficiency.

H3) Digital process maturity significantly enhances financial efficiency.

H4) Technical efficiency enhances financial efficiency.

H5 Moderators, particularly H5a) knowledge-related, H5b) business-related, H5c) control-related and H5d) risk-control related factors-positively moderate these relationships.

These hypotheses are now tested in a quantitative study. The results support businesses in the German mechanical engineering sector to optimize their R&D by comprehensively applying digital processes.

From an academic perspective the quantitative study part provides a novel, sector-specific causal model which explains the impact of digital process maturity on development efficiency and considers several moderators. The model is adaptable to other business sectors and countries.

4.2 Methodology of quantitative survey

The design of the quantitative survey comprises the selection of survey participants, the definition of the survey categories and scales, survey implementation and the statistical method of analysis.

4.2.1 Survey participant – selection and address

To explore the model for the German mechanical engineering sector, businesses in this sector are asked for participation. The study focusses on small- and medium sized companies since the sector analysis (chapter 3.3) and more specifically the interviews have shown that SME frequently struggle with digitalization and at the same time could gain major advantages by digitalizing R&D processes to a larger extent.

Ideally, executives in the field of R&D should answer the survey since they should be informed on digitalization maturity and efficiency of the development departments as to their function. The contact data of the R&D departments of the respective companies are selected from the companies' websites to reach the required addressees reliably.

The study participants are recruited through three channels. A first group is known to the author in persona, a second group is contacted via the author's linked-in profile and a third group is a Survey-Monkey recommended target audience.

The survey is devised as a digital multiple-choice questionnaire. The questionnaire is posted via the website Survey-Monkey and a link to the survey is sent to the addressed companies' R&D departments' contact email addresses.

The necessary number of valid survey responses can be calculated from the total population size N and for a certain confidence level (here 95%, resulting a z-value of 1.96) and a certain predefined error range e (here 10 %), e.g. using the sample size calculator provided by the statistical data collection portal Survey-Monkey.de and from the following common rule:

$$sample\ size = \frac{\frac{z^2 \cdot p(1-p)}{e^2}}{1 + \left[\frac{z^2 \cdot p(1-p)}{e^2 \cdot N}\right]}$$

With p = probability of fit; N = population; Z = confidence level; e = error range

Sample size requirements change based on what percentage of your sample selects a particular answer. When conducting a survey for the first time, statistic data collection portals recommend using p = 0.5 to calculate the optimal sample size (because most surveys have more than a single question and therefore more than a single percentage to evaluate). At p=0.5 is an estimation of the sample size that is neither too conservative nor too imprecise.

Provided that one questionnaire is submitted by company the population of German mechanical engineering businesses is 6,600. [249]Accordingly, the necessary sample size for a z value of z = 1,96, a probability level of 95% and an error range of 10% with described p above, is 95 companies.

4.2.2 Definition and coding of survey categories

To design the survey the part-questions by model items and adequate scales have to be defined.

In accordance with the work model, the survey comprises four sections:

1. General company information, which at the same time assesses business specific moderators
2. Data concerning digital maturity model application and the level of digital process maturity
3. Data concerning technical and financial R&D efficiency
4. Moderators of the impact of digital maturity

All survey elements are formulated positively in the form of questions or test statements to possibly avoid participants' biases. The model items are directly transformed into test statements.

The following table comprises the survey in the English version.

[249] KLINKUSCH, Julia. *Branchenprofil Maschinenbau in Deutschland: Stirbt der Klassiker aus?* [online] [viewed 6 September 2023]. Available from: https://www.ingenieur.de/karriere/branchenprofile/maschinen-und-anlagenbau/.

1st Survey section

Table 4.1: **Survey part 1 - General company information, which at the same time assesses business specific moderators**

Participant & Company: Please give us some information on yourself and your company!		
P1	Which sector is your business in?	(1) Agricultural equipment (2) Mining & metal processing (3) Driving & engines (4) Electric technologies & automation (5) Industrial Production machinery (6) Machinery for consumer good production (7) Other sectors
P2	What is your position in the company?	(1) Owner/ founder (2) CEO (3) Board member (4) Executive (5) Line employee (6) Other
MP3	What is the size of your company?	(1) 1-10 employees (2) 11-50 employees (3) 51-100 employees (4) 101 to 250 employees (5) 251- 500 employees (6) 501 to 1,000 employees (7) > 1,001 employees
MP4	To what extent is sophisticated technology important to your company?	(1) Not at all (2) Not very important (3) Intermediate important (4) Important (5) Highly important
MP5	What is the reach of your company's business operations?	(1) local (2) national (3) some international interactions (4) international in up to 5 countries (5) international in more than six countries

2nd Survey section

Section 2 of the survey assesses the extent to which digital processes in the company are mature (questions DM 1 to 5) and whether the company applies maturity models (MM1 and MM2).

To scale the maturity categories the survey refers back to the stages of the CMMI maturity model described in section 1.2.2, which is the only model adjusted to the requirements of engineering in particular. The CMMI model uses the following maturity stages: [250]

(0) initial

(1) managed

(2) defined

(3) quantitatively managed

(4) optimized

The maturity levels are coded in the form of a Likert scale and in common language in order to assess the maturity degrees by model item reliably.

Table 4.2: **Survey part 2 - General company information, which at the same time assesses business specific moderators**

Maturity of digital processes: Please inform us on digitalization in your company according to your personal judgement! How do you feel about the following statements with regard to your company?		
DM1	We use digital data management in all departments.	(1) Not implemented (2) In its early stages of implementation (3) Partly implemented (4) Fully implemented (5) Perfectly implemented & working
DM2	We use digital data transference in all departments.	Like DM1
DM3	Our products dispose of digital features and appliances.	Like DM1
DM4	Our customer management uses digital media and data resources.	Like DM1

[250] TEAM, SCAMPI Upgrade. Appraisal Requirements for CMMI, Version 1.2 (ARC, V1. 2). *Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University.* 2011, p5-7.

DM5	Our supply chain management uses digital media and data resources.	Like DM1
MM1	Does your company apply maturity models in some business field?	(1) No (2) Yes (3) Not sure
MM2	Does your company apply maturity models for the measurement of digitalization progress?	(1) No (2) Yes (3) Not sure

3rd Survey section

The third survey section collects information concerning R&D technical and financial efficiency again referring back to the model items by part question. To scale the efficiency categories of the model the survey uses a Likert scale, which - drawing on Balk[251] - equally comprises five stages:

Table 4.3: **Survey part 3 - Data concerning technical and financial R&D efficiency**

Efficiency of product development: Please inform us on the efficiency of product development in your company according to your personal judgement! How do you feel about the following statements with regard to your company?		
ET1	Our R& D schedules are accomplished.	(1) Not at all (2) Rarely (3) Partly (4) Usually (5) Always
ET2	We plan and control the number of design loops.	Like ET1
ET3	We are conform our R&D budgets.	Like ET1
ET4	Our products perform from a customer perspective.	Like ET1
ET5	We accomplish the defined (required) product specifications.	Like ET1
ET6	Our products are of high quality.	Like ET1
EF1	Wie effectively control project costs.	Like ET1
EF2	We effectively control project risks.	Like ET1
EF3	We realize the expected output per time unit.	Like ET1
EF4	Our company operates profitably.	Like ET1
EF5	Our business is performing well.	Like ET1

4th Survey section

[251] BALK, Bert M. Scale efficiency and productivity change. *Journal of productivity analysis*, **15.** 2001, pp. 159-183.

The fourth survey section measures the potential moderators of the impact of digitalization maturity on product development efficiency, i.e. knowledge-related, control-related and risk-related aspects. Business related aspects have been measured in section 1. to measure the moderators again a five-stages Likert scale is applied.

Table 4.4: **Survey part 4 - Moderators of the impact of digital maturity**

<u>Impacts on digitalization effectiveness:</u> Please inform us which factors take effect on the impact of digital technologies in your company according to your personal judgement! How do you feel about the following statements with regard to your company?		
MK1	Our employees are competent concerning digital technologies.	(1) I agree not at all. (2) I agree to a low extent. (3) I agree partly. (4) I agree to a large extent. (5) I fully agree.
MK2	Our employees dispose of expert knowledge in the field of digital technologies.	Like MK1
MK3	Our company practices interdisciplinary collaboration in the field of digitalization.	Like MK1
MC1	Our management supports digitalization.	Like MK1
MC2	Our employees enjoy autonomy in the implementation of digital technologies.	Like MK1
MC3	Digitalization projects are well budgeted.	Like MK1
MC4	Our organizational structures promote digitalization.	Like MK1
MR1	We effectively control investment risks in digital technologies.	Like MK1
MR2	We effectively control data security risks.	Like MK1

4.2.3 Statistical method of analysis (regression)

The statistical analysis comprises descriptive statistics, reliability testing, construct formation and causality analysis using a t-test to test H1 and regression modeling to test H2 to H5.

Descriptive analysis

The survey data are first analyzed descriptively in SPSS calculating the sample distributions. Then the distribution moments and the frequencies of the distributions are determined by part question.[252]

The descriptive analysis focuses on the first two moments of the distribution (mean, median, standard deviation). The mean shows the average of the results, the median, the value realized in the middle of the distribution, and the standard deviation characterizes distribution volatility.[253]

The data series are additionally tested for normal distribution using the Kolmogorov-Smirnov and Shapiro-Wilk test. Normal distribution is necessary to do ANOVA and is assumed if both tests are significant (i.e. significance values are below 0,05).

Reliability analysis and construct formation

Reliability analysis compiles and evaluates the individual items (part questions) to come to comprehensive constructs for further use in regression models. It includes the items (part questions) contained in a (prospective) scale e.g. “digital process maturity” as a construct and then determines the reliability for the overall construct as the sum of the items. To perform a reliability analysis, input-variables have to be based on a uniform scale, have uniform orientation and a uniform value range. This is the case here, due to their uniform measurement on a 5 level Likert scale.

The reliability of a construct is a measure for the degree of accuracy or internal consistency. Cronbach Alpha is the most important key ratio to assess reliability and refers the inherent variance of the factors to the total variance of the construct. Its maximum (ideal value) is 1. Cronbach's alpha should be at least 0.7 for more than 4 indicators in a construct. An Alpha value of 0.5 is acceptable for small datasets and less than four items. The value of Cronbach Alpha also increases with the number of indicators.

[252] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011, p380-382.

[253] COOK, Thomas D., Donald Thomas CAMPBELL, and William SHADISH. *Experimental and quasi-experimental designs for generalized causal inference:* Houghton Mifflin Boston, MA, 2002, p218-222.

If reliability according to Cronbach's Alpha is not reached, a principal component analysis without rotation is applied to eliminate items, that do not fit with the intended construct. The SPSS procedure principal component analysis is equally used to calculate to final construct as variables for use in the regression model. Essential tests are briefly explained:[254]

- The sum of squared factor loadings extracted for the relevant factors should be above 0.75 and ideally only a single factor should be extracted to reach a conclusive parameter construct.
- The Kaiser-Meyer-Olkin criterion (KMO) results from the agglomeration of MSA values and should be above 0.5.
- The Bartlett-Test checks the null hypothesis that the variables come from an uncorrelated population and should be rejected.

The method "Factor reduction" in SPSS is applied to condense the part-questions to constructs. It uses regression modelling to condense the items to constructs. The resulting constructs are metrically scaled from 1 to 5 and higher values indicate higher variable manifestations. The following constructs are formed and assigned the following coded:

Table 4.5: **Constructs for further evaluation resulting from reliability analysis**

I	**Explaining factors Digital process maturity**	**M**	**Moderators**	**T**	**Target factors (At consumers)**
MM	Maturity model application	MP	Business related moderators	ET	Technical efficiency
DM	Maturity of digital processes	MK	Knowledge related moderators	EF	Financial efficiency
		MC	Control related moderators		
		MR	Risk control related moderators		

The factor constructs are saved as standardized variables (mean = 0, standard deviation = 1,0) for further calculations.

<u>Mann-Whitney U-Test for paired samples to test H1</u>

A Mann-Whitney U-Test for unpaired samples is apt to test whether two-part samples within one main sample differ significantly concerning an item. It is applied if the items to be

[254] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011.

compared are ordinally coded. Here it is used to examine whether companies applying maturity models according to part question MM1 (“Does your company apply maturity models in some business field?”) and MM2 (“Does your company apply maturity models for the measurement of digitalization progress?”) differ concerning digital process maturity. The analysis considers only decided answers (i. e. 1 = no and 2 = yes, while undecided answers (3 = not sure) are omitted from the T-test. The Mann-Whitney-U Test is based on a comparison of data ranks, i. e. does not consider the distances between the coded values and used standardized values (i.e. the mean of the values is subtracted from the originally indicated values and the difference is divided by the standard deviation of the distribution).

The z-value is texted for significance by comparing it with the critical value of the standardized normal distribution. It checks whether, for a sample containing two characteristic values, the two sample mean values for a target variable differ significantly, considering the empirical variances and the number of cases per group. If the t-value of the sample is greater in magnitude than that of the t-distribution at a probability of 95% (Sig. 0.05), the zero-hypothesis (H0), that the distributions for both part samples are equal is rejected and the test hypothesis, that they are unequal (here H1) is adopted. [255]

The Mann-Whitney-U- test parameters result as follows:

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$

Where n_1 is the sample size of the part group with the higher rank and n_2 is the sample size of the part group with the lower rank and R_1, is the bigger of the rank sums.[256]

A Kolmogorov-Smirnov test of normality precedes the Mann-Whitney U Test to first assess the extent to which the distribution of DM 1 to DM5 differ for both part-groups. If Kolmogorov-Smirnov significance is below 0.5 the distributions of both part groups differ significantly in the form of their distributions, if Kolmogorov-Smirnov significance is above 0.5 they only differ in the height of their median.

Regression modeling & hypothesis tests for H2 to H5

[255] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011, p481.

[256] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011, p875-876.

The study uses a regression model to assess the impact of explaining factors and moderators on the target factors for H2 to H5.[257]

It is based on ordinary least square regression and uses a regression model of the following form, which x_i indicated the explaining factors I and the moderators M and Y indicates the targets T:

$$y = a + \sum_{i=1}^{n} b_i \cdot x_i + \varepsilon$$

The regression model estimates the parameters a and b_i by minimizing the average distance of each value pair i from a regression line. The estimate for b results as the ratio of the covariance of x and y and the variance of x with

$$b = \frac{s_{xy}}{s_x^2}$$

"a" is

$$a = \overline{y} - b \cdot \bar{x}.$$

To test the hypotheses an ANOVA test is conducted. ANOVA examines the share of variance from the total target variance explained by the model. ANOVA employs an F-test, examining the zero-hypothesis that the variables jointly do not explain the observed values at all. If ANOVA significance is below 0.05 (less than 5 % error probability) this assumption is rejected.[258] The individual explaining factors are tested based on a T-test and are accepted from a significance level of 95%. Hypotheses are assumed if the respective explaining factors or moderators are reliable based on the T-test.

To test H5 moderation analysis is used. It uses an interaction variable which is calculated as the product of the independent and the moderating factor. The regression model for testing H5 used the independent, the moderating, and the interaction parameter. The moderation effect is significant if both the interaction parameter and the moderator itself are significant according to the t-test. Sections 4.3 to 4.5 report on the descriptive analysis reliability and hypothesis tests.

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[257] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011, p499-501.

[258] COOK, Thomas D., Donald Thomas CAMPBELL, and William SHADISH. *Experimental and quasi-experimental designs for generalized causal inference:* Houghton Mifflin Boston, MA, 2002.

4.3 Descriptive analysis by items

Altogether 140 executives participated in the study. This result is representative and exceeds the necessary number of 72 participants calculated in section 4.2.1. The participants are from a broad range of business sectors. Most, 30% are in machinery production, 17.9% are in the automotive sector, and 15% in electric engineering and automation. All taken, almost 90% are in engineering.

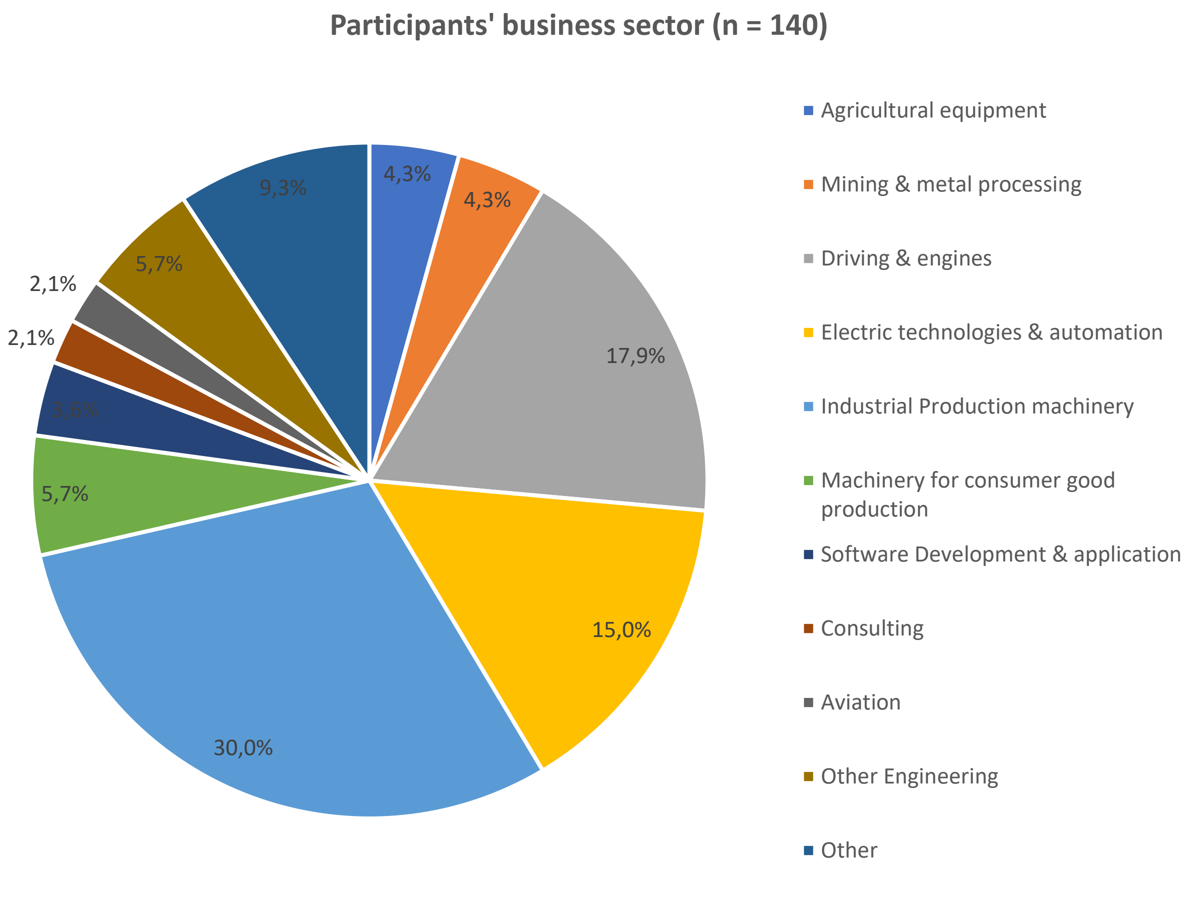

Figure 4.1: **Participants by business sector**

Classifying participants by their positions in their companies results Figure 4.2:

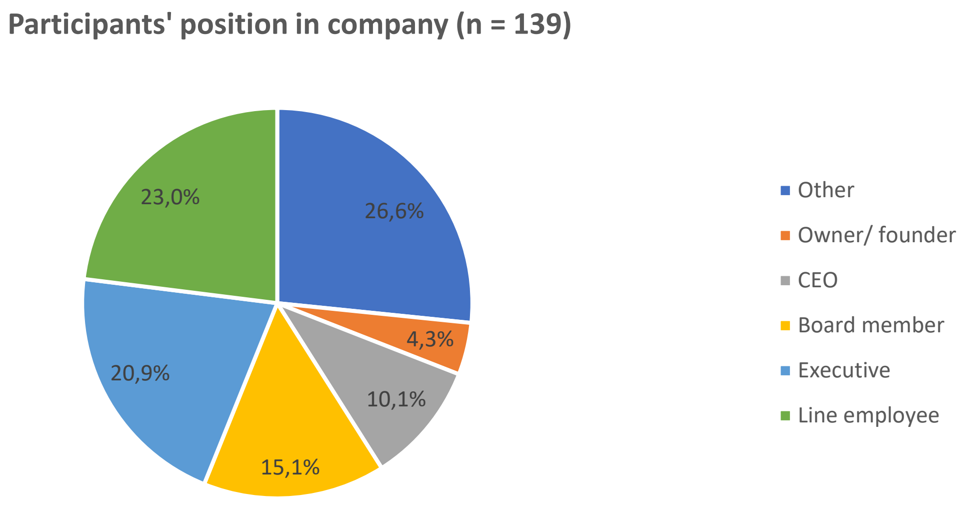

Figure 4.2: **Participants by positions in company**

Owners, founders, and CEOs account for 14.4% of the sample. 36% are board members or executives and another 23% are line employees. 26.6% hold other positions, e. g. freelancers or external employees.

The following table lists the sample moments of the items by part question:

Table 4.6: I**tem results (mean, Std. Dev., skewness, kurtosis) for the questions**

Item	valid	missing	mean	Std. Dev.	skewness	kurtosis	Min.	Max.
MP3	140	0	4,514	2,157	-0,238	-1,353	1	7
MP4	140	0	3,750	1,206	-0,678	-0,485	1	5
MP5	139	1	3,590	1,536	-0,513	-1,308	1	5
MM1	132	8	2,015	0,771	-0,026	-1,311	1	3
MM2	132	8	1,841	0,780	0,287	-1,298	1	3
DM1	132	8	3,015	1,126	-0,291	-0,556	1	5
DM2	132	8	3,152	1,052	-0,229	-0,220	1	5
DM3	130	10	3,146	1,195	-0,287	-0,651	1	5
DM4	132	8	3,136	1,117	-0,307	-0,620	1	5
DM5	132	8	3,144	1,049	-0,374	-0,111	1	5
ET1	124	16	3,113	1,098	-0,265	-0,531	1	5
ET2	125	15	2,992	1,208	-0,012	-0,782	1	5
ET3	124	16	3,081	1,166	-0,284	-0,806	1	5
ET4	125	15	3,664	1,198	-0,696	-0,435	1	5
ET5	125	15	3,472	1,215	-0,591	-0,605	1	5
ET6	125	15	3,808	1,169	-0,850	-0,093	1	5
EF1	125	15	3,480	1,215	-0,418	-0,763	1	5
EF2	125	15	3,448	1,267	-0,341	-0,946	1	5

EF3	124	16	3,476	1,246	-0,559	-0,572	1	5
EF4	124	16	3,758	1,164	-0,991	0,344	1	5
EF5	124	16	3,750	1,094	-0,887	0,325	1	5
MK1	123	17	3,122	1,142	-0,310	-0,739	1	5
MK2	123	17	3,138	1,051	-0,023	-0,338	1	5
MK3	123	17	3,285	1,191	-0,274	-0,638	1	5
MC1	123	17	3,504	1,327	-0,501	-0,902	1	5
MC2	123	17	3,171	1,143	-0,141	-0,734	1	5
MC3	122	18	3,262	1,141	-0,295	-0,500	1	5
MC4	123	17	3,220	1,258	-0,274	-0,901	1	5
MR1	122	18	3,008	1,168	0,047	-0,737	1	5
MR2	123	17	3,325	1,271	-0,367	-0,865	1	5

All available ranks have been assigned for each part question. The minima and maxima correspond to the coded range. Average values are mostly higher than the mean of the distribution. In correspondence skewness values are negative for all parameters (but MR1), indicating left skewed distributions of frequencies. All kurtosis values except EF5 are negative indicating flatter distributions than the normal curve and lighter tails. Respondents tend to indicate positive values and less extreme values than observed for a classical normal distribution. Details on frequency distributions are reported in the following paragraphs.

Business related moderating items assess company size (MP3), relevance of technological sophistication (MP4) and international reach of the businesses (MP5).

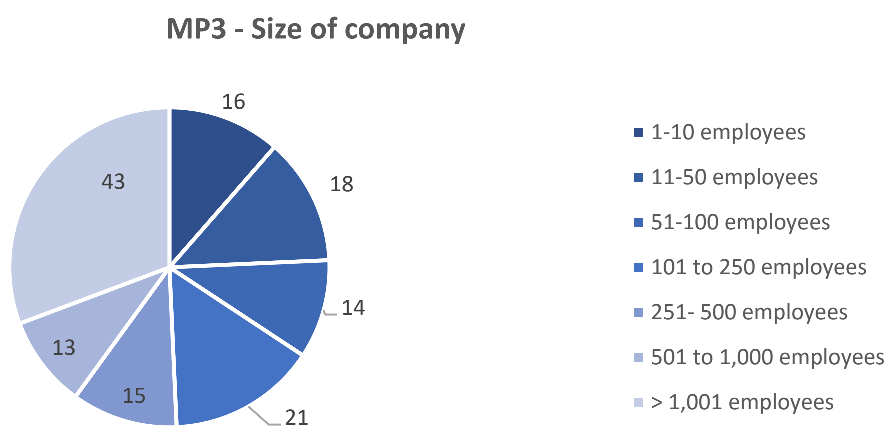

Figure 4.3: **Company size (MP3) - – distribution of frequencies – absolute figures**

43 companies (30.7%) employ more than 1,001 people, while 24.3% (16 companies) employ less than 50 people. Comparing these results to an official statistic of the distribution

of frequencies in mechanical/industrial engineering in Germany,[259] large companies of more than 1,000 employees are overrepresented in this sample, while in Germany average these account for about 2,05% of companies. Small and very small companies, which account for more than 63% of the population of Germany's mechanical engineering companies,[260] are underrepresented in the sample.

About half of the companies in the sample (46.8%) operate internationally in more than six countries: Only about 30% operate locally or on a national level only (compare Figure 4.4). This observation corresponds to the distribution of company sizes. Large companies tend to maintain international activities.

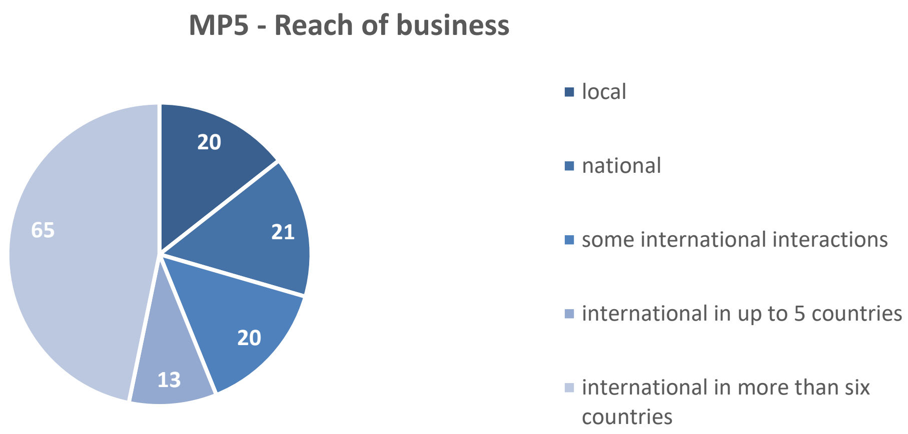

Figure 4.4: **Reach of surveyed businesses – distribution of frequencies – absolute figures**

For about 62% of the surveyed companies, technology is of very high relevance or importance, while only about 15% are low-tech businesses.

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[259] STATISTA. *Betriebsanzahl im deutschen Maschinenbau nach Beschäftigtengrößenklassen 2021 | Statista* [online] [viewed 7 September 2023]. Available from: https://de.statista.com/statistik/daten/studie/236301/umfrage/betriebsanzahl-im-deutschen-maschinenbau-nach-beschaeftigtengroessenklassen/.

[260] STATISTA. *Betriebsanzahl im deutschen Maschinenbau nach Beschäftigtengrößenklassen 2021 | Statista* [online] [viewed 7 September 2023]. Available from: https://de.statista.com/statistik/daten/studie/236301/umfrage/betriebsanzahl-im-deutschen-maschinenbau-nach-beschaeftigtengroessenklassen/.

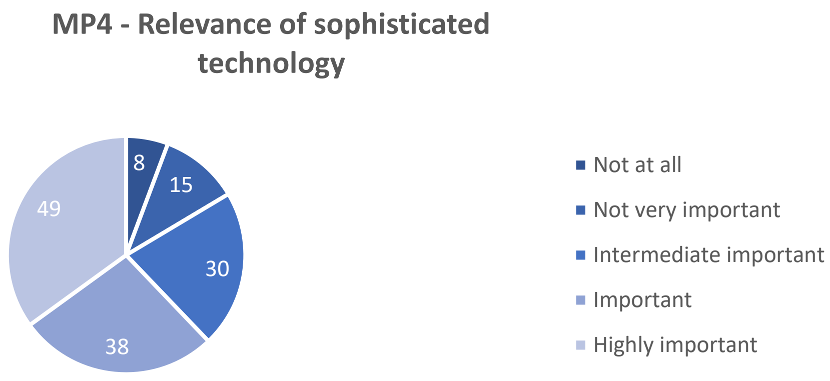

Figure 4.5: **Relevance of technology to surveyed companies – distribution of frequencies – absolute figures**

About 40% of the surveyed companies apply maturity models in some business field. 37.1% apply maturity modeling to measure digitalization progress. However, 23% to 30% of participants are not certain about the application of maturity models in their companies. 39.4% are certain that maturity modeling does not play a role in the measurement of digitalization progress and 28.8% assert that maturity models are not applied in any business field in their companies (compare Figure 4.6):

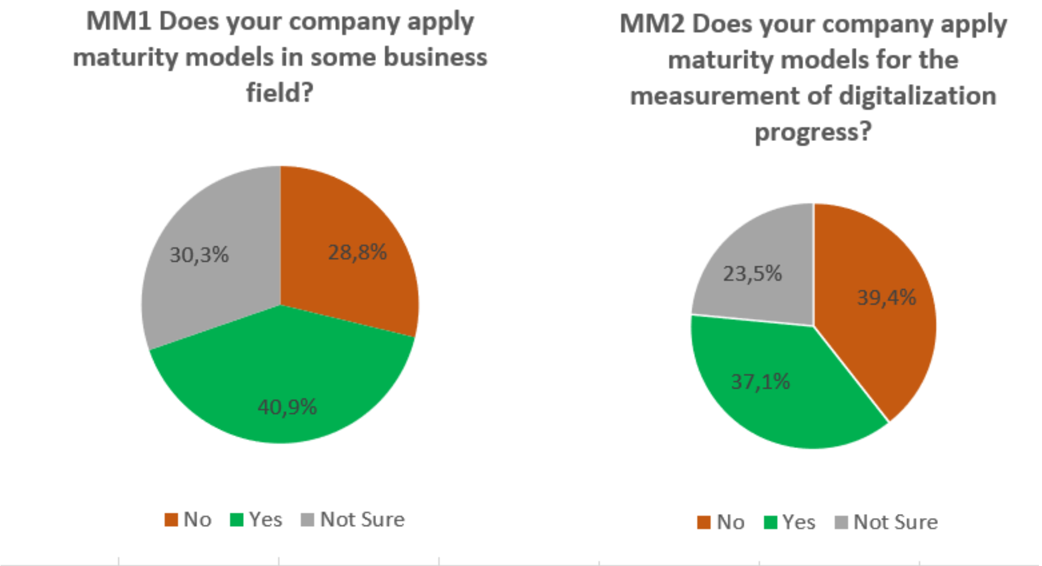

Figure 4.6: **Application of maturity models in the surveyed companies**

The frequency distributions of the items for digital process maturity (DM1 to DM5) are displayed in Figure 4.7. Between 9 and 11% of companies have not implemented any digital data management so far. Another 10 to 13% are in the early stage of implementation. Full implementation progress however has been reached in 34% to 38% of the sample, of which however only about two thirds find it perfectly implemented and working:

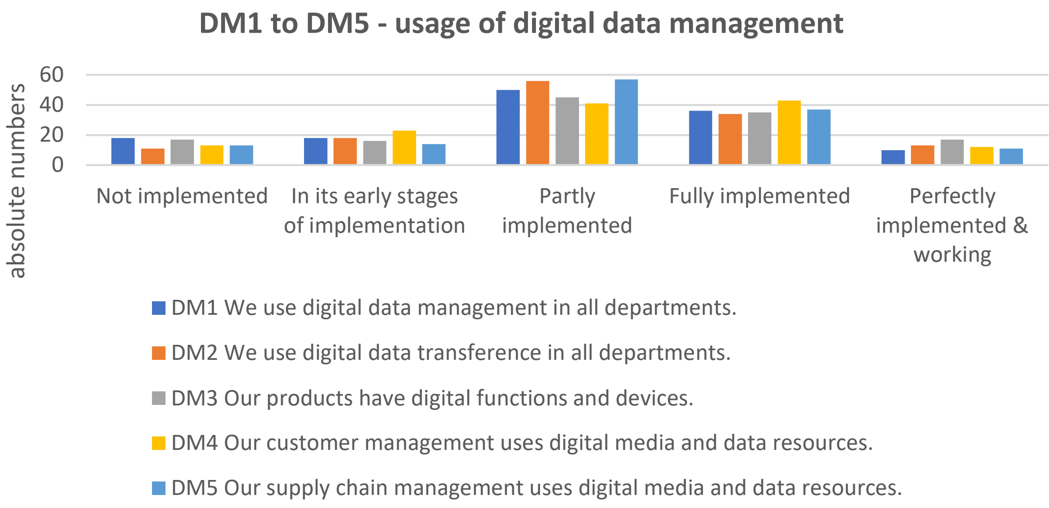

Figure 4.7: **Frequency distributions of items concerning usage of digital data management**

An analysis of the indicated values of the items ET 1 to ET 6 (technical efficiency) is reported in Figure 4.8:

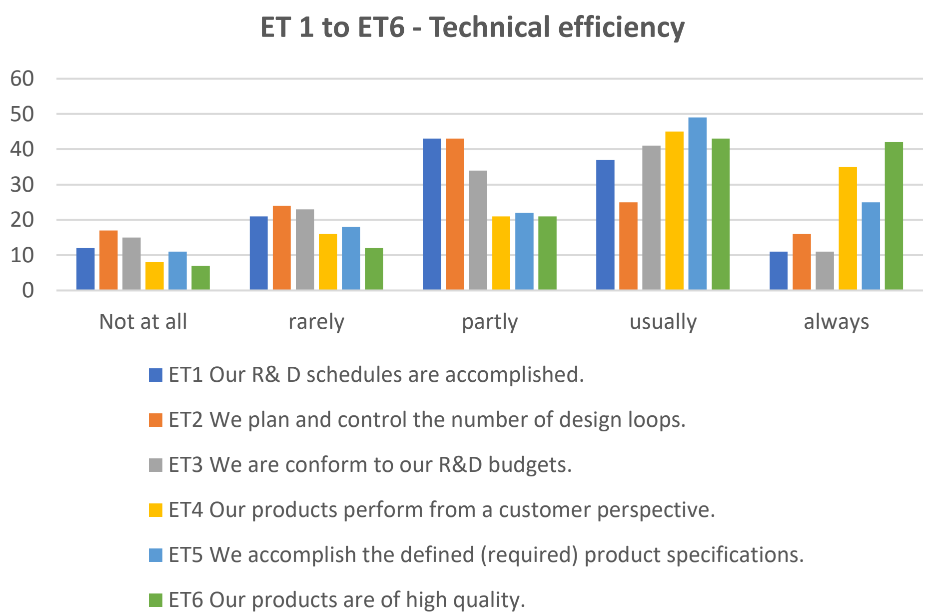

Figure 4.8: **Frequency distributions of items concerning technical efficiency**

While participants are only partly convinced that their R&D schedules are accomplished and the number of design loops is controlled, most agree that their companies reach the defined or required product specifications and that their products perform from a customer perspective. Results for financial efficiency (items EF1 to EF5) are reported in Figure 4.9.

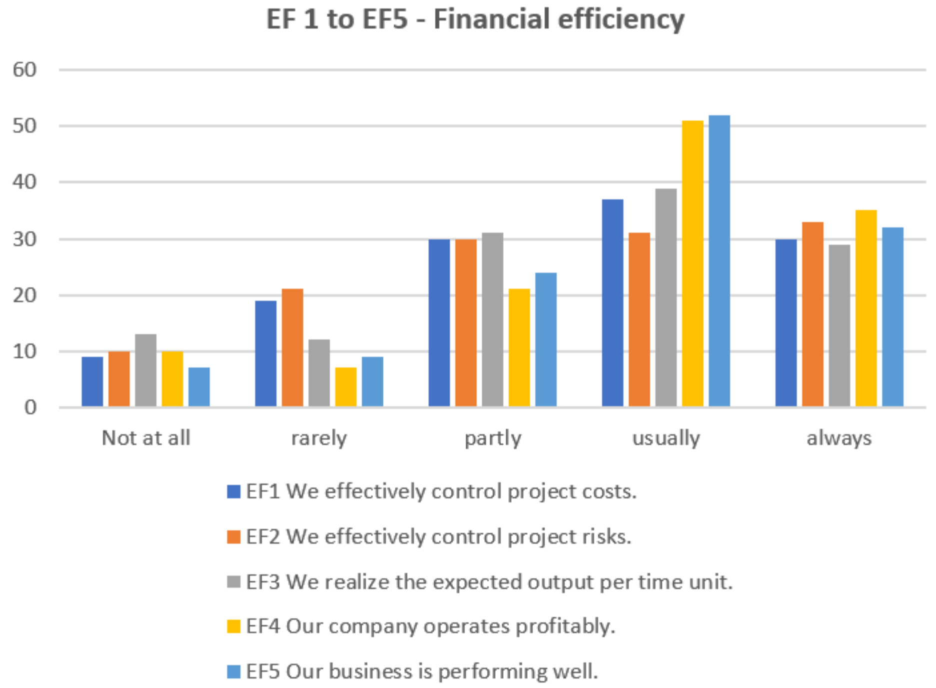

Figure 4.9 **Frequency distributions of items concerning financial efficiency**

It shows that the majority of participants are convinced that their company controls costs and risks, realizes expected outputs, operates profitably and usually or always perform well while only a minority of less than 25% agree to the test statements not at all or to a very limited extent.

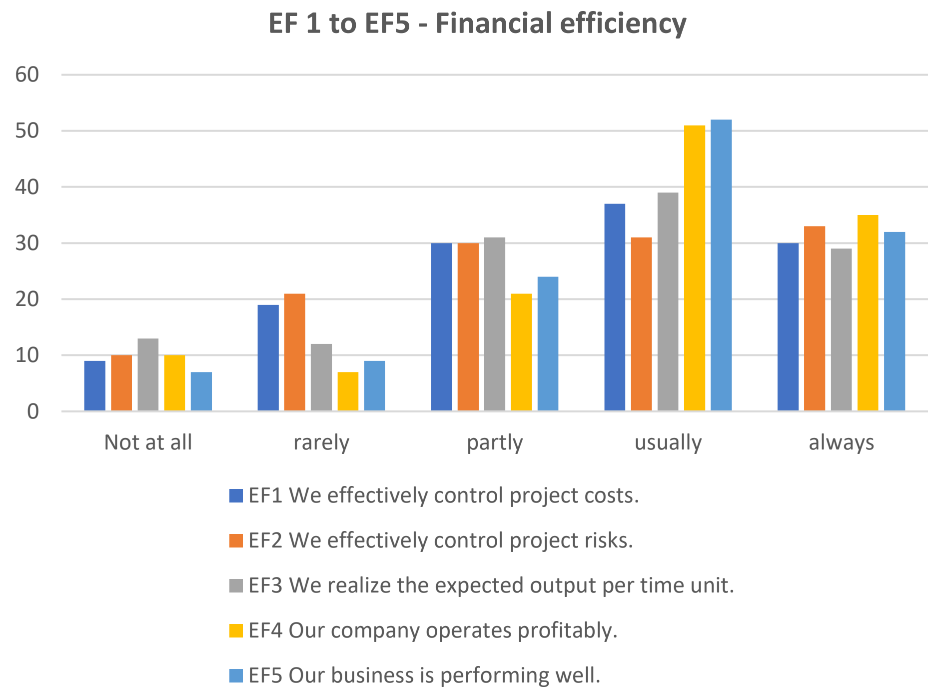

Figure 4.10: **Frequency distributions of items concerning financial efficiency**

According to the item-wise analysis of the distribution of frequencies of the moderators, participants are divided on their companies' knowledge-related competencies. Most indicate partial agreement to test statements MK1 to MK3 (compare Figure 4.11) (means 3.2 to 3.2).

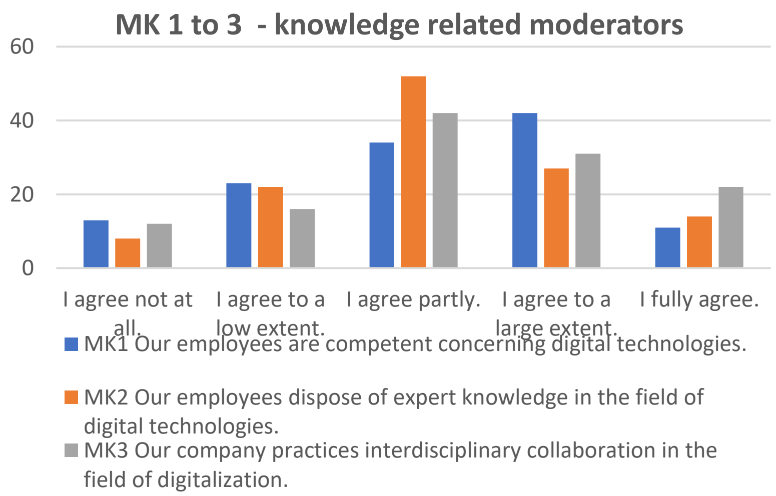

Figure 4.11: **Frequency distributions of items MK1 to MK3 concerning knowledge-related moderators**

The frequency distributions for items MC1 to MC4 control-related moderators are summarized in .. Participants show strongest support for MC1, i. e. assert strong managerial support for digitalization (mean: 3.5), while they are of different opinion on the extent to which digitalization projects are sufficiently budgeted (mean: 3.26) and on the level of autonomy employees enjoy in the implementation of digital technologies (mean: 3.17). Results for the two risk-control-related parameters MR1 and MR2 show mean values of 3.0 and 3.3. Respondents find data security related risks controlled more effectively than investment risks in digital technologies.

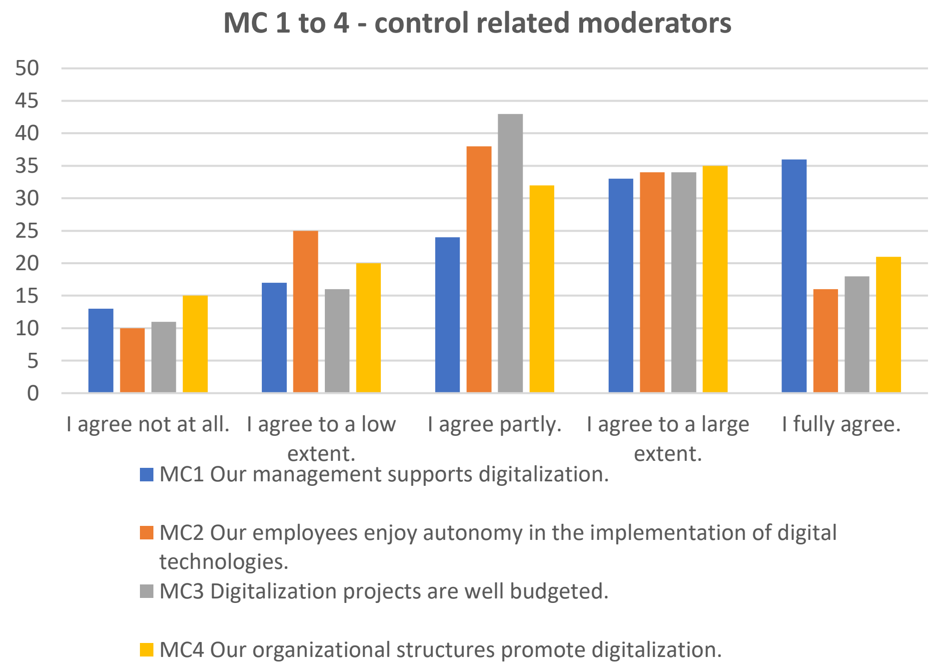

Figure 4.12: **Frequency distributions of items concerning control-related moderators**

4.4 Reliability tests and construct formation

To analyze the hypotheses, item-wise results are summarized to constructs which then become part of the regression models. The study uses explorative factor analysis and reliability testing to examine the constructs. The calculation results are summarized in Table 4.7:

Table 4.7: **Summary of reliability analysis**

Construct	Item names	No. of Items	Cronbach Alpha	Factors	Var. Extraction	KMO	Bartlett
			! > 0.7	! =1		!> 0.5	!< 0.05
DM	DM1 to DM5	5	0,860	1	64,15%	0,83	0,000
MM	MM1, MM2	2	0,834	1	85,73%	0,5	0,000
ET	ET1 to ET6	6	0,852	1	57,58%	0,814	0,000
EF	EF1 to EF5	5	0,851	1	62,72%	0,806	0,000
MP	MP3, MP4, MP5	3	0,610	1	59,11%	0,604	0,000
MK	MK1, MK2, MK3	3	0,833	1	75,18%	0,719	0,000
MC	MC1 to MC4	4	0,838	1	64,43%	0,813	0,000
MR	MR1, MR2	2	0,780	1	82,09%	0,5	0,000

The reliability analysis based on Cronbach Alpha delivers fully reliable constructs for DM, MM, ET, EF, MK, MC and MR, with C.R. values above 0.7. The reliability of MP is acceptable with 0.61, since MP comprises only three constructs. [261]

For each construct one factor is extracted and variance extraction is between 59.11 % (MP) and 85.73% (MM). KMO is above 0.5 for all constructs. For two- item constructs (MM and MR) KMO cannot be above 0.5, but the constructs are highly reliable based on the variance extraction of more than 80%. The Barlett-test is significant for all constructs. Based on these results all constructs are accepted.

4.5 Regression and test of hypotheses

4.5.1 Test of H1

H1 assumes that "Businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models." To test this hypothesis a Mann-Whitney U Test comparing the mean ranks for survey questions DM1 to DM5 for businesses answering MM1 and MM2 by yes or no are compared based on the standardized values of the distribution. Undecided participants ("not sure") are not considered in the evaluation.

MM1 differentiates businesses applying maturity models (2 = yes) and not applying maturity models (1 = no) in some business field.

Comparing the two subgroups for MM1 the following results are found (Table 4.8):

[261] BROSIUS, Felix. *SPSS 19:* MITP-Verlags GmbH & Co. KG, 2011, p829.

Table 4.8: **Mann-Whitney-U-Test of differences in DM1 to DM5 and DM for groups applying or not applying maturity models in any business field**

MM1 Does your company apply maturity models in some business field?

					differing median	differing distribution
		N	Mean rank	Sum of ranks	Mann-Whitney U Test Sig.	Kolmogorov-Smirnov-Test Sig.
ZDM1: We use digital data management in all departments.	1,00 No	38	37,91	1440,5	0,007	0,124
	2,00 Yes	54	**52,55**	2837,5		
ZDM2: We use digital data transference in all departments.	1,00 No	38	35,47	1348	0,000	0,067
	2,00 Yes	54	**54,26**	2930		
ZDM3: Our products have digital functions and devices.	1,00 No	38	35,86	1362,5	0,001	0,062
	2,00 Yes	53	**53,27**	2823,5		
ZDM4: Our customer management uses digital media and data resources.	1,00 No	38	38,95	1480	0,018	0,276
	2,00 Yes	54	**51,81**	2798		
ZDM5: Our supply chain management uses digital media and data resources.	1,00 No	38	35,49	1348,5	0,000	0,048
	2,00 Yes	54	**54,25**	2929,5		
ZDM: Digital Process Maturity	1,00 No	38	33,34	1267	0,000	0,002
	2,00 Yes	53	**55,08**	2919		

The sample size for the test is 91 or 92, since participants undecided on respective part questions MM1 or MM2 are omitted. Table 4.8 shows that part groups applying or not applying maturity models in some business field differ significantly, whereas the group applying maturity models shows significantly higher ranks for all part questions DM1 to DM assessing the extent of digital data management in the companies. The Mann-Whitney U test significance is below 0.05 for all part questions indicating that the median of digital data process maturity is significantly lower for the part group not applying maturity models than for the group applying maturity models. The results for part questions DM1, DM2, DM3, DM4 correspond in the form of the distributions based on Kolmogorov-Smirnov test, while DM5 and DM differ in the form of distributions. **Hypothesis H1 is accepted for MM1.**

The same analysis is done for part groups differing concerning MM2, the application of maturity models for the measurement of digitalization progress Table 4.9). Sample size for the test is 100 and 101 respectively, since not all participants answered the respective part questions.

Table 4.9: **Mann-Whitney-U-Test of differences in DM1 to DM2 for groups applying or not applying maturity models for the measurement of digitalization progress**

MM2: Does your company apply maturity models for the measurement of digitalization progress?

		N	mean rank	Sum of ranks	differing median Mann-Whitney U Test Sig.	differing distribution Kolmogorov-Smirnov-Test Sig.
ZDM1: We use digital data management in all departments.	1,00 No	52	42,78	2224,5	0,003	0,013
	2,00 Yes	49	**59,72**	2926,5		
ZDM2: We use digital data transference in all departments.	1,00 No	52	44,32	2304,5	0,013	0,19
	2,00 Yes	49	**58,09**	2846,5		
ZDM3: Our products have digital functions and devices.	1,00 No	51	40,75	2078	0,000	0,047
	2,00 Yes	49	**60,65**	2972		
ZDM4: Our customer management uses digital media and data resources.	1,00 No	52	44,73	2326	0,021	0,167
	2,00 Yes	49	**57,65**	2825		
ZDM5: Our supply chain management uses digital media and data resources.	1,00 No	52	41,72	2169,5	0,001	0,003
	2,00 Yes	49	**60,85**	2981,5		
ZDM: Digital Process Maturity	1,00 No	51	40,82	2082	0,001	0,004
	2,00 Yes	49	**60,57**	2968		

The comparison illustrates that for each part question DM1 to DM5 and in total (DM) businesses answering MM2 by yes dispose of the higher digital process maturity than businesses answering part question MM2 by no. The difference in the median is significant according to Mann-Whitney U Test. Its significance is < 0.05 each time. According to Kolmogorov-Smirnov, test DM2 and DM4 differ in the form of the distributions the others correspond. Based on these results, **hypothesis H1 is accepted for MM2 as well and thus fully accepted.** Businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models.

4.5.2 Test of H2, H3 and H4

To test H2 to H4 simple regression models are applied.

Hypothesis H2 assumes that digital process maturity significantly enhances technical efficiency.

Hypothesis H3 assumes that digital process maturity significantly enhances financial efficiency.

Hypothesis H4 assumes that technical efficiency enhances financial efficiency.

The three regression models are summarized concerning R, R^2 and corrected R^2 and concerning ANOVA significance based on the F Test in Table 4.10.

Table 4.10: Model Summary and ANOVA tests of hypotheses H2, H3 and H4

			Model summary					ANOVA			
	x	y	R	R²	corr. R²	cng. In F	Sig. Chng. in F	sqr. Sum	sqr. means	F	Sig.
H2	DM	ET	0,691	0,477	0,473	110,318	0,000	58,647	58,647	110,32	0,000
H3	DM	EF	0,612	0,374	0,369	71,754	0,000	45,652	45,652	71,754	0,000
H4	ET	EF	0,846	0,716	0,714	303,069	0,000	86,834	86,834	303,07	0,000

The summary (Table 4.10) shows that the explaining factors (x) produce reliable models explaining a significant share of the target (y) variance in each case. The ANOVA Tests are also significant.

The regression model coefficients confirm the significant results (Table 4.11):

Table 4.11: **Regression coefficients for H2, H3 and H4**

Model-coefficients			Non standardized model	Standardized model		
y	x	coeff.	Std. Err.	Stand.Beta	T	Sig.
	const.	0,012	0,066		0,189	0,851

H2	ET	DM	0,687	0,065	0,691	10,503	0,000
		const.	0,018	0,072		0,254	0,800
H3	EF	DM	0,618	0,073	0,612	8,471	0,000
		const.	0,008	0,048		0,172	0,864
H4	EF	ET	0,851	0,049	0,846	17,409	0,000

All three regression coefficients for the models H2, H3 and H4 are significant at the 99% level. The scatter plots illustrate these results:

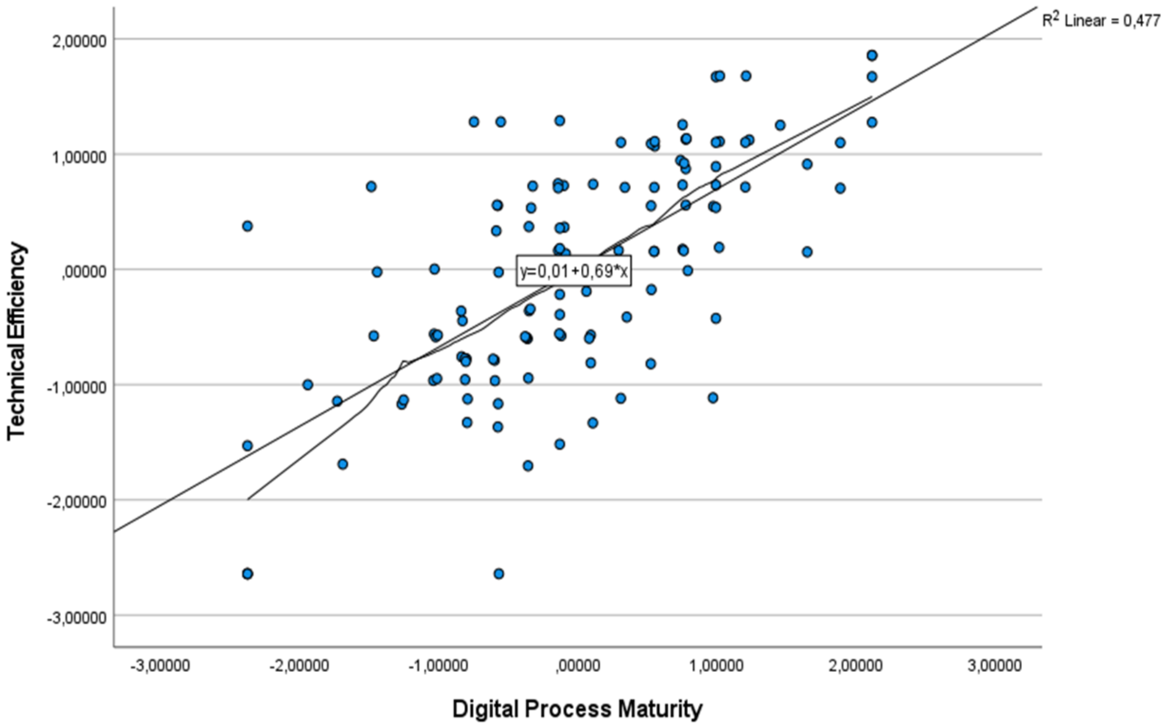

Figure 4.13: **Scatter plot for hypothesis H2**

An increase in technical efficiency produces a linear increase of digital process maturity with a regression line of y = 0.01 + 0.69 *x for the unstandardized model (compare Figure 4.13). Similar observations are made for financial efficiency, which increases linearly with growing digital process maturity (compare Figure 4.14). The regression line of the unstandardized model is y= 0 0.02 + 0.62 * x.

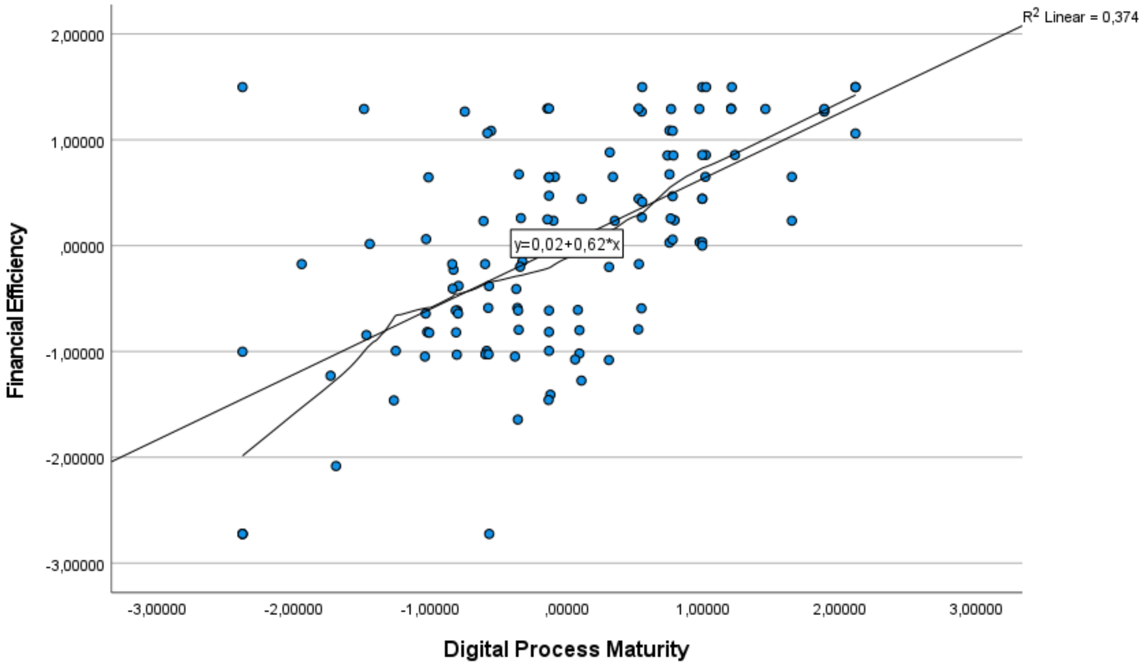

Figure 4.14: **Scatter plot for hypothesis H3**

Finally, technical efficiency increases financial efficiency linearly as shown in Figure 4.15:

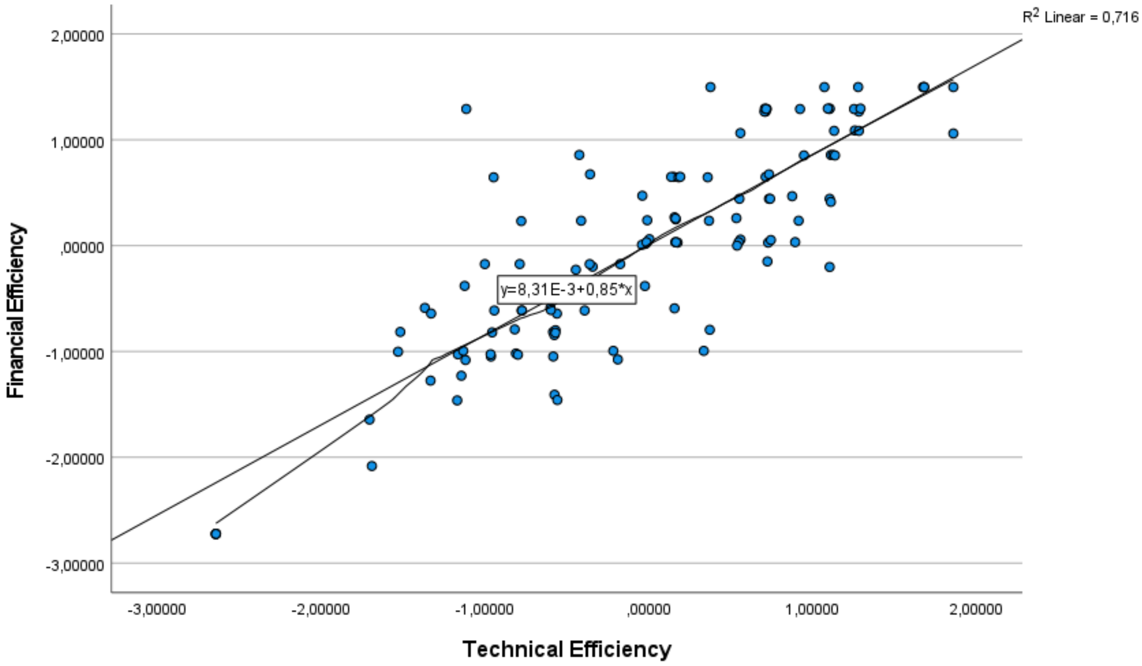

Figure 4.15: **Scatter plot for hypothesis H4**

The regression line for the unstandardized model confirming H4 is: y= 0.00831 + 0.85 *x.

Accordingly, **H2, H3 and H4 are accepted**. Digital process maturity significantly enhances technical efficiency as well as financial efficiency. Technical efficiency significantly enhances financial efficiency.

4.5.3 Test of H5

Hypothesis 5 assumes that H5a) knowledge-related, H5b) business-related, H5c) control-related and H5d) risk-control related factors, positively moderate the impact of digital process maturity on technical and financial efficiency.

First the moderating effect for the relationship of digital process maturity on technical efficiency is analyzed. Model summaries for the potentially relevant moderators MK, MP, MC and MR are printed in Table 4.12:

Table 4.12: **ET-model summaries including moderators MK, MP, MC and MR**

Moderating effect in models relating digital process maturity to technical efficiency

Moderator		R	R²	corr. R²	chng. In R²	chng. In F	Sig Chng in F	Durbin-Watson
MK	knowledge-related	0,754	0,568	0,557	0,568	51,27	0,000	1,995
MP	business-related	0,702	0,493	0,48	0,493	38,249	0,000	1,999
MC	control-related	0,756	0,572	0,56	0,572	51,574	0,000	1,722
MR	risk-control related	0,766	0,586	0,576	0,586	54,786	0,000	1,888

As observed for the unmoderated models, all four models explain a significant share of the variance in the target parameter ET (technical efficiency).

Table 4.13: **ANOVA analysis of ET - models including moderators MK, MP, MC and MR**

ANOVA of moderating effects in models relating digital process maturity to technical efficiency

Modell		sqr. Sum	srq means	F	Sig.
MK	knowledge-related	69,291	23,097	51,27	0,000
MP	business-related	60,472	20,157	38,249	0,000
MC	control-related	68,132	22,711	51,574	0,000
MR	risk-control related	71,329	23,776	54,786	0,000

The ANOVA tests of the total model fit of the models explaining technical efficiency by digital process maturity and the moderators MK, MP, MP, MC and MR are all significant at the 99% level. The analysis of regression coefficients for each model differentiates, which parameters are responsible for model significance (compare Table 4.14):

Table 4.14: **Regression coefficients of ET - models including moderators MK, MP, MC and MR**

Regression coefficients			non-standardized	standardized			collinearity
Target	**ET**	coefficient	Beta	T	Sig.	Tolerance	VIF
MK	constant	0,037		0,520	0,604		
	ZDM: Digital Process Maturity	0,400	0,403	4,827	0,000	0,531	1,884
	ZMK: Knowledge-related Moderat	0,417	0,415	4,958	0,000	0,528	1,895
	Interaction DM-MK	-0,026	-0,031	-0,501	0,617	0,991	1,009
MP	constant	-0,023		-0,308	0,759		
	ZDM: Digital Process Maturity	0,606	0,607	7,667	0,000	0,685	1,46
	ZMP: Business-related Moderator	0,155	0,154	1,899	0,060	0,657	1,523
	interaction DM-MP	0,062	0,071	1,051	0,296	0,949	1,053
MC	constant	0,018		0,255	0,799		
	ZDM: Digital Process Maturity	0,381	0,381	4,628	0,000	0,546	1,831
	ZMC: Control-related Moderators	0,441	0,444	5,413	0,000	0,55	1,818
	interaction DM-MC	-0,011	-0,013	-0,215	0,830	0,967	1,034
MR	constant	0,083		1,164	0,247		
	ZDM: Digital Process Maturity	0,359	0,361	4,309	0,000	0,509	1,965
	ZMR: Riskcontrol-related Moderat	0,457	0,456	5,467	0,000	0,514	1,947
	Interaction DM-MR	-0,093	-0,102	-1,696	0,093	0,987	1,013

Table 4.14 shows that for models MK, MC and MR the knowledge-related, control- and risk-control related factors are significant controls but not moderators, since the interaction variables are not significant at the 95% level. MP (business-related factor) is not significant at all.

For target technical efficiency the moderating impact of knowledge-related, business-related, control-related and risk-control-related factors according to **H5a to H5 is rejected** based on this test. There is a significant positive controlling effect for knowledge, control and risk-control related factors.

The test of H5 for financial efficiency is done in the same way:

The model summaries for models explaining financial efficiency by the input digital process maturity and the controls MK, MP, MC and MR are all significant at the 99% level according to Table 4.15:

Table 4.15: **EF-model summaries including moderators MK, MP, MC and MR**

Model summary - Moderating effect in models relating digital process maturity to financial efficiency								
target	EF	R	R²	corr. R²	chng. In R²	chng. In F	Sig Chng in F	Durbin-Watson
MK	knowledge-related	0,712	0,507	0,494	0,507	39,437	0,000	1,89
MP	business-related	0,616	0,38	0,364	0,38	23,889	0,000	2,014
MC	control-related	0,736	0,542	0,53	0,542	45,362	0,000	1,925
MR	risk-control related	0,756	0,571	0,56	0,571	50,606	0,000	1,903

The ANOVA tests for the total model fit of these regression models are also highly significant according to Table 4.16:

Table 4.16: **ANOVA analysis of EF- models including moderators MK, MP, MC and MR**

ANOVA of Moderating effects in models relating digital process maturity to financial efficiency						
	Modell	sqr. Sum	srq means	F	Sig.	Sig.
MK	knowledge-related	61,105	3	20,368	39,437	0,000
MP	business-related	46,185	3	15,395	23,889	0,000
MC	control-related	65,31	3	21,77	45,362	0,000
MR	risk-control related	68,584	3	22,861	50,606	0,000

The analysis of the regression coefficients for each of the models results from Table 4.17:

Table 4.17: **Regression coefficients of EF - models including moderators MK, MP, MC and MR**

Regression coefficients		non-standardized	standardized			collinearity	
Target	**EF**	coefficients	Beta	T	Sig.	Tolerance	VIF
MK	constant	0,027		0,36	0,720		
	ZDM: Digital Process Maturity	0,275	0,273	3,074	0,003	0,544	1,837
	ZMK: Knowledge-related Moderators	0,504	0,497	5,584	0,000	0,54	1,852
	Interaction DM-MK	-0,008	-0,01	-0,146	0,884	0,978	1,022
MP	constant	-0,024		-0,3	0,765		
	ZDM: Digital Process Maturity	0,608	0,601	6,89	0,000	0,698	1,433
	ZMP: Business-related Moderators	0,031	0,031	0,349	0,728	0,665	1,503
	interaction DM-MP	0,081	0,091	1,21	0,229	0,944	1,059
MC	constant	0,019		0,253	0,801		
	ZDM: Digital Process Maturity	0,232	0,231	2,678	0,008	0,537	1,861
	ZMC: Control-related Moderators	0,561	0,56	6,534	0,000	0,543	1,842
	interaction DM-MC	-0,005	-0,005	-0,082	0,935	0,966	1,035
MR	constant	0,073		1	0,319		
	ZDM: Digital Process Maturity	0,174	0,172	2,014	0,046	0,515	1,942
	ZMR: Riskcontrol-related Moderators	0,621	0,615	7,271	0,000	0,525	1,905
	Interaction DM-MR	-0,076	-0,081	-1,309	0,193	0,974	1,027

Neither interaction variable is significant. Thus, the impact of MK, MP, MC and MR is not a moderating one. There is a controlling effect of MK, MC and MR due to the significance of the knowledge-related, control-related and risk-control related constructs. Business related moderators are insignificant.

Hypotheses H5 a to H5d are rejected for financial efficiency (EF) based on these results. There is no significant moderating effect of knowledge, business, control and risk-control-related factors in the relationship between digital process maturity and technical or financial efficiency. However, there is a controlling effect for knowledge-related, control-related and risk-control-related constructs.

4.5.4 Complementary analysis of the controlling impact of business-related parameters

"Business-related moderators" are a three-factorial construct composed of MP3, size of company, MP4 usage of sophisticated technology, and MP5 national/international reach of the business. The reliability test (section 4.4) has provided comparatively low (although acceptable) Cronbach Alpha of 0.610 and a variance extraction of only 59.11 % for the construct. Business-related moderators have proven insignificant to explain the relationship of digital process maturity and technical or financial efficiency. An assessment to the extent to which individual elements of the construct "business-related factors" are responsible for this result is of interest.

A complementary regression analysis of hypothesis H5b splitting the construct MP up into its elements MP3, MP4 and MP5 is done to analyze individual item impacts on the relationship of digital maturity and technical and financial efficiency:

The model summary for the target parameter technical efficiency results satisfactory R-values and total model significance is 99%.

Table 4.18: **ET-model summaries including moderators MP3, MP4 and MP5**

Model summary - analysis of moderators MP3, MP4, MP5 in Model digital maturity on technical efficiency

Target ET	R	R^2	corr. R^2	chng. In R^2	chng. In F	Sig. chng. in F	Durbin-Watson
MP3	0,693	0,481	0,468	0,481	36,728	0,000	2,012
MP4	0,718	0,516	0,503	0,516	42,212	0,000	2,097
MP5	0,696	0,484	0,471	0,484	36,854	0,000	2,014

Also, the ANOVA analysis of the total model fit of a regression model explaining technical efficiency by process maturity and the moderators MP3, MP4 and MP5 is significant at the 99% level:

Table 4.19: **ANOVA analysis of ET- models including moderators MP3, MP4 and MP5**

ANOVA of MP3, MP4 and MP5 moderating effects in models relating digital process maturity to technical efficiency

Target ET		sqr. Sum	srq means	F	Sig.
MP3	size of company	59,121	19,707	36,728	0,000
MP4	sophisticated technology	63,398	21,133	42,212	0,000
MP5	reach of business	59,334	19,778	36,854	0,000

The regression coefficients show the origin of model significance:

Table 4.20: **Regression coefficients of ET - models including moderators MP3, MP4 and MP5**

Regression coefficients		non-standar	standardized			collinearity	
Target	**ET**	coefficient	Beta	T	Sig.	Tolerance	VIF
MP3	constant	-0,002		-0,033	0,974		
	ZDM: Digital Process Maturity	0,684	0,688	10,001	0,000	0,923	1,084
	ZMP3: company size	-0,008	-0,008	-0,113	0,910	0,925	1,081
	IDMMP3	0,058	0,061	0,92	0,359	0,987	1,013
MP4	constant	-0,007		-0,096	0,924		
	ZDM: Digital Process Maturity	0,559	0,562	7,258	0,000	0,678	1,475
	ZMP4 : sophisticated technology	0,24	0,244	3,073	0,003	0,645	1,551
	IDMMP4	0,052	0,059	0,889	0,376	0,922	1,085
MP5	constant	-0,015		-0,207	0,836		
	ZDM: Digital Process Maturity	0,645	0,647	8,693	0,000	0,791	1,264
	ZMP5: Company reach	0,096	0,098	1,254	0,212	0,72	1,388
	IDMMP5	0,061	0,063	0,903	0,368	0,885	1,13

Factors MP3 and MP5   company size and company reach are insignificant. Factor MP4 – the usage of sophisticated technology has got a significant positive controlling, but no moderating effect on technical efficiency. The interaction variables are insignificant, the factor MP4 itself is significant however, and explains 24 % of the variance of the target technical efficiency.

A corresponding analysis is done for the target financial efficiency and the inputs “digital process maturity” and the factors “company size” (MP3), “usage of sophisticated technology” (MP4) and “company reach” (MP5). Again, the model summary provides highly significant R^2 values:

Table 4.21: **EF-model summaries including moderators MP3, MP4 and MP5**

Model summary - analysis of moderators MP3, MP4, MP5 in Model digital maturity on financial efficiency

Target EF	R	R²	corr. R²	chng. In R²	chng. In F	Sig Chng in F	Durbin-Watson
MP3	0,614	0,377	0,361	0,377	23,82	0,000	2,042
MP4	0,636	0,405	0,39	0,405	26,743	0,000	1,978
MP5	0,616	0,38	0,364	0,38	23,854	0,000	2,038

Th ANOVA test of total model significance also accounts for a highly reliable model:

Table 4.22: **ANOVA analysis of the EF- model including moderators MP3, MP4 and MP5**

ANOVA of MP3, MP4 and MP5 moderating effects in models relating digital process maturity to financial efficiency

Target EF		sqr. Sum	srq means	F	Sig.
MP3	size of company	46,016	15,339	23,82	0,000
MP4	sophisticated technology	49,377	16,459	26,743	0,000
MP5	reach of business	46,142	15,381	23,854	0,000

An analysis of the reliability of the individual coefficients by T-tests however comes to the result that only the factor MP4 is significant as a control. Neither MP3, MP4 or MP5 are significant as moderators. The interaction variables are insignificant.

Table 4.23: **Regression coefficients of EF - models including moderators MP3, MP4 and MP5**

Regression coefficients		non-standardized	standardized			collinearity	
Target	**EF**	coefficient	Beta	T	Sig.	Tolerance	VIF
MP3	constant	0,007		0,089	0,930		
	ZDM: Digital Process Maturity	0,618	0,612	8,163	0,000	0,938	1,066
	ZMP3: company size	-0,011	-0,011	-0,142	0,888	0,935	1,069
	IDMMP3	0,051	0,053	0,724	0,470	0,992	1,009
MP4	constant	-0,035		-0,439	0,661		
	ZDM: Digital Process Maturity	0,538	0,533	6,151	0,000	0,673	1,487
	ZMP4 : sophisticated technology	0,183	0,185	2,096	0,038	0,645	1,551
	IDMMP4	0,112	0,126	1,702	0,091	0,913	1,095
MP5	constant	0,003		0,042	0,966		
	ZDM: Digital Process Maturity	0,65	0,642	7,898	0,000	0,803	1,245
	ZMP5: Company reach	-0,073	-0,074	-0,862	0,390	0,724	1,382
	IDMMP5	0,035	0,036	0,468	0,641	0,883	1,133

4.6 Discussion of empirical results

Chapter 4 summarizes the results of the hypotheses' tests and adjusts the work model. Using triangulation, the qualitative and quantitative study results are brought together to explain the model relationships content-wise.

4.6.1 Summary of hypothesis-tests

Section 4.5.1 has tested hypothesis H1 using a Mann-Whitney-U-Test and found that businesses applying (group 1) and not applying (group 2) maturity models in general or for the measurement of digitalization success, differ significantly in terms of digital process maturity. Applying companies exceed their non-applying counterparts significantly in digital process maturity.

Hypotheses H2 to H4 have been tested in section 4.5.2 using simple regression models. These have shown that digital process maturity increases technical and financial efficiency significantly and that technical and financial efficiency stand in positive correlation.

Summarizing the analysis of hypothesis H5 on the impact of moderators in the relationship of digital process maturity and technical or financial efficiency,

- neither of the assumed factors is a moderator due to lacking significant of the interaction parameters.
- the constructs knowledge-related, control-related and risk-control-related factors have proven highly reliable and are highly significant controls of technical and financial efficiency.
- The construct "business-related factors" is decomposed due to comparatively low reliability and insignificance on the whole. The factor MP4, technological sophistication, has found a highly significant control of technical and financial efficiency, but not a significant moderator.

The following table summarizes the major results for the hypotheses tests (next page):

Table 4.24: **Summative results of hypotheses' tests**

H	Hypothesis	Input	Output	Test Type	OK?	Comments
H1	Businesses applying maturity models dispose of higher digital process maturity than businesses dispensing with maturity models.	DM1 to DM5, DM	classified by MM1 and MM2	Mann-Whitney-U Test	yes	
H2	Digital process maturity significantly enhances technical efficiency.	DM	ET	regression	yes	
H3	Digital process maturity significantly enhances financial efficiency.	DM	EF	regression	yes	
H4	Technical efficiency increases financial efficiency.	ET	EF	regression	yes	
H5a	Knowledge-related moderators positively moderate the impact of digital process maturity on technical and financial efficiency.	MK	ET, EF	regression, moderation analysis	no	MK controls ET and EF positively.
H5b	Business-related moderators positively moderate the impact of digital process maturity on technical and financial efficiency.	MP	ET, EF	regression, moderation analysis	no	MP3 (level of technical sophistication) controls ET and EF positively.
H5c	Control-related moderators positively moderate the impact of digital process maturity on technical and financial efficiency.	MC	ET, EF	regression, moderation analysis	no	MC controls ET and EF positively.
H5d	Risk-control related moderators positively moderate the impact of digital process maturity on technical and financial efficiency.	MR	ET, EF	regression, moderation analysis	no	MR controls ET and EF positively.

4.6.2 Model summary

Based on the results of the hypotheses tests the research model developed in section 3.6.2 based on the qualitative interview study is now adjusted:

The test of H1 has shown that businesses applying maturity models in general and for digital maturity measurement in particular outperform companies without maturity models concerning digital process maturity. Digital process maturity increases business technical efficiency (beta 0.691) (H2) and financial efficiency (H3) (beta: 0.618) significantly. There is a positive interaction of technical and financial efficiency (H5) (Beta 0.851). Knowledge-related, control-related and risk-control-related factors as well as the application of sophisticated technology positively control the impact of digital process maturity on both technical and financial efficiency.

The construct "knowledge-related factors" refers to employee competence (MK1) and expertise in digital technologies (MK2) and corporate interdisciplinary collaboration in the field of digitalization (MK3).

The construct "control-related factors" refers to managerial support for digitalization (MC1), employee autonomy in digital technology implementation (MC2), budgeting of digitalization projects (MC3) and organizational structures promoting digitalization (MC4).

The construct "risk-control related factors" refers to the control of investment risks in digital technologies (MR1) and the management of data security risks (MR2).

Businesses performing in these fields achieve progress in digital process maturity, which increases their technical and financial efficiency. These valid and reliability tested relationships are summarized and quantified in the final model of the thesis (Figure 4.16 on the following page).

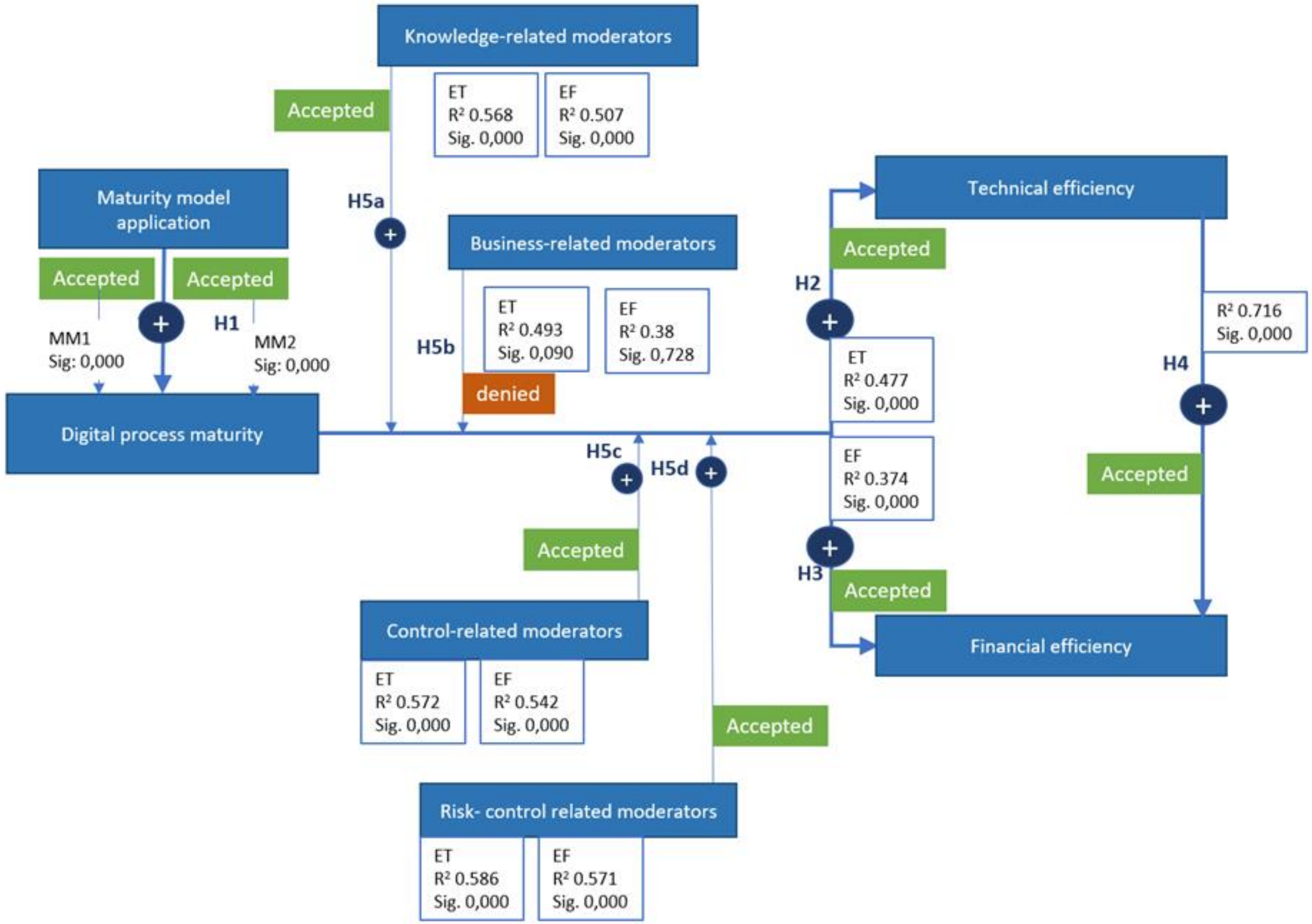

Figure 4.16: **Empirical Founded Model**

As detailed in previous section the study uses triangulation to link back the quantitative results of the survey (section 4.5) to the qualitative insights of the expert interview-based study in the German mechanical engineering industry (section 3.5). The study thus comes to a comprehensive understanding of the causal background of the reliability tested model.

4.6.3 Triangulation - Impact of digital process maturity on efficiency

The sector analysis of German mechanical engineering in section 3.3 has shown that digital technologies have greatly changed and are about to further advance development and production processes in the mechanical engineering value chain.[262] However, German companies are still partly reluctant to adopt digital innovations, like industry 4.0 and stick to established and proven manual and mechanical processes. [263]

The quantitative survey among 140 German businesses which were done in mechanical engineering mainly (compare Figure 4.1), confirms this divide. The descriptive analysis of Items DM1 to DM5 indicates that about one third of companies have fully or even perfectly implemented digital technologies, while about 20% of participating companies do not rely on digital technologies or are in the early stages of digital technology of application. About half of the participants have partly adopted digital data management systems (compare Figure 4.7). German businesses in the mechanical engineering sector thus differ significantly as to their digital process maturity and readiness to get engaged in digitalization.

Businesses delaying or even ignoring the advances of digital technologies and media risk to be overtaken by international competitors as to technical and financial efficiency.

The quantitative survey has confirmed that **digital process maturity significantly increases technical efficiency** (beta: 0.691) (acceptance of hypothesis H2). Where technical efficiency refers to the timely accomplishment of R&D schedules, the control of design loops, conformity to R&D budgets, product performance in customer application,

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[262] DISPAN, Jürgen and Martin SCHWARZ-KOCHER. *Digitalisierung im Maschinenbau. Entwicklungstrends, Herausforderungen, Beschäftigungswirkungen, Gestaltungsfelder im Maschinen-und Anlagenbau,* 2018, p11.

[263] HACKSTEIN, Sascha. Maschinenbau und Digitalisierung: Eine Branche im Zwiespalt. *Produktion Online*, 2018. Available from: https://www.produktion.de/wirtschaft/maschinenbau-und-digitalisierung-eine-branche-im-zwiespalt-388.html.

the accomplishment of intended product specifications and high product quality standards (compare Figure 4.8).

The interview analysis explains why digital process maturity enhances technical efficiency in business practice: Digital process maturity means that data are processed, stored, analyzed and optimized digitally mainly. Digital data management improves the interaction of R&D and production department e. g. by 3D virtual design and digital schedule coordination. The integrative management of the product development and design process saves manpower, coordination costs and avoids transmission and planning errors and thus enhances the technical efficiency of the inner value chain. Digital process management in production contributes to an improved scheduling and error-free operation of the production process, by amending the coordination of machinery utilization and the way of raw and half products in the production process.

The digital coordination of inner corporate value chain enables businesses to interconnect with their supply chain partners and customers through virtual media. Digital process coordination is essential to plan just in time delivery and coordinate manufacturing processes. Digital data management improves product management and servicing in operation at the customer level. Digital technologies enable products to report service requirements and potential failure back to the supplier and thus avoid and amend on problems early. Digital technologies thus improve customers' product quality perception and customer satisfaction in application.

The quantitative study has also shown that **digital process maturity significantly increases financial efficiency** (beta = 0.618). Financial efficiency refers to the control of project costs and risks, the achievement of expected outputs per time unit, operation profitability and financial performance (compare Figure 4.10). Based on the interviews, the drivers and impetus of this cause and effect are obvious:

Digitalization improves the interlink between all business departments, management, administration, R&D, production, marketing and delivery logistics. Processes that had to be organized manually before, now use digital media, e. g. e-mail correspondence, SAP based production planning and scheduling. Digital technologies replace human efforts and rationalize daily communication and interaction activities. Human output and efficiency per work hour increase with the effect that the costs per output unit diminish.

Obviously, investment costs in digital technologies are significant and the net positive effect only unfolds after some time of operation. The positive cost saving impact of digitalization however is sustainable, since human inputs are reduced for good as soon as all departments have successfully progressed to digital system application.

It has been shown that digital technologies improve product quality and customer satisfaction. Digitalization thus unfolds positive impacts at the revenue side as well. Performing high-quality products are well accepted with customers, enable companies to open up new customer segments, sell more than less advanced competitors and thus gradually increase the market prices per unit sold. In effect digitalization contributes to step up production amounts, increase units sold and revenue per unit and in total, with the effect that incomes increase.

The contribution of digitalization to financial efficiency thus is twofold: Digitalization save production costs, and also increases output amounts and revenues. In effect, business performance and profitability increase. Digitalized companies realize a competitive edge in the market and expand their reach and customer base more rapidly than competitors. Digitalization is the foundation of sustainable growth towards international markets.

With the acceptance of hypothesis 4, the quantitative survey has proven that **technical efficiency strongly contributes to financial efficiency** (beta: 0.851). The above discussion as well as the interview section proofs this result. Technical efficiency means a rationalization of R&D and production, reduces transaction efforts in internal management and administration as well as in supply chain coordination. In effect, technically efficient companies save costs at every stage of the production process and in the inter-corporate value chain. Technical efficiency further contributes to develop, produce and deliver performing products and continuously develop products according to the most recent technical standards. Optimal output quality drives market demand, sales, and finally enables companies to rise prices and expand into growing markets. Technical efficiency is the major thrust of financial efficiency at the level of costs, pricing and amounts sold.

4.6.4 Triangulation - Impact of maturity model application on digital process maturity

Digital process maturity has thus proven a highly desirable target to maximize technical and financial efficiency. The study demonstrates, how businesses can reliably reach digital process maturity:

The quantitative section has shown that businesses applying maturity models are more advanced in digital process maturity than their competitors, which do not apply maturity models yet (hypothesis H1: sig. = 0.000).

The interview section does not inform on maturity model application, since neither of the interviewed businesses applies maturity models, the theory section (compare 1.2), however, explains why maturity model application contributes to achieve and advance corporate digital process maturity:

Maturity models support the assessment of value creation excellence, i. e. inform businesses to what extent their (digital) processes performance, and in what respect the intended objectives of digitalization have not yet been reached. The implementation of maturity models in corporate practice presupposes, that businesses analyze and understand their processes and identify development targets.[264] Maturity models require the definition of an intended development process. In application, maturity models continuously inform businesses on achievements made and on further steps required to realize the intended goals. Maturity models thus support businesses in the gradual advancement to technological perfection.[265]

Maturity models have supported all entrepreneurial processes but are particularly valuable in IT-development and application. As compared to general quality management tools maturity models are specified for particular departments and are also apt to design and analyze interdepartmental interaction. Maturity models thus enable businesses to analyze and systematically improve their IT systems to the requirements of their value chain.[266]

Maturity models are capability-oriented, i. e. focus on the competencies required and to be developed in each department and in inter-departmental interaction. It is essential to improve IT processes competence since the success of IT application depends on the

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[264] METTLER, Tobias. Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, **3**(1-2). 2011, pp. 81-98.

[265] COSIC, Ranko, Graeme SHANKS, and Sean MAYNARD. Towards a business analytics capability maturity model. *23rd Australasian Conference on Information Systems Proceedings*, (14). 2012, p1.

[266] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017, 55-56.

capabilities of the concerned individuals and teams to apply IT routines effectively in the value creation process.[267]

IT-technologies are not static but are developing dynamically, which means that models assessing, and guiding system development should be flexible to adapt to technological changes. Maturity models fulfil this requirement since they define a way of evolution from low to higher quality standards and are apt for company-specific adaptation.[268]

In sum, maturity models are ideal concepts to accompany the introduction and continuous development and interlinking of digital data management systems in corporations. The empirical results of the quantitative survey prove that companies applying maturity models are more advanced in digital process maturity than companies advancing less planful. This is plausibly based on the theoretical foundations of this study.

4.6.5 Triangulation - Controlling effects

A series of controlling factors codetermine the extent to which digital process maturity in effect unfolds technical and financial efficiency gains.

The quantitative survey has found that knowledge-related factors control the impact of digital process maturity on technical and financial efficiency. Knowledge related factors comprise employee expertise and competence in the management of digital technologies and the practice of interdisciplinary collaboration on digitalization. The interview results provide insights on the mechanism of this effect: employees competent to work in digital space are open to apply new technologies in everyday professional practice and realize performing results using digital applications. To build knowledge in digital environments interdisciplinary collaboration is helpful. Assistance from internal IT experts or external agencies supports employees in the development of digital expertise and in case of application difficulties. Expertise and technical collaboration contribute to utilize digital systems efficiently, which reduces costs in the production process and maximizes production output by avoiding costly shut-downs and coordination time. Employee

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[267] SCHMUTTE, Andre M., and Peter F.-J. NIERMANN. Der „Stresstest" für die Wettbewerbsfähigkeit: Systematische Potenzialanalyse mit Reifegradmodellen. *Managemententscheidungen:* Springer Gabler, Wiesbaden, 2017, pp. 57-72., p57.

[268] WESTERMANN, Thorsten. *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen-und Anlagenbaus:* Dissertation, Universität Paderborn, 2017, p55-56.

competence and collaboration thus contribute to technical efficiency in the application of digital equipment.

The quantitative survey shows a positive controlling effect of “control-related factors” in the relationship of digital process maturity and technical and financial efficiency. This construct refers to managerial support, employee autonomy in digital technology implementation as well as sufficient budgeting and supportive organizational structures to digitalization projects. Based on the interviews this observation is plausible: Experts observe an increase of employee motivation when adequate management support is perceived and when employees dispose of the necessary freedom to utilize and adjust available digital technologies to work requirements. Sufficient financial resources are essential to adapt digital technologies to business practice. Although adequate budgeting seems to cause additional implementation costs at first sight, these investments pay back in the mid-term when installed digital systems work without failure and are applicable to the required business cases effectively.

The quantitative analysis discloses a further controlling effect of risk-control related factors, specifically the management of investment risks and data security risks. This effect is plausible from the qualitative results of the expert interviews: An early analysis of IT related investment risks before deciding on the introduction of new costly technologies avoids investment failure in the film stretching company. A comprehensive data security concept ensures the frictionless operability of digital systems in both surveyed companies. The prevention of down-times is essential to effectively control operation costs and save transaction expenses for failure management.

The survey finally has shown that the application of “sophisticated technologies” is positively correlated to technical and financial efficiency in the context of digital process maturity. The interview in the film stretching company confirms that the high technological standards the business uses, enable it to make efficient use of digital technologies at all. Interview-based observations on the relevance of a minimum critical business size or international reach to reach digital process maturity have not been confirmed as significant in the survey.

Summarizing the results of the triangulation of survey-based insights with the interview results, the plausibility of all quantitative results is confirmed based on the qualitative expert statements:

Digital process maturity increases technical and financial efficiency, which are strongly correlated. This effect is strengthened by employee expertise and collaboration, managerial support, sufficient budgeting and an effective risk management system. To realize digital process maturity and the promised efficiency effects, the application of maturity models is crucial.

4.7 Management Implications

Develop digital process maturity

Digital process maturity is the key to technical efficiency and financial efficiency. A change in digital process maturity explains more than 60% of the variance of technical efficiency and financial efficiency for the analyzed sample of German companies in mechanical engineering (compare results for test of H2 and H3 in section 4.5.2). Businesses intending to increase their technical and financial efficiency should thus develop their digital process maturity. Digital process maturity comprises a series of intertwined competencies: Digital data management concerns the transference, storage and analysis of business-related data in local networks and on open platforms.

Digital data management should involve the whole supply chain. Digital coordination system support just-in time delivery processes and the coordination of supply amounts, location and timing. Supply chain coordination gains in flexibility when manual processes are substituted by digital technologies. Digital documents are accessible on-time across all departments, which reduces information discrepancy and eases the coordination of orders, preproduction, delivery and the in-house production flow.

Digital data management extends to customer interaction. Customers order products online and digital data management allows to implement the orders in the current production cycle without delay. Digital order routing reduces production downtimes, waiting times, erroneous delivery paths and increases product quality and thus customer satisfaction. Customer data bases are useful to maintain customer contact beyond the immediate purchase phase. Digital applications in end products ensure assistance in case of service requirement or failure and contribute to maximize customer satisfaction.

Introduce and apply maturity models

The way to digital process maturity, however, is a process involving many agents and stakeholders across all business departments and is not managed at short notice.

The study has provided an overview of five maturity models for the engineering sector. Available maturity models differ in their structure between hierarchical (QMMG, PEMM or 5C architecture) and object-oriented solutions (EFQM or CMMI-DEV) (compare Table 1.3). Their aptitude to the organization of data management processes or other maturity development processes differs. Businesses should select an adequate maturity model depending on their development requirements. Businesses relying on a top-down leadership concept could prefer a hierarchical maturity model approach, while decentralized businesses could prefer object-oriented solution.

For the development of digital maturity systems, a maturity model with a strong technical or engineering focus offers itself. The 5C architecture represents a maturity management approach designed for IT applications and cyber-physical systems and has proven for computer integrated manufacturing but remains focused on digital applications. Businesses combining manual and physical processes and digital data management could prefer a broader approach like the CMMI-DEV, which includes the whole corporation, e. g. human resource development and managerial support.

With growing system comprehensiveness, the competence requirements to operate the maturity model effectively increase. Businesses establishing a full-range maturity model could trust in an external expert agency to guide the monitoring process or build an own in-house department responsible for maturity modeling. Partial models assisting the implementation of individual software solutions or digital applications at the level of departments could be managed by an individual responsible or an implementation team or taskforce.

The intended range and reach of digital process maturity growth determines the breadth and complexity of the applied model. The project range should be determined initially to make a founded choice and implement maturity modelling successfully.

Manage controlling conditions to maximize efficiency

Beyond maturity model application, a series of controlling factors has been identified as crucial to develop digital process maturity successfully and thus enhance technical and financial efficiency:

Businesses require employee competence and expert knowledge to achieve digital process maturity. Targeted human resource development programs in the field of digital data management could be cast to sustainably develop the digital expertise of the work force. In case of new recruitments responsible managers should prefer employees with profound qualifications in the field of digital data management and digital systems development. External experts could support the development of digital competences and could take over tasks that are beyond the qualification of in-house staff, e.g. digital accounting and quality management. Maturity models are helpful to coordinate and integrate human resources to enhance digital process maturity across all business departments.

The development of digital process maturity is codetermined by control-related factors. Specifically managerial support, engagement and expertise is required to select and develop an adequate maturity model and to motivate the line workforce to use the system effectively. At the same time employees require sufficient autonomy to experiment on and apply digital systems in the professional practice. Performance targets should be designed so that personal development is encouraged and rewarded.

Digitalization projects should be adequately budgeted to be practicable. Businesses should limit the range of digitalization e. g. to individual departments initially and fund these projects adequately rather than establish a company-wide project, that finally fails due to an underestimation of the required financial efforts. Digital systems mirror organizational structures and shape them. To implement new IT technologies successfully managers should ensure that organizational structures are flexible for transformation, when digital standards require it. Frequently, hierarchical levels can be reduced in depth in the course of digitalization since routines are automated and work force is saved. Executives should plan ahead which rationalizations are feasible in what time when embarking of new IT systems.

Risk control is a further mediator of technical and financial efficiency in digitalization processes. Businesses should assess the investment costs of new digital applications critically and calculate the expected benefit of the technology to assess amortization times. Digital technologies should be flexible to adopt to innovations and potentially changing business requirements. To make use of digital technologies efficiently a thorough analysis of in-house competencies should be made before the investment decisions is taken to ensure that the technology can be implemented and applied adequately and to prevent bad investments.

Data security is a major risk in digital data management. The replacement of physical documentations by digital accounts entails the risk that data are accessed illegitimately or are lost for good in case of malware attacks or system failure. Successful digitalization presupposes the establishment of cyber-security systems, access control and malware protection e. g. in the form of a firewall from the first day onwards. If in-house competencies in the field of IT security are unavailable, businesses are advised to cooperate with an external expert partner.

Summing up the management recommendations, businesses should develop their digital process maturity in order to enhance technical and financial efficiency. Maturity models contribute to systematically plan, implement and continuously improve the process of digitalization. In the mechanical engineering business early and decisive steps in digital process maturity are of particular importance to maintain a competitive advantage in a rapidly internationalizing supply and distribution market.

CONCLUSIONS AND SUGGESTIONS

The author presents the conclusions, connecting the conducted empirical research with the theoretical and analytical part.

Conclusions

1. By integrating insights from Organizational Systems Theory, the knowledge-based view, the dynamic capabilities framework, and agile development, a comprehensive theoretical framework for understanding the causal relationships between digital process maturity and organizational efficiency, both technical and financial, can be established. This not only advances the extant literature but also offers a multi-theoretical lens for studying complex organizational phenomena.
2. Empirical evidence validates the causal model, demonstrating that digital process maturity, understood through knowledge-intensive processes, has a substantial positive effect on business efficiency. This gives credence to the role of digital process maturity as a pivotal construct in the modern business landscape.
3. One of the notable findings from this study is the confirmation that a multi-faceted approach to knowledge resource management—encompassing dynamic capabilities and agile methodologies—leads to an inimitable value creation process. This insight enhances our understanding of how flexible competencies and bottom-up engineering processes can provide businesses with competitive advantages in rapidly evolving markets.
4. Furthermore, digital process maturity as a prerequisite for achieving high levels of technical and financial efficiency in an organization can be explicitly identified. This can be seen as a key contribution, as it provides managers and policymakers with actionable insights into improving operational effectiveness.
5. A nuanced view of digital process maturity emerges from this dissertation, revealing its dependency on the seamless integration of various knowledge resources. This integration requires dynamic evaluation and constant adaptation to changing technological paradigms. Such a process, when administered collaboratively, is found to be central to financial business performance.
6. An added value of this dissertation is its ability to integrate disparate empirical findings from prior studies into a unified work model. This model posits that digital

process maturity exerts a significant positive influence on both technical and financial efficiencies, thereby adding empirical rigor to the theoretical discourse.

7. Importantly, the empirical section of this thesis confirms the validity and reliability of the research model. It was found that increases in digital process maturity are strongly correlated with corresponding increases in technical and financial efficiency. This outcome substantiates the relevance of the multi-theoretical perspectives adopted in this study.
8. One of the more intricate aspects of this research is its investigation into the various determinants and moderators that influence the impact of digital process maturity on technical and financial efficiency. This nuanced exploration categorizes these factors into four distinct but interconnected groups: knowledge-related, business-related, control-related, and risk-control related. Knowledge-related factors include the competence, collaboration, and technological expertise of employees, which our study identifies as crucial for enabling an organization's digital transformation processes. Business-related factors delve into the organizational aspects such as size, geographical reach, and technological maturity level, providing a macro view of how digital process maturity is contextualized within the broader business landscape. Control-related factors, including managerial support, budget allocation, and organizational structure, serve as instrumental levers for executing and monitoring digital transformation initiatives. Lastly, risk-control related factors encompass investment risks and data security risks, adding another layer of complexity to the model.
9. While the empirical data did not establish these factors as statistical moderators in the relationship between digital process maturity and efficiency, they were revealed to be significant control variables. These controls add layers of complexity that must be accounted for in real-world applications, signaling the need for multi-faceted strategies that consider a broad spectrum of internal and external conditions. Understanding these factors not only enriches our theoretical comprehension but also offers practical guidance for businesses seeking to enhance their digital process maturity. This comprehensive breakdown represents a significant contribution to our understanding of the intricacies involved in digital transformation efforts and provides a robust framework for future research and practical implementations.

10. Additionally, this research has dissected the complex array of determinants and moderators influencing the effectiveness of digital process maturity. These range from knowledge-related factors like employee competence to risk-control elements like data security. While not statistical moderators, they serve as significant controls that business leaders must consider in their strategic planning.
11. In a distinctive departure from the controlling effects of knowledge-related, control-related, and risk-related parameters on technical efficiency, the application of maturity models presents a direct and influential mechanism for amplifying digital process maturity, consequently improving both technical and financial efficiencies. The research makes a compelling case for the adoption of maturity models as a simplified yet highly effective means of driving organizational performance, specifically for companies operating in knowledge-intensive sectors within the digital landscape. By elucidating this direct causal relationship, the dissertation fills a critical gap in the extant literature and offers actionable insights for business leaders. The potency of maturity models in accelerating digital transformation—substantiated through empirical findings—emphasizes their role as indispensable tools for firms aspiring to excel in the digitally competitive environment. This aspect underscores the necessity for strategic incorporation of maturity models into an organization's digital data management practices, thereby marking a significant contribution to both academic discourse and practical applications in digitalization.
12. A ground-breaking finding of this research is the empirical substantiation that the application of maturity models significantly boosts digital process maturity. This insight, drawn from a survey conducted in the mechanical engineering sector, fills a notable gap in existing literature, highlighting the operational benefits of maturity models in enhancing digital transformation processes.

Suggestions

1. To managers of companies with product development:

1.1 Develop digital process maturity.

Abolish manual routines and paperwork and transgress to a paperless office layout to save coordination costs and expenses for printing and physical storage. A homogenous data management system with well-defined access regulations should be established to provide employees and involved partners on-time access to all relevant documents. Cloud based data storage and administration systems are an essential step-stone on the way to digital process maturity. To achieve a high level of digitization, interfaces that hinder a seamless data flow must be adapted in a way that prevents information loss. This can be achieved through integrated software solutions but needs to be evaluated on an individual basis for each company. Furthermore, additional digital solutions should be introduced in areas of the company where analog processes still dominate.

1.2 Introduce and apply maturity models.

Trust in maturity models to systematically develop the digital process maturity. Maturity models are management systems designed to organize, supervise, analyze and improve managerial or organizational processes or equally the development of object related maturity conditions or people's capabilities. As it has been shown that companies using maturity models exhibit a significantly higher level of digitization, the mere adoption of a maturity model already constitutes a substantial contribution to improvement.

1.3 Manage controlling conditions to maximize efficiency.

Employee knowledge-development, managerial support, adequate funding investment, and data-security risk control are necessary to advance on the path to digital process maturity. Ensure, these terms are well supported. This support should be provided through the allocation of sufficient financial resources, appropriate employee training, and demonstrated open support from the leadership. To minimize potential risks, appropriate integrated data management systems and risk monitoring should accompany this process.

2. To scientist and researchers:

2.1 Expand information base.

A broader information base for the review is desirable to better found the research model. Further research strands, e. g. technology acceptance research and leadership theory, should be included in the review-based model development to accomplish the initial model by further explaining factors.

2.2 Close research gaps

The complexity of the issue and hitherto existing academic reluctance to address the topic of digital process maturity leave many gaps and fields of further research in mechanical engineering and further technology-related business sectors in Germany and globally. An intensification of the collaboration between universities and business practitioners is desirable to fill this void.

2.3 More empirical evidence

Researchers should use the model development in this dissertation and gather more empirical evidence. For 200 or more participants a structural equation model could be drafted which would detail the interactions between different inputs and controlling parameters and would differentiate the impacts of the individual items. Thus, more comprehensive insights and recommendations to mechanical engineering companies could be gained.

The results and derived conclusions match with the author's experience within the field of product development. The empirical results reflect on a broad basis the comments of the experts. It is definitely a differentiator, whether companies rely on digital appliances or not. Also the in the business well known problem of software interfaces was reflected in the results, leading the given recommendations. All in all, the results are conclusive, reflect practical experience, coincide with the analytical part and also confirm the theoretical classification. The work can therefore be considered a great success.

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Appendices

Review results on success impacts of maturity models (peer reviewed journal contributions retrieved from Scopus and other databases)

Empirical studies assessing effect of maturity model application on other performance targets by publication date an author – Part 1						
Year	**authors**	**IT technology**	**method**	**Measure of digital process maturity**	**Moderators of digital maturity effect**	**Targets and observed relationships**
2016	Titov et al.	Russian IT companies	Case study in Russian engineering company	• CMM Model		• Cost, time and quality effect of CMM positive
2016	Secundo et al.	University transfer efficiency	University survey	• PM2 model of process maturity		• Efficiency of technology transfer office concerning strategy, organization, HR, technology, industry links networking
2016	Mishra & Murray	US Fed. Gov Technology projects	82 projects regression analysis	• Process maturity CMMI model	• Complexity risk • Contracting risk • Execution risk	• Project performance increases and risks are attenuated by CMMI
2016	Dominguez et al.	Maturity model for integrated systems assessment	2 surveys Factor analysis of maturity levels regression analysis	• IMSM (integrated management systems maturity)	• Audit typology, integrated vision, organizational integration	• Attained maturity levels according to employee assessment
2016	Deijkman et al.	Organizational properties influencing BPM	Survey among 2708 German & Dutch organizations	• Business process management maturity	• Mediators: innovativeness, size, age region	• Business performance increases with maturity (level 2) • Innovativeness and region positively mediate maturity
2016	Berghaus & Back	Maturity in digital business transformation	Survey 547 participants from 417 Swiss & German companies Cluster analysis	• DMM (digital maturity model) 9 dimensions		• Identification of 5 maturity stages • Few strategically planned transformation processes
2015	Tarhan et al.	Maturity models in business performance management	Review of 62 studies on BPMM	• Comparison of different models		• Business maturity models enhance performance

2015	Biltci et al.	Performance measurement and management impact of maturity models	12 European manufacturing organizations Expert interviews	• Different maturity models	• Model characteristics	• Maturity models promote organizational learning & effective performance management and assessment
Empirical studies assessing effect of maturity model application on other performance targets by publication date an author – Part 2						
Year	**authors**	**IT technology**	**method**	**Measure of digital process maturity**	**Moderators of digital maturity effect**	**Targets and observed relationships**
2011	Rönkkö et al.	Agile IT development	Survey in 72 software SME	• Process maturity using CMMI	• Agile methods	• Software product development performance benefits from agile development but not from CMMI
2009	Bellini & Lo Storto	CMM impact in Italian software company	Quantitative data analysis of single company 1978-2001	• CMM model		• Knowledge Management & Learning in software organization • Productivity increase
2008	Wang et al.	Software flexibility impact on project performance	Project manager survey (n = 212) Survey SEM	• Software flexibility	• Management interventions	• Project performance • Control activity enhances success • Control activity enhance software flexibility + performance
2008	Lockamy et al.	Maturity model of supply chain cooperation	Database analysis of 18 European companies	• Process capability • Process maturity	• Supply chain uncertainty	• Supply chain performance
2007	Tiku et al.	Benchmarking electronic companies	Qualitative case study in electronic company	• Maturity model measuring organizational practices (CMM)		• Ability to design develop and manufacture reliable electronic products • Customer reliability requirements
2007	Na et al.	Risk control of overseas outsourcing of US software projects	Survey among Korean software firms, SEM	• Standardization • Requirement uncertainty • TBQ/ CMMI	• Functional development risk • System development risk	• Subjective performance, cost and schedule overrun • Product performance
2006	Tullio & Bahli	Impact of software process maturity on performance risk		• CMM	• Risk of project performance	• Software project performance increased by maturity • Risk is diminished

Empirical studies assessing effect of maturity model application on other performance targets by publication date an author – Part 3						
Year	**authors**	**IT technology**	**method**	**Measure of digital process maturity**	**Moderators of digital maturity effect**	**Targets and observed relationships**
2006	Jorgenssen & Boer	Comparison of maturity models and other continuous improvement models	Survey and review of literature	• CI • Maturity models	• Integration of several maturity models • Organizational capabilities • Company size	• Maturity models enhance speed and cost performance, relationship performance, organizational performance
2004	Jiang et al.	Survey among software engineers	CMM	• Software development maturity (CI maturity)		• Project performance depending on activity on five maturity levels • Managerial control enhances performance
2003	Ashrafi	Software process improvement comparison of different maturity models	Survey in New England among 200 software engineers descriptive	• CMM • ISO	• Quality factors e.g. correctness, maintainability, verifiability, efficiency	• Advanced process management • Software process improvement methodologies differ in their effect on quality • Ideally integrate CMM and ISO
2002	Kuliboer & Ashrafi	Impact on software process improvement on product	Survey (n =67) among New England developers	• Software process improvement strategies (ISO)		• Quality, cost, on-time delivery • Customer satisfaction
2001	Dooley et al.	Impact of maturity on new product development performance	Survey of 39 new product development programs	• CMM	• company size, • market volatility, • company type	• Generalization of maturity concept becond software engineering • CMM enhances cost and timeliness, product success

Interviews

Interview TB

1. Könnten Sie uns bitte mitteilen, welche Produkte Ihr Unternehmen herstellt und welche Aufgabe Sie in Ihrem Unternehmen wahrnehmen?
   Abteilungsleiter Entwicklungssparte, Flugphysik und Konzeptentwicklung; Luftfahrtunternehmen, >1000MA
2. Welche Produkte oder Prozesse werden in Ihrem Unternehmen neu entwickelt?
   Kleinflugzeuge und Turbopropflugzeuge

Prozessreife

3. Was verstehen Sie persönlich unter digitaler Prozessreife?
   Ein digitaler Prozess muss die unterschiedlichen Anforderungen an die Entwicklung eines komplexen Produktes abbilden. Das bedeutet, die Informationsaufbereitung für unterschiedliche Gruppen, eine gemeinsame Datenbasis und digitale Kommunikation.
4. In welcher Hinsicht bestimmen digitale Technologien den Wertschöpfungsprozess in ihrem Unternehmen?
   Vor allem im Engineering, Anforderung an schnellere Entwicklung, funktioniert am besten mit einer gemeinsamen, einheitlichen Datenbasis.
5. Besteht in Ihrem Unternehmen ein Bewusstsein für die Bedeutung digitaler Prozessreife und wie wird dies gegebenenfalls deutlich?
   Rudimentäres Bewusstsein, ist aber der Schlüssel für zukünftige Weiterentwicklung.
6. Unternimmt Ihr Unternehmen Anstrengungen, um die digitale Prozessreife zu messen und wenn ja welche Maßstäbe werden eingesetzt?
   Nein.

Effizienz in der Produktentwicklung

7. Wodurch ist Effizienz in der Produktentwicklung in Ihrem Unternehmen gekennzeichnet? Wo wird sie messbar?
   Entwicklung sucht immer die besten Lösung, hier besteht der Fehler, dass diese einzelnen Abteilung sich nicht als integraler Bestandteil der Firma sehen. Technisch an Produktleistungsdaten messbar. Betriebswirtschaftlich ist die Zeit für die Produktentwicklung an einem Produkt relevant, von dem sich die Firma Erfolg verspricht.
8. Wie wirkt sich technische Effizienz in der Produktentwicklung auf finanzielle Effizienz bzw. finanzielle Parameter aus?
   Technische Effizienz führt zum Einhalten der budgetierten Entwicklungskosten, hochwertiges Produkt mit geringem Ressourceneinsatz.

Zusammenhang zwischen digitaler Prozessreife und Produktentwicklung

9. Sind Sie persönlich der Auffassung, dass der Grad der Digitalisierung *(digitalen Prozessreife, wenn Begriff klar ist..)* in Zusammenhang mit der Effizienz von Produktentwicklungsprozessen steht? In welcher Hinsicht denken Sie, dass digitale Prozessreife wichtig für den Produktentwicklungsprozess ist?

Ja, aber nicht exklusiv.

10. In welcher Hinsicht könnte der effektivere oder vermehrte Einsatz digitaler Technologien dazu beitragen, dass die Produktentwicklung in ihrem Unternehmen effizienter abläuft?
    Je komplexer das Produkt, desto unterschiedlichere Effekte, desto mehr Spezialisten erforderlich. Hier ist die Reduktion der Schnittstellen hilfreich. Datenverwaltung ist besser. Es gibt fast bei jedem Projekt alte Daten, die Wiederverwendet werden können. Dokumentation findet besser statt.

Moderatoren des Zusammenhangs zwischen Digitaler Prozessreife und Produktentwicklung

11. Welche Faktoren sind für die Effizienz der Produktentwicklung (neben dem Einsatz digitaler Technologien) besonders wichtig? *(a bis c nur, wenn keine eigenen Ideen kommen)*
    Transparenz Abteilungsübergreifend, Verständnis für Effekte aus einzelnen Entwicklungsbereichen, Schärfen des Blickes „über den Tellerrand".
    Interdisziplinäres Zusammenarbeiten.
12. Denken Sie, dass für jedes Unternehmen andere Faktoren dafür entscheidend sind, wie effizient die Produktentwicklung abläuft und welche Faktoren sind in Ihrem Unternehmen ggf. spezifisch?
    Grundlegende Themen sind in allen Unternehmen gleich, fachlich einschlägige Punkte können sich aber sehr unterscheiden.

Interview TK

1. Könnten Sie uns bitte mitteilen, welche Produkte Ihr Unternehmen herstellt und welche Aufgabe Sie in Ihrem Unternehmen wahrnehmen?
   Leiter Structural Engineering, Luftfahrtunternehmen, >1000MA
2. Welche Produkte oder Prozesse werden in Ihrem Unternehmen neu entwickelt?
   Kleinflugzeuge und Turbopropflugzeuge

Prozessreife

3. Was verstehen Sie persönlich unter digitaler Prozessreife?
   Es ist ein etablierter Prozess, das hochgradig computerunterstütze Abarbeiten von Entwicklungsprozessen.
4. In welcher Hinsicht bestimmen digitale Technologien den Wertschöpfungsprozess in ihrem Unternehmen?
   Einschätzung, wenn 0% Arbeiten mit Schreibmaschinen ist und 100% Stand der Technick, würde ich uns knapp unter der Hälfte sehen.
5. Besteht in Ihrem Unternehmen ein Bewusstsein für die Bedeutung digitaler Prozessreife und wie wird dies gegebenenfalls deutlich?
   Teilweise, bei einem Teil der Belegschaft. Es gibt Mitarbeiter, die gerne neue Tools einführen möchten, andere Mitarbeiter stehen dem etwas reservierter gegenüber. Gründe dafür sind, dass sie sich nicht gerne auf etwas neues umstellen, aber auch das Hindernis der zeitlichen und finanziellen Investition.

6. Unternimmt Ihr Unternehmen Anstrengungen, um die digitale Prozessreife zu messen und wenn ja welche Maßstäbe werden eingesetzt?
   Keine bekannten Anstrengungen.

Effizienz in der Produktentwicklung

7. Wodurch ist Effizienz in der Produktentwicklung in Ihrem Unternehmen gekennzeichnet? Wo wird sie messbar?
   Messen würde ich die Effizienz daran, ob es einen etablierten Prozess gibt, das ist im Unternehmen ganz gut umgesetzt, und wie viele Design Loops erforderlich sind. Also Messgröße wäre für mich die durchschnittliche Anzahl der Designloops.
8. Wie wirkt sich technische Effizienz in der Produktentwicklung auf finanzielle Effizienz bzw. finanzielle Parameter aus?
   Direkter Zusammenhang ist mir nicht bekannt, aber ich nehme an, dass es ein sehr durchschlagender Effekt ist, der mehrfach wirkt. Einerseits ein besseres Ergebnis in kürzerer Zeit, andererseits ist man nachhaltiger, auch in Hinsicht auf später auftretende Ereignisse.

Zusammenhang zwischen digitaler Prozessreife und Produktentwicklung

9. Sind Sie persönlich der Auffassung, dass der Grad der Digitalisierung *(digitalen Prozessreife, wenn Begriff klar ist..)* in Zusammenhang mit der Effizienz von Produktentwicklungsprozessen steht? In welcher Hinsicht denken Sie, dass digitale Prozessreife wichtig für den Produktentwicklungsprozess ist?
   Ja, allerdings gibt es eine zeitliche Komponente. Man muss den Break Even Point im Auge haben, zuerst ist es eine Investition und die Amortisation tritt erst nach einer gewissen Zeit ein.
10. In welcher Hinsicht könnte der effektivere oder vermehrte Einsatz digitaler Technologien dazu beitragen, dass die Produktentwicklung in ihrem Unternehmen effizienter abläuft?
    Bei Bauabweichungen wird aktuell noch sehr viel mit Papier gearbeitet, Informationsfluss des Freigabeprozesses ist sehr unübersichtlich.

Moderatoren des Zusammenhangs zwischen Digitaler Prozessreife und Produktentwicklung

11. Welche Faktoren sind für die Effizienz der Produktentwicklung (neben dem Einsatz digitaler Technologien) besonders wichtig? *(a bis c nur, wenn keine eigenen Ideen kommen)*
    Schritt für Schritt zur richtigen Zeit, Idee, Konzept, Vorauslegung usw… Nicht damit beginnen bereits Zeichnungen in die Produktion zu bringen, bevor Konstruktionsmerkmale ausdetailliert sind. Unternehmensführung hat die Möglichkeit auf handelnde Personen so einzuwirken, dass diese Handlungsweise etabliert wird.
12. Denken Sie, dass für jedes Unternehmen andere Faktoren dafür entscheidend sind, wie effizient die Produktentwicklung abläuft und welche Faktoren sind in Ihrem Unternehmen ggf. spezifisch?
    Ich glaube die Problematik ist in jedem Unternehmen ab einer gewissen Größe (ab 150MA) gleich, da es dann ein gewisses Spektrum an unterschiedlicher Charakteren gibt, das dazu führt.

Interview BG

1. Könnten Sie uns bitte mitteilen, welche Produkte Ihr Unternehmen herstellt und welche Aufgabe Sie in Ihrem Unternehmen wahrnehmen?
   Das Unternehmen stellt Folienreck-Anlagen her, wo über Extrusionstechnik Kunststoffe und Additive vermengt und aufgeschmolzen werden um über Längs- und Querreckung unterschiedlichste Folien für Verpackungen, Industrie- und Konsumgüter herzustellen. Meine Tätigkeit dabei ist die elektrische Projektleitung, d.h. die gesamtverantwortliche Betreuung der eingesetzten elektrischen Komponenten und der zugehörigen Software.
2. Welche Produkte oder Prozesse werden in Ihrem Unternehmen neu entwickelt?
   Die bestehenden Reckanlagen für die unterschiedlichsten Materialien werden kontinuierlich weiterentwickelt hinsichtlich Geschwindigkeit und Ausstoß, Effizienz, dem Einsatz alternativer Rohstoffe etc. Auch firmeninterne Prozessabläufe werden ständig analysiert und weiterentwickelt.

Prozessreife

3. Was verstehen Sie persönlich unter digitaler Prozessreife?
   Unter digitaler Prozessreife verstehe ich, dass der Datenstamm einer Firma möglichst großflächig digital verfügbar ist, möglichst wenig manuelle Überführungs- bzw. Konvertiertätigkeiten notwendig sind und so ein Firmenprozess digital abbildbar ist.
4. In welcher Hinsicht bestimmen digitale Technologien den Wertschöpfungsprozess in ihrem Unternehmen?
   Der gesamte Wertschöpfungsprozess baut im Unternehmen auf digitale Technologien auf, das umfasst sämtliche Abteilungen und Prozesse wie z.B. Entwicklung und Materialwirtschaft. Nicht zuletzt hat auch das Endprodukt einen hohen Digitalisierungsgrad, darüber hinaus gibt es aktuell massive Bestrebungen die Prozessoptimierungen des Endkunden besser durch Software unterstützen und nachverfolgen zu können.
5. Besteht in Ihrem Unternehmen ein Bewusstsein für die Bedeutung digitaler Prozessreife und wie wird dies gegebenenfalls deutlich?
   Eindeutig ja. Im Vergleich zu anderen mir bekannten Unternehmen wird jede Änderung an einem Prozess bzw. die Einführung neuer Prozesse ausschließlich digital abgebildet.
6. Unternimmt Ihr Unternehmen Anstrengungen, um die digitale Prozessreife zu messen und wenn ja welche Maßstäbe werden eingesetzt?
   Ist mir nicht bekannt.

Effizienz in der Produktentwicklung

7. Wodurch ist Effizienz in der Produktentwicklung in Ihrem Unternehmen gekennzeichnet? Wo wird sie messbar?
   Zum Bespiel durch das beständige Bestreben, doppelte Datenhaltung im gesamten Unternehmen zu vermeiden: Haben bis vor einiger Zeit die Abteilungen mechanische Konstruktion und elektrische Projektierung noch mit komplett separierten Entwicklungstools gearbeitet und die gegenseitig notwendigen Spezifikationen manuell bearbeitet und ausgetauscht, wird nun eine gemeinsame Datenbasis genutzt. Dessen Vorteil bzw. Effizienzsteigerung wird ev. noch nicht bei einer Entwicklungsiteration sichtbar. Dreht man aber mehrere Änderungsschleifen, wie es in der

Praxis oft vorkommt, sieht man eine weitaus höhere Effizienz durch Fehlervermeidung an den zugrunde gelegten Daten.

8. Wie wirkt sich technische Effizienz in der Produktentwicklung auf finanzielle Effizienz bzw. finanzielle Parameter aus?
Siehe Punkt 7: Fehlervermeidung schlägt sich in verminderten Kosten nieder.

Zusammenhang zwischen digitaler Prozessreife und Produktentwicklung

9. Sind Sie persönlich der Auffassung, dass der Grad der Digitalisierung *(digitalen Prozessreife, wenn Begriff klar ist..)* in Zusammenhang mit der Effizienz von Produktentwicklungsprozessen steht? In welcher Hinsicht denken Sie, dass digitale Prozessreife wichtig für den Produktentwicklungsprozess ist?
Ja, meiner Meinung nach unmittelbar. Digitale Prozessreife kann und sollte dazu führen, dass alle Beteiligten ein gleiches Datenbild haben und Fehler vermieden werden.
10. In welcher Hinsicht könnte der effektivere oder vermehrte Einsatz digitaler Technologien dazu beitragen, dass die Produktentwicklung in ihrem Unternehmen effizienter abläuft?
Digitalisierungsgrad ist im Unternehmen bereits sehr hoch, trotzdem gibt es noch immer Stellen wo Daten doppelt gehalten werden, die in Folge dann natürlich auch doppelt gepflegt werden müssen. Hier ist noch etwas Potenzial. Bei allen Vorteilen durch Überführung in digitale Prozesse darf man aber nicht eine gewisse notwendige Flexibilität aus den Augen verlieren. Die Erfahrung zeigt, dass Prozesse wenn Sie wie gedacht durchlaufen werden, durch Digitalisierung sehr effizient werden können. Wenn aber vom Standard abgewichen werden muss, führt ein starr festgelegter Prozess ohne Eingriffsmöglichkeiten zu einer Explosion der Aufwendungen. Dies sollte immer mit berücksichtigt werden.

Moderatoren des Zusammenhangs zwischen Digitaler Prozessreife und Produktentwicklung

11. Welche Faktoren sind für die Effizienz der Produktentwicklung (neben dem Einsatz digitaler Technologien) besonders wichtig? *(a bis c nur, wenn keine eigenen Ideen kommen)*
Der größte Effizienzfaktor ist meiner Meinung nach ein Menschlicher. Mitarbeiter sollten motiviert und befähigt werden, über den eigenen Tellerrand zu blicken. Wer seine Blase verlässt und die angrenzenden Teilbereiche bzw. das große Ganze sieht, trägt unmittelbar und nachhaltig zu einer Effizienzsteigerung bei.

   Inwiefern ist das im Unternehmen vorhandene Wissen wichtig?

   Ist im Unternehmen aufgrund der Bedienung einer gewissen Nischen-Sparte extrem wichtig. Hier ist die Expertise von erfahrenen Kollegen unverzichtbar.

   Inwiefern ist gutes Risikomanagement wichtig?

   Sehr wichtig in unserer Branche. Da es um sehr große und teure Einzelanlagen, wird vor jedem Projekt eine Risikobewertung hinsichtlich diverser Unwegbarkeiten durchgeführt (neue Rohstoffe, neue Technologien, schwierige Umstände bzgl. Zielland). Je nachdem welcher Risikofaktor dem Projekt dann zugeordnet wird, werden zusätzliche Entwicklungsschleifen, Abstimmungsmeetings u.ä. durchgeführt.

12. Denken Sie, dass für jedes Unternehmen andere Faktoren dafür entscheidend sind, wie effizient die Produktentwicklung abläuft und welche Faktoren sind in Ihrem Unternehmen ggf. spezifisch?
    Sowohl als auch, ich denke alles was den Datenstamm eines Unternehmens betrifft kann man hier eine Schnittmenge hinsichtlich Digitalisierung und Effizienz finden, die universell sein kann. Das gilt auch für die Fähigkeit der Mitarbeiter über den Tellerrand zu blicken. Andere Faktoren können weitaus mehr branchen- oder unternehmensspezifisch sein, bei uns z.B. die Internationalität (zu einem großen Teil in Schwellenländern), die Größe einzelner Projekte, ...

Interview MS

1. Könnten Sie uns bitte mitteilen, welche Produkte Ihr Unternehmen herstellt und welche Aufgabe Sie in Ihrem Unternehmen wahrnehmen?
   Übernahme von Folienstreckanlagen nach einem Jahr Gewährleistung und dann Service, Modernisierung und Instandhaltungsdienstleistungen, also AfterSales.
2. Welche Produkte oder Prozesse werden in Ihrem Unternehmen neu entwickelt?
   Eigene Abteilung, Business Development, kümmert sich um interne Prozessoptimierung und die Entwicklung von neuen Produkten und Dienstleistung.

Prozessreife

3. Was verstehen Sie persönlich unter digitaler Prozessreife?
   Ausgehend von den Prozessen im Haus, Digitalisierung, weg von manuellem Bearbeiten (beispielsweise Telefonat, Mail, Ausfüllen in SAP etc…), bedeutet ein reifer Prozess ist durchgehend innerhalb einer Eingabeoberfläche.
4. In welcher Hinsicht bestimmen digitale Technologien den Wertschöpfungsprozess in ihrem Unternehmen?
   Digitale Kundenprozesse und interne Prozesse; Bei Kundenprozessen ist gerade ein neues Produkt auf den Markt gekommen, dass den Prozess zwischen Kunden und Firma zu hohem Grad digitalisiert (digital supply chain), neue Geschäftsmodelle können durch Digitalisierung etabliert werden.
5. Besteht in Ihrem Unternehmen ein Bewusstsein für die Bedeutung digitaler Prozessreife und wie wird dies gegebenenfalls deutlich?
   Eindeutig ja. Budgetierung von Digitalisierungsprojekten.
6. Unternimmt Ihr Unternehmen Anstrengungen, um die digitale Prozessreife zu messen und wenn ja welche Maßstäbe werden eingesetzt?
   Ist mir nicht bekannt.

Effizienz in der Produktentwicklung

7. Wodurch ist Effizienz in der Produktentwicklung in Ihrem Unternehmen gekennzeichnet? Wo wird sie messbar?
   KPIs werden gemessen, Reaktionszeiten hin zum Kunden, Anfragebeantwortung, Arbeitsstunden pro Auftrag, Fallbearbeitung

8. Wie wirkt sich technische Effizienz in der Produktentwicklung auf finanzielle Effizienz bzw. finanzielle Parameter aus?
   Reduzierung der projektspezifischen Kosten, Fokussierung auf Kerntätigkeit, erhebliche Kosteneinsparung.

Zusammenhang zwischen digitaler Prozessreife und Produktentwicklung

9. Sind Sie persönlich der Auffassung, dass der Grad der Digitalisierung *(digitalen Prozessreife, wenn Begriff klar ist..)* in Zusammenhang mit der Effizienz von Produktentwicklungsprozessen steht? In welcher Hinsicht denken Sie, dass digitale Prozessreife wichtig für den Produktentwicklungsprozess ist?
   Reifegrad steht nicht per se mit der Effektivität in Zusammenhang, das hängt von der einsatzgerechten Implementierung der Digitalisierung in den Prozess ein.
10. In welcher Hinsicht könnte der effektivere oder vermehrte Einsatz digitaler Technologien dazu beitragen, dass die Produktentwicklung in ihrem Unternehmen effizienter abläuft?
   Reduktion Entwicklungszeit, Unterstützung von Tätigkeiten, Schaffung von Transparenz.

Moderatoren des Zusammenhangs zwischen Digitaler Prozessreife und Produktentwicklung

11. Welche Faktoren sind für die Effizienz der Produktentwicklung (neben dem Einsatz digitaler Technologien) besonders wichtig?
   Risikomanagement, klare Strukturen, Budgetierung
12. Denken Sie, dass für jedes Unternehmen andere Faktoren dafür entscheidend sind, wie effizient die Produktentwicklung abläuft und welche Faktoren sind in Ihrem Unternehmen ggf. spezifisch?
   Es gibt sicher Punkte die in jedem Unternehmen gleich sind, besonders bei Herstellern. Im Anlagenbau ist beispielsweise Datenschutz (kundeneigene Fertigungsparameter) etwas, das eventuell bei anderen Unternehmen nicht so wichtig ist.