UNIVERSITA' DEGLI STUDI DI PADOVA

DIPARTIMENTO DI SCIENZE ECONOMICHE ED AZIENDALI "M.FANNO"

CORSO DI LAUREA MAGISTRALE / SPECIALISTICA IN BUSINESS ADMINISTRATION

TESI DI LAUREA

"MEASURING THE FIRM COMPETITIVENESS BY THE CAPACITY OF OPERATIONAL FLEXIBILITY USING INDUSTRY 4.0 "

RELATORE:

CH.MO PROF. ELEONORA DI MARIA

LAUREANDO/A: DEMET ALTUNAY

MATRICOLA N. 2046959

ANNO ACCADEMICO 2022 – 2023

Il candidato dichiara che il presente lavoro è originale e non è già stato sottoposto, in tutto o in parte, per il conseguimento di un titolo accademico in altre Università italiane o straniere.
Il candidato dichiara altresì che tutti i materiali utilizzati durante la preparazione dell'elaborato sono stati indicati nel testo e nella sezione "Riferimenti bibliografici" e che le eventuali citazioni testuali sono individuabili attraverso l'esplicito richiamo alla pubblicazione originale.

The candidate declares that the present work is original and has not already been submitted, totally or in part, for the purposes of attaining an academic degree in other Italian or foreign universities. The candidate also declares that all the materials used during the preparation of the thesis have been explicitly indicated in the text and in the section "Bibliographical references" and that any textual citations can be identified through an explicit reference to the original publication.

Firma dello studente

D.Altunay

Table of Contents

INTRODUCTION

The journey from Industry 1.0 to Industry 4.0 has marked a remarkable evolution in manufacturing practices and changed the way businesses operate.

The beginning of the *First Industrial Era*, which occurred in the 18th century, came along with the introduction of the utilization of waterpower for various industrial processes and the emergence of the steam engine. People at the time were already familiar with this innovative technology of the steam engine. The most significant progress in enhancing human productivity during this era was achieved by using these innovations, particularly the steam engine, in the field of manufacturing. The *Second Industrial Revolution* began in the 19th century with two key innovations: the development of electricity as a source of power and the introduction of assembly lines. Henry Ford (1863-1947) played a pivotal role in this revolution. He introduced the concept of mass production, which involved the cost-efficient manufacturing of large quantities of products. In Ford's case, he applied these ideas to the production of vehicles, particularly automobiles. One of Henry Ford's notable contributions was the implementation of the assembly line and conveyor belt system in car manufacturing. Instead of assembling each car in front of a stationary platform, he divided the manufacturing process into a series of partial steps, with each step taking place at different stations along a moving conveyor belt. This innovation significantly increased the speed and reduced the cost of car production. In the 1970s, the *Third Industrial Revolution* began with the introduction of partial automation through memory-programmable controls and computers. This marked the starting point for the optimization of the entire production process without the need for human intervention. For instance, this era saw the emergence of robots capable of executing tasks autonomously. Industry 3.0 serves as the intermediary stage, connecting Henry Ford's pursuit of increased productivity in manufacturing to the intelligent, automated processes of smart manufacturing that are now evolving in Industry 4.0. (Sharma, A., & Singh, B. J., 2020)

In the era of Industry 4.0, a shift toward “smart production,” where advanced technologies are integrated into the manufacturing process started to improve efficiency and responsiveness. With the advent of Industry 4.0, the role of production is still undergoing significant changes. Instead

of traditional manufacturing methods, smart production systems aim to be more adaptable and responsive to changing demands and conditions. The National Institute of Standards and Technology defines smart manufacturing as the use of fully integrated and collaborative manufacturing systems that can respond in real-time to changing demands and conditions within the factory, across the supply network, and in response to customer needs. To achieve the goals of Industry 4.0 and smart manufacturing, it's essential to integrate data across the entire business, including production, procurement, supply chain, design, product life cycle management, quality, operations, and logistics. The goal is to enable a seamless flow of data throughout the organization. Another critical aspect of Industry 4.0 is the need for efficient data services and analytics. This involves gathering data from machines, sensors, and systems in the manufacturing process and then analyzing that data to extract meaningful profitable insights. (Nayyar, A., &Kumar, A.,2020)

The term "Industry 4.0" holds particular significance for German manufacturing due to its origins and implications. It emerged from the German government's initiative, the Zukunftsprojekt Industrie 4.0, announced in 2011 by Henning Kagermann, Wolf-Dieter Lukas, and Wolfgang Wahlster at the Hannover Fair. This initiative was a response to the challenges posed by advancing digitalization and automation trends in the industrial sector.

Germany's well-established historical and global standing as a manufacturing leader highlights the significance of Industry 4.0 within the country. This initiative was designed to enhance Germany's traditional strengths in manufacturing by incorporating cutting-edge technologies, integrating data-driven processes, and extensively implementing automation in production. The overarching aim was to maintain Germany's competitive edge in manufacturing on the world stage, revitalizing its position as an industry frontrunner. Consequently, the term "Industry 4.0" became closely associated with Germany's strategy to leverage technological advancements and reaffirm its prominence in manufacturing within a swiftly evolving industrial environment.

However, there are still some challenges in the way of becoming data data-ready businesses that German manufacturing companies need to have in this era. Due to the increasing trend of globalization, German manufacturing companies have faced mounting pressure to compete effectively in recent years, not only in their domestic market but also on an international scale. One of the most notable factors influencing manufacturing is the trend toward individualization. This means that consumers increasingly seek customized or personalized products that cater to

their unique preferences and needs. This trend is not only driven by technological advancements but also by societal desires for tailored solutions. In addition to that, data security has become a prominent concern in Germany, particularly among technology-intensive German SMEs, who are apprehensive about the risk of their hard-earned knowledge and information being misappropriated in the context of digitally interconnected collaborative structures. Cyberattacks have also become public events, which can strain diplomatic relationships between nations. In this context, concerns about integration into digitalized, interconnected industrial value-added strategies have grown, resulting in obstacles to the interconnection of devices and machines, as well as integration into external networks. (Schroeder, W.,2016)

The motivation behind this research stems from the profound impact of data management and customization on the German manufacturing industry, particularly within the context of Industry 4.0. With a strong foundation in existing research findings concerning data readiness and the challenges faced by manufacturing companies, this study seeks to contribute valuable insights. By focusing on the experiences and practices of a specific manufacturing company in Germany, the aim is to highlight the real-world applications of data technologies, the adaptability of such technologies in the evolving Industry 4.0 landscape, and the dynamics of customer relationships. This research serves as a bridge for the gap between theoretical knowledge and practical implementation, providing a comprehensive understanding of how data management and customization play pivotal roles in shaping the future of the German manufacturing sector, thereby offering valuable guidance to both researchers and industry stakeholders.

In this thesis, the following research questions will be addressed:

a. What data integration technologies are employed in the context of smart manufacturing for customization strategies?

b. What challenges and obstacles do German manufacturers face when preparing for data-driven operations?

c. Building upon recent research on data readiness in German manufacturing companies, what percentage of these companies prioritize customer-related data and are they aware of the rising consumer preferences for tailored products?

d. What strategic approaches can be adopted by German manufacturers who are in the process of becoming fully digitalized to establish a customer-centric business model?

Chapter 1 Traditional Manufacturing to Smart Manufacturing Models

The evolution of manufacturing paradigms has reflected changing consumer demands, technological advancements, and economic dynamics. Traditional manufacturing models, rooted in mass production and standardized offerings, were designed to achieve economies of scale and streamline operations. While these models facilitated efficient production, they often struggled to address the diverse preferences and personalized needs of consumers and fast-changing market trends. The emergence of Industry 4.0 signifies a transformative move away from conventional manufacturing methods, embracing customer-centric customization models that harness the power of data and digital technologies to enhance innovation and operational efficiency. In recent years, the rapid advancements in information technology and the emergence of data science have paved the way for the era of data-driven smart manufacturing.

As the Federal Ministry of Education and Research noted (as cited in Prof. Dr. Iris Gräßler, 2014), flexible product technologies allow manufacturers to adjust the properties of their products to meet the specific needs and preferences of customers. It's a departure from traditional manufacturing, where products are typically fixed once production begins. The strategic use of software plays a pivotal role in this adaptability. Manufacturers can create product variations and differentiate their offerings without the need for significant changes in the hardware or physical components. These flexible technologies often lead to shorter product life cycles. Additionally, by adapting products more closely to customer needs and offering customization, the products are more likely to be utilized to their full potential.

Manufacturers are now equipped with real-time data analytics, predictive maintenance, and IoT-enabled machinery, which enables them to respond swiftly to customer demands and adapt to market changes with precision and quality. As a result, the traditional idea that manufacturing involves a trade-off between producing a large quantity of identical products (mass production) and making customized or unique products is becoming less clear or distinct. Manufacturers can now achieve economies of scale while delivering personalized products, which were once considered mutually exclusive.

1.1 Pre-Smart Manufacturing Era in Germany

Traditional manufacturing practices in Germany, are rooted in a legacy of precision engineering and production excellence, on the other hand, this model included several limitations when measured against the backdrop of customer-centric manufacturing models. Historically, German manufacturing has been recognized for its commitment to high-quality, standardized products. However, this approach resulted in rigid production processes that were not easily adaptable to the diverse and ever-evolving demands of the extensive customer base and often relied on mass production. While the focus on quality and precision remained a cornerstone of German manufacturing, the need for flexibility and responsiveness to customer-specific requirements became increasingly apparent in a world where customization and individualization are key drivers of competitiveness in the Industry 4.0 era. In this section of the thesis, this study will delve into some of these limitations and explore how they shaped the path toward smart manufacturing.

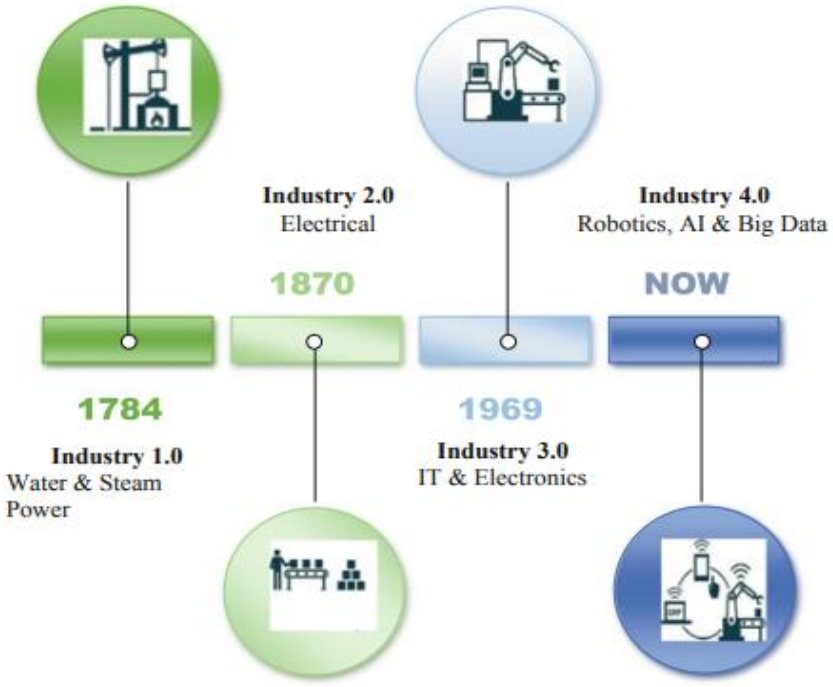


Figure Source: Sharma, A., & Singh, B. J. (2020). Evolution of Industrial Revolutions: A Review. (Page12)

1.1.2 **Challenges**

- *Lack of Flexibility and Customization*

Mass customization involves producing products that can be tailored to meet individual customer preferences and needs using flexible manufacturing processes with the efficiency of mass production (mass customization). These customized products can be developed in company-to-customer continuous interaction, a process known as "co-design.", the prerequisite of mass customization. (Piller, F., Petra, K., 2004)

On the other hand, arranging all manufacturing processes quickly according to the specific customer's needs or changing market trends, cannot be fulfilled through traditional, one-at-a-time production methods, therefore it was creating biggest barrier to becoming flexible. Instead, it only focuses on manufacturing processes that are efficient and capable of handling mass demand.

Traditional manufacturing had several limitations when it came to being flexible and accommodating customization, such as fixed production lines, limited automation, inefficient material usage, and lack of data-driven decision-making. All these limitations resulted in the need for a modern approach to manufacturing that combines cost-efficiency with customization, which is often referred to as "mass customization."

- *Limited Connectivity and Data Utilization*

Before the Smart Manufacturing era, traditional manufacturing systems in Germany had limited connectivity and data utilization capabilities. This meant that real-time data collection, analysis, and remote monitoring were not as readily available.

Traditional manufacturing software and technologies are not suitable for smart manufacturing because they face challenges in fully integrating and collaborating. This is primarily because various vendors develop these systems, each using different interfaces or protocols. As a result, these systems often don't work seamlessly together, hindering the efficient sharing of data and coordination of tasks. Another limitation of traditional manufacturing software is its inability to perceive and respond to real-time changes effectively. In the context of the factory, supply chain, and market, these systems cannot gather sensory data that would allow them to detect and react

promptly to changes both within the manufacturing environment and in the external market. This real-time data is crucial for making quick, informed decisions and adjustments to production processes. (Cui, Y., Kara, S., & Chan, K. C. 2020).

- *Sustainability and Environmental Concerns*

Historically, when assessing a production system, manufacturers primarily focused on four key categories of attributes, which are cost (the expenses involved), time (how quickly products are produced), quality (the standard of the products), and flexibility (how adaptable the system is to changes). Nowadays, additional factors have become important in assessing manufacturing performance. These include energy efficiency (how efficiently energy is used) and resource efficiency (how efficiently materials and resources are used). These aspects are now integral to evaluating a production system's sustainability, emphasizing the need for environmentally responsible and efficient manufacturing processes. (Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G., & Thiede, S.,2015, p (619))

The following figure represents this shift from traditional to sustainable manufacturing with advanced technologies.

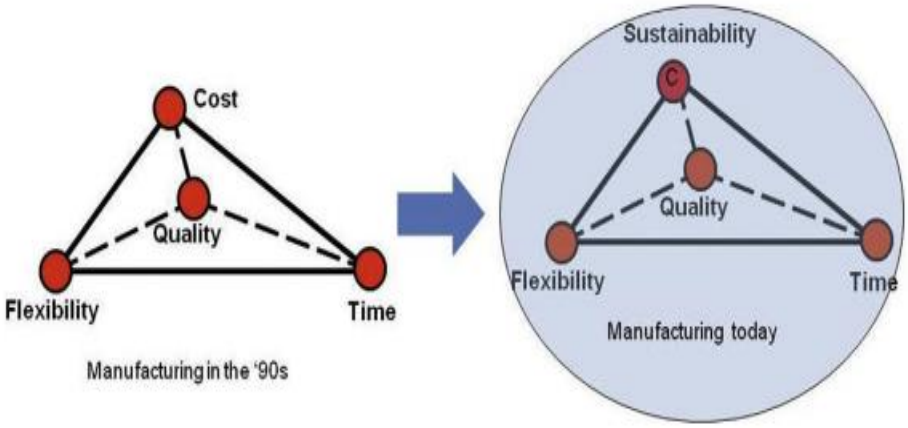


Figure Source: Manufacturing decision-making attributes in the 1990s and at present time (Salonitis and Stavropoulos, 2013)

1.2 Information Revolution

The Information Revolution in Germany marked a pivotal starting point in the nation's manufacturing history. This revolution is part of the broader global shift towards digitization, using information and communication technologies to drive innovation, efficiency, and economic growth.

In the book by Piller (2020), it is noted that the renewed debate on information, which started in 1993, was the third attempt in Germany. The earlier two attempts occurred in the 1970s and 1980s. Each phase was characterized by a different focus and context. In the past, it was often driven by political motivations and ideological considerations. It was used as a basis for justifying state research funding and efforts related to liberalization and deregulation (as cited in Trautwein-Kalms (1997), p. 169). However, in the 1990s, the focus shifted more toward economic considerations. The discussion now centers on the microeconomic benefits that result from the adoption of new technologies and their broad application in various sectors of the economy. (as cited in Kubicek (1997), p. 387)

This period signifies a notable shift towards data-centric manufacturing, where information technology, such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Product Data Management (PDM), and related systems, assumed a critical role in overseeing data from production and supply chain processes. During this time, design processes underwent digital transformation, and there was a strong emphasis on enhancing production efficiency through methodologies like Flexible Manufacturing and Just-in-Time production. (Zhang, C. & Chen, D. & Tao, F. & Liu, A. 2019)

The Information Revolution as "The 'development process,' as described in 'Mass customization, 2006' by Frank T. Piller, symbolizes the transition from an industrial to an information society, driven by the increasing adoption of new ICT technologies and their transformative impact on information processing and utilization in manufacturing. They highlight that these technologies have empowered companies to overcome traditional market entry barriers, including capital constraints, access to distribution channels, and national borders by changing industrial value-creation activities. This newfound capability has, in turn, facilitated market differentiation strategies. In well-established markets, the adoption of ICT technologies provides opportunities for precise customer targeting, enabling price differentiation and the provision of tailor-made

products for specific usage contexts. Moreover, the integration of ICT can stimulate the creation of entirely new products, potentially leading to a shift or expansion in a company's strategic focus, thereby driving differentiation. (Nagel, K., Erben, R.,Piller, F.,1999)

According to Piller, as part of a structural change caused by ICT, more and more people are being employed in professions whose essential work content is the creation, processing, and dissemination of information in Germany. Information-based products and services (Informationsbasierte Produkte und Dienste) required more employees at that time.

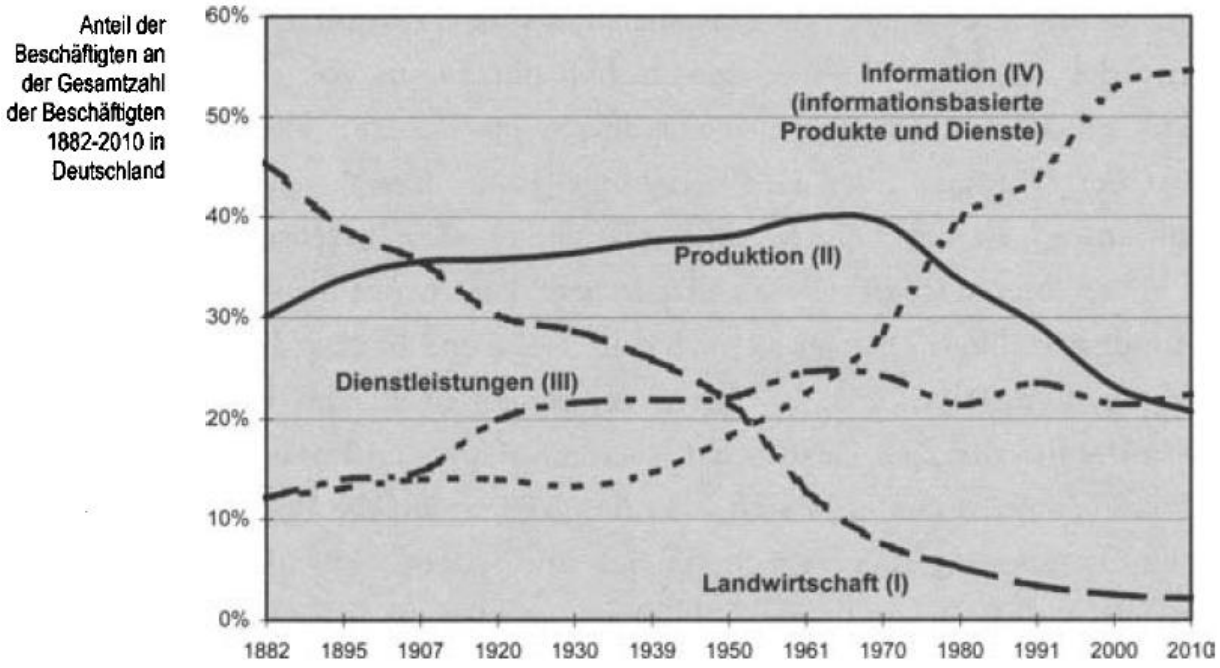


Figure Source: Filler, F. T. (2020). *Share of employees in the total number of employees 50% from 1882 to 2010 in Germany*. The book of Mass Customization. P (32)

The information revolution in German manufacturing is an **ongoing process**, and it has led to a more agile, efficient, and competitive manufacturing sector in the country. It continues to shape the future of manufacturing by restructuring business models and its internal-external organizations.

1.3 Mass Customization - *Hybrid Competitive Strategy*

This passage explains that the disconnect or gap between what manufacturers were offering and what consumers and changing market conditions were required as result of the inflexible processes and unchanging product designs associated with mass production. There was a growing need for a fundamental shift in thinking – a paradigm shift – that could enable production strategies to be more adaptable to the dynamic and evolving preferences of consumers. This need for change led to the development of customization models, which were better suited to aligning what manufacturers were producing with what consumers desired in a more flexible and personalized way.

Mass customization implies a remarkable and **hybrid competitive strategy** that transcends the boundaries of traditional business models defined by Porter (1980), he outlined strategies like cost leadership, differentiation, and focus (Porter, M.,1980). Mass customization, however, goes beyond these traditional boundaries and introduces a revolutionary approach. It embodies the flexibility to offer customers tailored products while still benefiting from the efficiencies of mass production, challenging the idea that firms must exclusively opt for one competitive strategy (implementing both cost leadership and differentiation strategy simultaneously). The dichotomy of being customer-centric while maintaining economies of scale is the essence of mass customization, which challenges the conventional assumptions laid out by Porter. In today's ever-evolving markets and the age of Industry 4.0, mass customization has become an essential avenue for companies to address the diverse needs of their customers and adapt to the rapidly changing business landscape, thus redefining the competitive strategies that drive success in the modern business world.

This strategic approach in manufacturing is where companies aim to provide customized or personalized products to a larger market while keeping the production costs as low as possible, like those of mass-produced items. This concept is positioned between two other strategic approaches: pure differentiation, which focuses solely on creating unique, customized products; and pure cost leadership, which is centered on producing standardized, low-cost products in large quantities. The exact position of a company on this spectrum between differentiation and cost leadership depends on its chosen strategy. Some companies may lean more towards differentiation, prioritizing customization to cater to specific customer needs even if it involves

higher costs. Others may emphasize cost leadership by efficiently producing a variety of products to reach a broader market while still maintaining competitive pricing. In essence, mass customization allows businesses to strike a balance between meeting individual customer demands and maintaining cost-efficiency in their production processes.

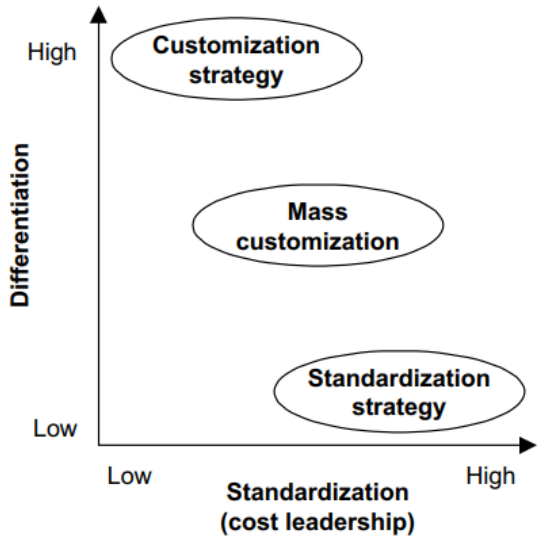


Figure source: The book of Complexity management strategies; adapted from Schuh and Schwenk (2001, p. 62)

Gilmore, J. H. and Pine, B. J. (1997) introduced four approaches to mass customization, each offering unique ways to tailor products and services to individual customer needs while maintaining the efficiency of large-scale production.

- Collaborative Customization: In this approach, manufacturers work closely with individual customers to design and produce products that align with their specific requirements. Collaborative customization is characterized by direct communication between the customer and the company, allowing for a high degree of personalization. Customers actively participate in the design process, selecting features, materials, and other product attributes to create a unique end product. This approach is often seen in industries where highly personalized products are needed, such as custom-made clothing or bespoke furniture.

- Adaptive Customization: Adaptive customization focuses on providing a range of pre-designed product options that customers can choose from. These options are created based on extensive market research and customer segmentation. The manufacturer offers a menu of features, configurations, or variations, and customers select the combination that best suits their needs. This approach allows for a degree of personalization within predefined boundaries and is commonly seen in industries like automotive, where customers can choose from various vehicle features and options.

- Cosmetic Customization: Cosmetic customization involves offering a variety of aesthetic choices to customers. While the core product remains the same, customers can personalize the product's appearance, colors, branding, or other superficial aspects. Cosmetic customization provides customers with the feeling of uniqueness without significantly altering the product's underlying functionality. This approach is often used in industries like electronics, where customers can choose from different device colors and custom skins.

- Transparent Customization: Transparent customization combines both the personalization aspects of collaborative customization and the predefined choices of adaptive customization. In this approach, customers are presented with a set of options that can be individually customized. However, these options are carefully curated by the manufacturer to ensure that they are feasible within the production process and do not lead to inefficiencies. The goal is to balance flexibility and practicality, allowing customers to create personalized variations while maintaining the benefits of efficient production. Transparent customization is found in various industries, including personal computing, where customers can configure their devices by selecting components and features from a predetermined list.

These four approaches collectively represent the spectrum of mass customization strategies, from highly personalized and collaborative experiences to more standardized but flexible options. By employing these approaches, companies can effectively meet the diverse requirements of their customers while also keeping their production processes efficient and cost-effective. In essence,

they offer a balance between offering unique, individualized products and maintaining operational effectiveness. (Pine II, B. J., 1993)

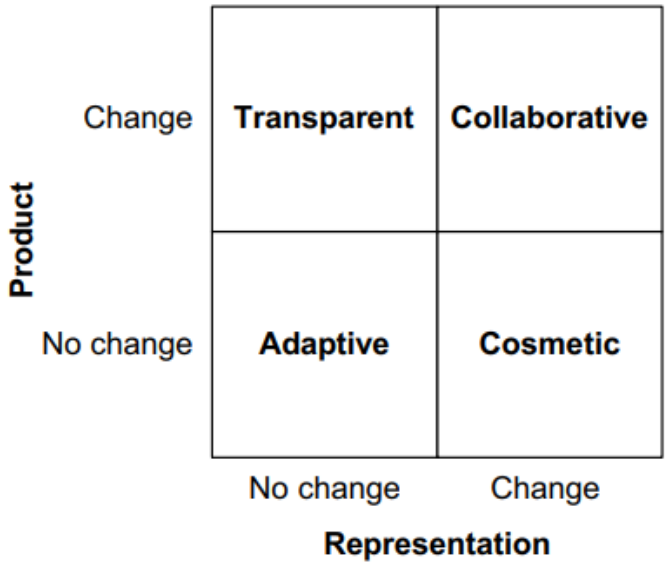


Figure source: *Four approaches to mass customization* (Gilmore & Pine, 1997, p. 95)

Chapter 2 Data Management in German Manufacturing

With the advent of electronic data processing and the automation of production processes within organizations, data has evolved into a powerful competitive tool. In today's rapidly changing market landscape, data has transitioned from being merely beneficial to becoming an indispensable factor for ensuring market flexibility and competitiveness.

There is a dynamic relationship between data management and operational flexibility because both concepts are intrinsically linked and mutually reinforcing. In this transformative era of manufacturing, the full potential of Industry 4.0 technologies is harnessed when data management and operational flexibility are leveraged in perfect harmony. Data management, including the collection, analysis, and utilization of vast data streams, empowers companies in informed decision-making, efficiency and productivity, remaining agile in a highly dynamic business environment, and many more. Having high-quality data and being able to manage, analyze, govern, handle, and use it, in turn, enhances operational flexibility, allowing manufacturers to respond to changing market dynamics, customer preferences, and unforeseen challenges with agility and precision. Therefore, the synergy between data management and operational flexibility lies at the core of Industry 4.0, enabling companies to unlock the full potential offered by advanced technologies and fostering a future of adaptable, customer-centric production models.

From IoT-enabled sensors capturing real-time data on machinery performance to cloud-based analytics platforms processing large volumes of datasets, modern manufacturers are equipped with powerful tools for data-driven decision-making. Data management has evolved beyond simple storage, extending into the domain of immediate accessibility, converting raw data into practical, actionable insights.

The figure below represents different stages of data for businesses, each reflecting a transformative role that data has played over time. Over time, data has undergone a transformative journey within companies' business processes and overall performance. In its initial stages, during the 1960s and 1970s, data primarily played the role of a result of processes, supporting specific business functions without contributing direct value to the enterprise. As the years progressed, especially with the rise of Manufacturing Resource Planning (MRP) and

Enterprise Resource Planning (ERP) systems in the 1980s and 1990s, data evolved into an essential facilitator of company-wide business process management, enabling the implementation of standardized processes on a global scale. In the new millennium, data took on a pivotal role as an enabler of products and services, exemplified by various smart offerings. In recent years, data has reached a significant milestone, where it has become a product and is treated as a product that can be bought and sold. In recent years, data marketplaces have emerged where individuals or organizations can request access to specific data through Application Programming Interfaces (APIs) and are charged based on the amount of data they use or the time they have access to it. (Industrial Data Space: Digital Sovereignty Over Data, 2016. The Fraunhofer-Gesellschafts)

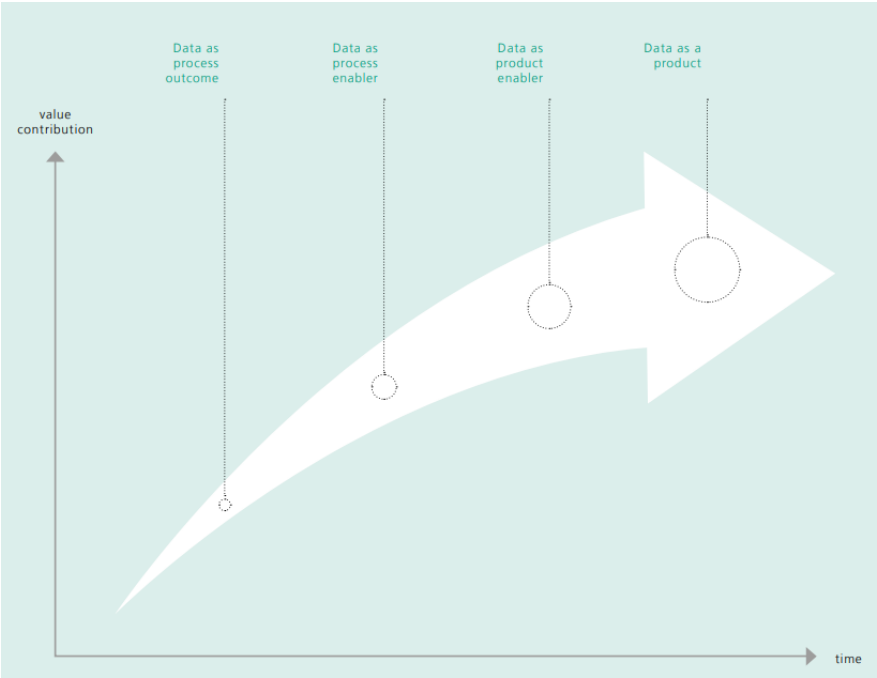


Figure Source: Industrial Data Space: Digital Sovereignty Over Data, 2016. The Fraunhofer-Gesellschafts. ` *Development of the role of data in the performance of businesses*`

2.1 The Mutual Drivers: Data Management and Industry 4.0

Data Management is at the core of Industry 4.0, enabling the seamless operation and connectivity of advanced technologies and serving as a driving force in reshaping the manufacturing

landscape. Industry 4.0 represents the integration of advanced into the manufacturing environment which enables real-time insights to optimize and automate manufacturing processes. Industry 4.0, with its cutting-edge tools, facilitates the handling of vast and complex data sets by providing the means for real-time analytics, predictive maintenance, and enhanced decision-making. Therefore, data management and Industry 4.0 are mutual drivers because they drive each other's success. Both are necessary for the digital transformation in manufacturing, where data is not just a resource but a dynamic force for Industry 4.0 to function efficiently by fostering collaboration and efficiency..

A critical determinant for ensuring that products and services align with customer demands is the effective use of data, encompassing customer information, product details, and more. Data serves as the bridge connecting industrial production and intelligent services. The ability to treat data as a valuable company asset is gaining increasing significance for organizations. On the other hand, it poses new challenges such as the growing complexity of production and logistics operations. Manufacturers need to embrace some new procedures necessary for service provision. When considering the escalating number of product features, ever-decreasing product lifecycles, shorter delivery schedules, legal requirements, and the globalization of value-creation processes, it becomes evident that traditional organizational principles and management strategies are no longer adequate for handling this level of complexity. In this scenario, "Industry 4.0" encapsulates four essential components that act as a roadmap for proactive manufacturers seeking to promptly adapt to evolving customer needs through the efficient utilization of data:

– **networking** of humans and machines

– **automatization** of processes and systems

– end-to-end **information transparency**

– decision-making support offered by **assistance systems**

(White paper Industrial Data Space, 2016. The Fraunhofer-Gesellschafts)

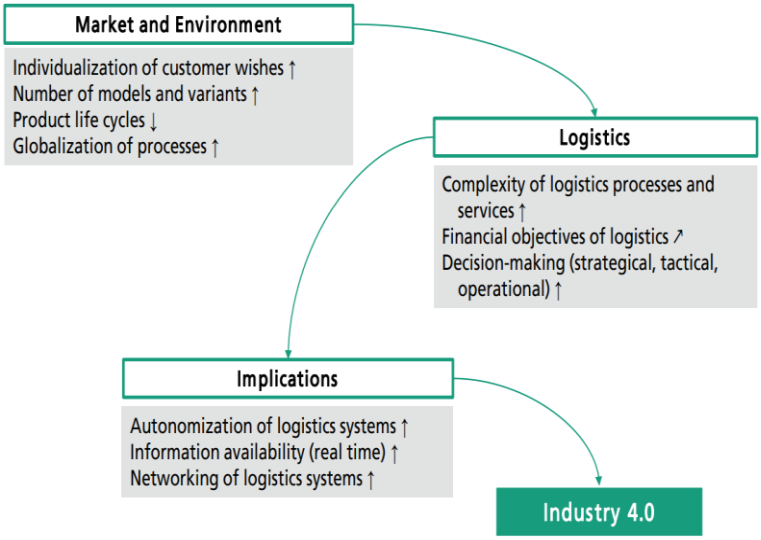


Figure Source: Prof. Dr. Jan Jürjens (N.D.), The Industrial Data Space: Digital Industrial Platform Across Value Chains in All Sectors of The Economy.

2.2 Actors in the Open Data Ecosystem

A data ecosystem represents a dynamic and interconnected network comprising various entities, including organizations, companies, and individuals, all of whom recognize the intrinsic value of data and actively engage in its utilization, sharing, and trading. The functions and relations of each actor play distinct interdependent roles.

"A set of independent activities having the aim of creating value upon data in order to exploit it as a product." (Attard, J., Orlandi, F., Auer, S. (2016), p3)

Realizing the opportunities presented by open data ecosystems depends on fostering collaboration among various key actors. This collaborative effort involves not only those who provide data but also those who consume it and those who innovate by creating new services and applications based on the available data. Once the synergy among different actors is captured, it will not only unlock the full potential of open data but also promote innovation, transparency in decision-making, and economic growth. (F. Kitsios, N. Papachristos and M. Kamariotou, 2017)

The following are the primary requirements for a collaborative environment, often referred to as an ecosystem (A. Immonen, M. Palviainen, and E. Ovaska, 2014):

Data provider: They are the originators of the essential data, responsible for supplying it to the ecosystem. This data can originate from internal sources, including sensors and devices, or be collected from external sources through bilateral agreements with business partners. Data providers encompass a wide range of entities, such as businesses, government agencies, research institutions, or any organization possessing valuable data. Their pivotal role lies in making data accessible, a critical factor in ensuring the flexibility and efficiency of the manufacturing process.

Data Consumer: Following the acquisition of data from data providers, data consumers utilize data for various purposes. Businesses, researchers, analysts, or individuals all of whom play a pivotal role in the data ecosystem, can be included in this category. Data consumers process the acquired data within the context of specific business activities, subsequently integrating and transforming it into data models. These models serve as the foundation for making well-informed decisions, deriving valuable insights, fostering innovation, and providing essential support for their operational endeavors.

Data Broker: Data brokers act as intermediaries in the data ecosystem. They connect data providers with data consumers. Data brokers often aggregate and organize data from multiple sources, making it easier for data consumers to access the information they need. They may also offer services related to data quality, integration, or privacy.

Data Service Providers: Data services refer to the tools, platforms, and technologies that enable data processing, analysis, and transformation. These services can include data storage, data analytics, data visualization, and more. Data services providers offer solutions to help data consumers manage and derive value from data efficiently.

End-Customer: The end-customer represents the final user or beneficiary of the data-driven insights and services. This can be an individual making a purchasing decision, a company's customer, a citizen using a government service, or anyone who directly benefits from the information and services delivered through the data ecosystem.

In the data ecosystem, these roles collaborate to ensure data is collected, processed, shared, and used effectively, contributing pivotal in harnessing the full potential of data (Data Economy-DEMAND project, 2019). Collaboration and interaction among each actor contribute to

manufacturing companies to make informed decision-making, innovation, and the overall functioning of businesses. Each role plays a vital part in maintaining a healthy and productive data ecosystem.

2.3 Advantages

2.3.1 Data-Driven Production Optimization

With the increasing connectivity of manufacturing systems, effective data management has become a crucial tool for optimizing the value chain. Data is a valuable resource that, when leveraged correctly, enhances manufacturing's operational processes by imparting agility and responsiveness to manufacturers. The ability to optimize operations enables them to make adaptive decisions and respond effectively to a rapidly changing business environment. From real-time monitoring to predictive analytics, modern manufacturers are equipped with an array of tools for collecting, processing, and analyzing data throughout the production cycle.

(Ungermann, F., Kuhnle, A., &Stricker, N.,2019)

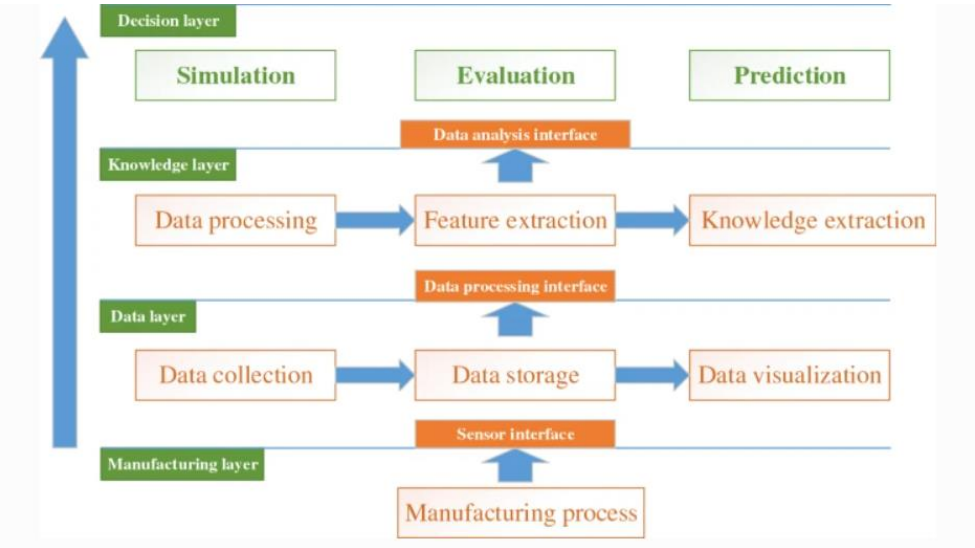


Figure source: Xu, K., Li, Y., Liu, C.(2020). Advanced Data Collection and Analysis in Data-Driven Manufacturing Process. ` *The framework of data-driven manufacturing*`

Data-driven product optimization also creates new management opportunities because only what can be measured can be managed. This enables companies to better control and improve business activities by quantifying and analyzing various aspects of their operations through data. This, in turn, leads to greater efficiency and effectiveness. For example, potential assessments and risk assessments can be made before making important decisions and reliable monitoring and adaptive data governance can be implemented. Data-driven adaptability isn't merely about reacting to external factors. It's also about optimizing internal processes for continuous improvement. Adaptive strategies enable manufacturers to identify inefficiencies, monitor equipment health, and predict maintenance needs in real time. Adaptive strategies extend beyond the factory floor to the entire supply chain. The result is a more agile and cost-effective production environment, poised for operational excellence.

On the other hand, during the product optimization process, predictive maintenance for the health of equipment and products is important and made possible by the integration of data management as shown in the top figure. Access to high-quality and real-time data opens the door to less costly unplanned downtime and less need for routine, time-based maintenance by foreseeing potential equipment failures and proactively addressing maintenance needs.

This is exampled with The Potential Failure Curve, often referred to as the P-F Curve by Green D. (2023). This curve is a graphical representation commonly used in the field of equipment and asset maintenance and reliability over time.

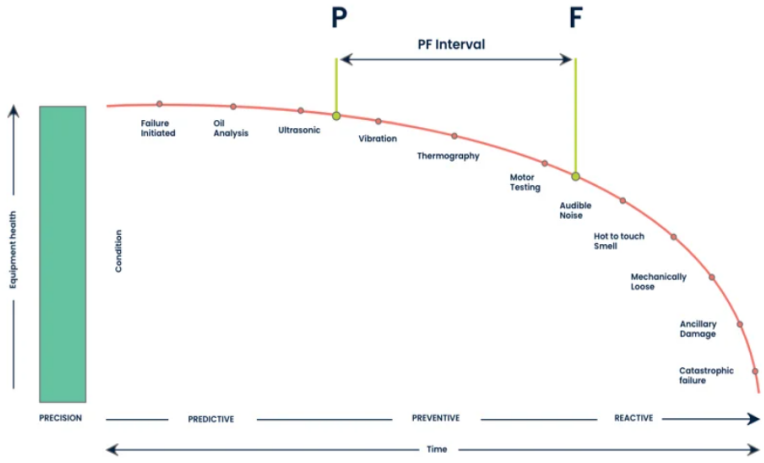


Figure source: Green, D. (2023, July 11). *The P-F curve*: All you need to know!

Its primary purpose is to help organizations detect potential failures early in the "P" stage through various methods, such as inspections, monitoring, and data analysis. This early detection allows organizations to take prompt action to prevent equipment or processes from experiencing functional failure. The utilization of data-driven insights plays a critical role in enabling predictive and proactive maintenance strategies, ensuring that maintenance activities are executed precisely when needed, rather than adhering to a fixed schedule. This data-driven optimization results in reduced costs and minimized operational disruptions. Furthermore, by averting functional failures and enhancing equipment reliability, data-driven maintenance contributes to comprehensive operational optimization, which, in turn, has the potential to elevate product quality and customer satisfaction.

2.4 The Dual Role of Being Data Provider and Recipient

High-quality data has become an indispensable asset, essential for a company's long-term competitiveness. The task of producing and maintaining high-quality data has grown increasingly complex, especially within the constraints of traditional value chains. Instead, the interconnected global business landscape created opportunity and gave rise to data ecosystems. Manufacturers now are able to combine, enrich, and share their distinct data sources, forging a collaborative approach to data management.

Collaborative data management, where companies work in tandem with others, offers additional benefits and maximizes synergy among manufacturing companies. Data ecosystems provide participants with the means to broaden their reach to data sources. This collaborative approach to data usage, often referred to as "data sharing," empowers organizations in their way of digitalization, for example, they can create a richer customer profile, which is essential for tailoring products and services.

The Industrial Data Space initiative, launched at the end of 2014 in Germany, is a significant and collaborative effort that aims to create a secure and standardized framework for the exchange of data in the industrial and manufacturing sectors. The Industrial Data Space is a new way of handling data to foster a secure, standardized, and collaborative environment for data sharing in the industrial and manufacturing sectors, ultimately contributing to the advancement of Industry

4.0 and the digital transformation of industries. (White paper Industrial Data Space, 2016. The Fraunhofer-Gesellschafts)

In autumn 2021, the Institut der Deutschen Wirtschaft conducted a survey encompassing German companies in industrial sectors and industry-related service providers. The survey results were subjected to a comprehensive evaluation, focusing on various company-specific attributes. The findings illuminate a noteworthy trend, indicating that a substantial 71 percent of German companies currently fall short of achieving optimal data management efficiency. Furthermore, an equally substantial 73 percent of these companies do not engage in collaborative data management efforts with their peers. Interestingly, when collaborative data management does occur, a prevailing pattern emerges, where companies predominantly assume the role of data recipients rather than data providers. Companies can reap significant benefits by sharing the data they generate with other enterprises, particularly those engaged in value-added processes, as highlighted in a 2020 MIT Technology Review Insights report. This collaborative data sharing, coupled with heightened supply chain transparency, can result in accelerated production speeds and reduced machine downtime. Such practices grant companies the agility to respond adeptly to evolving market dynamics and shifting customer preferences. They can also expedite the development of innovative products and services, enabling the provision of highly tailored offerings. (Büchel, Jan / Engels, Barbara, 2022)

From an overall economic perspective, joint data management proves to be advantageous for continuous growth. The term 'joint' doesn't imply that multiple parties must use an originally identical dataset simultaneously; rather, it signifies that multiple parties can modify the same dataset, employ it at different times, or for distinct purposes. To engage in data sharing with other companies or receive data from them, certain prerequisites must be met. Companies should maintain their data in digital formats as comprehensively as possible, as non-digitized data lacks meaningful compatibility with other sources. For instance, analog data storage is less amenable to analysis when combined with digitally received data in a shared dataset. Effective data self-management by companies is also a vital aspect of successful joint data management, allowing for efficient collaboration with other enterprises or the utilization of data from external sources.

Effective data management plays a pivotal role in fostering collaboration within and beyond manufacturing enterprises. It enables a seamless exchange of information, facilitating direct communication between customers and suppliers. In this digital age, customers can transmit their

specific requirements directly to their suppliers, ensuring a clear and instant channel for conveying their needs. Conversely, suppliers can reciprocate by sharing essential data, such as updates on outstanding deliveries, in a digital format. This data-driven interaction streamlines the production and supply chain processes, enhancing efficiency and responsiveness to customer demands.

The following figure (Institut der deutschen Wirtschaft Köln e. V, October 2022) shows the proportion of companies in Germany that make their data available to other companies or receive data from other companies, results by industry in percent, n = 1,002

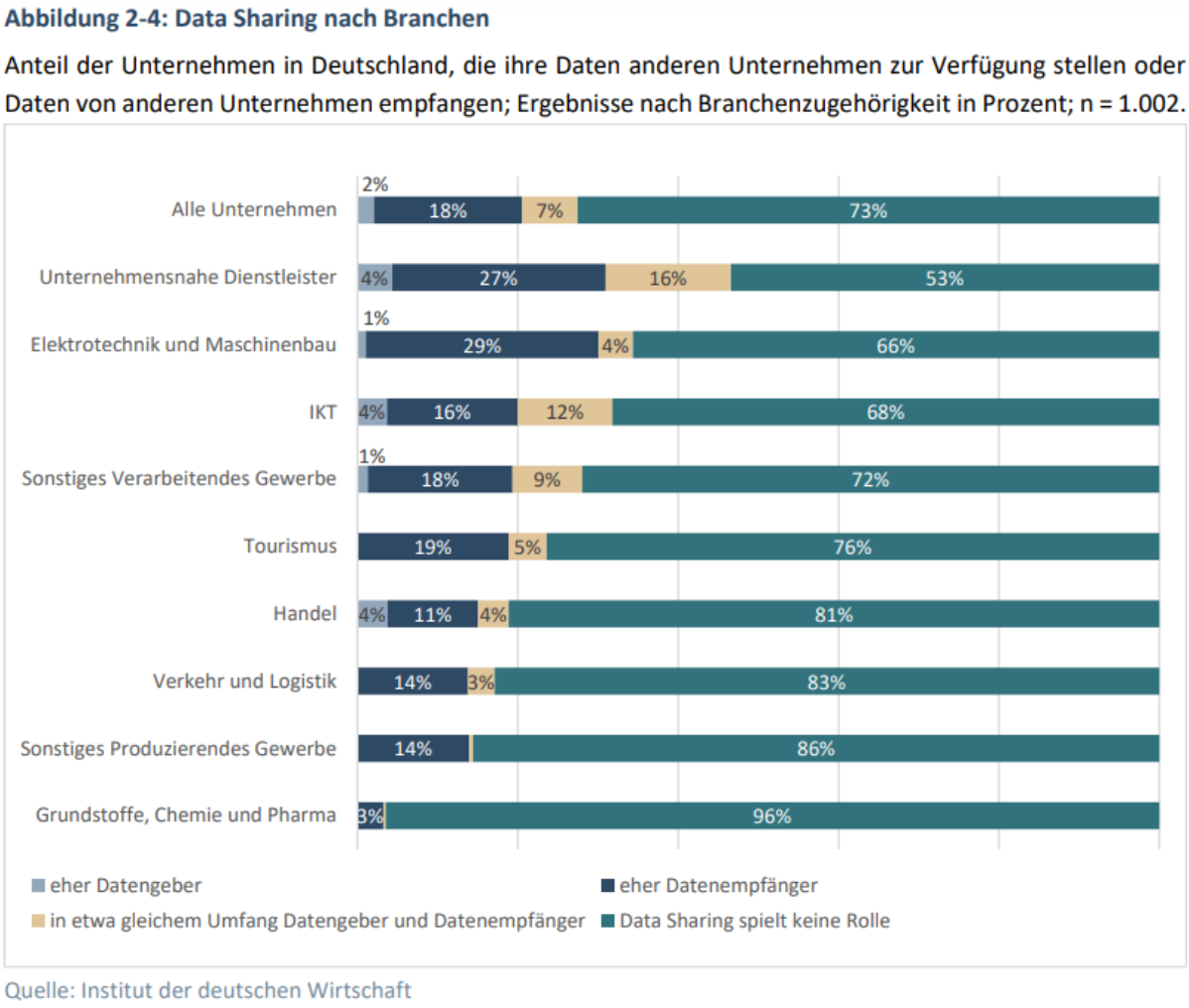


Figure source: Büchel, J.& Engels, B., Institut der deutschen Wirtschaft Köln e. V, October 2022.

` Proportion of companies in Germany that make their data available to other companies or receive data from other companies; Results by industry in percent; n = 1.002`

Based on a study involving 1002 German companies, the findings reveal that 18 percent of these companies (category of Alle Unternehmen) are predominantly recipients of data, meaning they mainly receive data from other companies. Additionally, 2 percent of these companies primarily act as data providers, meaning their main role is to share data with other companies. Moreover, 7 percent of the companies in the study serve as both data providers and recipients, signifying they engage in the exchange of data with other businesses.

2.5 The Concept of Data Economy Readiness Among German Manufacturers

Röhl et al. (2021) and Demary et al. (2019) maturity survey study gained the term data economy readiness which refers to German company's ability to manage data efficiently.

This readiness aligns with a company's preparedness for the data-driven economy, a term frequently employed to characterize its ability to navigate this modern economic landscape. To qualify as 'data economy ready,' a company must demonstrate its adeptness in efficiently storing diverse data types, effectively managing data operations, and pursuing a diverse array of objectives through data utilization. This criterion reflects the evolving demands of the contemporary data-driven business environment.

In the illustration below, it can be seen to what extent companies sustain good data management practices. The survey, encompassing approximately 1,000 companies in Germany operating within industrial sectors and industry-related services during the autumn of 2021, reveals that the majority have not yet achieved proficiency in data management.

The survey's findings highlight that merely 29 percent of these companies (referred to as Alle Unternehmen) possess the capacity for efficient data management, earning them the classification of being 'data economy ready,' as depicted in Figure 1. Notably, medium-sized and large enterprises (Groß und Mittel Unternehmen) outperform their smaller counterparts in this regard. (Readiness Data Economy- DEMAND project, 2019)

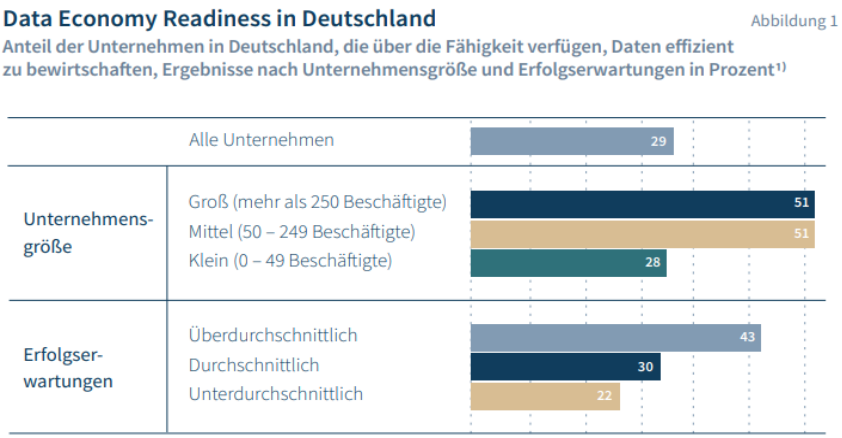


Figure source: Readiness Data Economy- DEMAND project, 2019

`Proportion of companies in Germany that have the ability to manage data efficiently, results by company size and expectations of success in percent`

The ZEW Mannheim survey carried out between December 2021 and January 2022 examined data utilization and collection practices among 1177 companies operating in the **manufacturing sector (47%)** and information sectors (63%). The findings from this research indicated a positive correlation between a company's size and its understanding of the advantages associated with data, as well as the extent to which data was utilized. Along with this survey, this study also revealed the types of data that are presently stored in digital format within the surveyed companies. Notably, 84% of manufacturing companies maintain customer master data(referred to as `Stammdaten Kunden`). Furthermore, the utilization of customer master data exhibits a direct correlation with the company's workforce size. Companies with over 100 employees display a heightened focus on managing customer master data, whereas those with fewer employees show relatively lower levels of interest in this aspect of data management.

In evaluating this result, the prominence of customer master data storage among manufacturing companies becomes evident. The fact that 84% of these firms are actively preserving this type of data underscores its significance in their operations. It is noteworthy that as the company's size grows, so does its emphasis on maintaining customer master data, indicating a recognition of its value in enhancing customer relationships and business strategies. However, for smaller companies with fewer employees, the relatively lower priority placed on customer master data

suggests an area where potential improvements in data management and customer engagement could be explored. As the digital landscape continues to evolve, companies, regardless of size, should consider harnessing customer master data effectively to drive growth and competitiveness in their respective industries. (Erdsiek, Daniel and Rost, Vincent, (2022)- ZEW)

Customer master data is typically stored in a centralized database or Customer Relationship Management (CRM) system and this system has an even greater potential for mass customization. Customer data is stored, changed, updated, and accessed by various departments within the manufacturing company, including sales, marketing, customer service, and finance, to ensure a coordinated approach to customer interactions and relationship management, using special treatment of the customer and special marketing campaigns. Properly managed customer master data helps companies improve customer service, sales, and overall customer satisfaction while enabling data-driven decision-making. Customer master data is instrumental in achieving successful customization in manufacturing. It enables manufacturers to meet individual customer needs, boost customer loyalty, and remain competitive in an ever-evolving market, all while optimizing internal processes and resource allocation. (Keuper, F., 2002)

Abbildung 1: Datenarten, die systematisch in digitaler Form gespeichert werden, nach Sektor

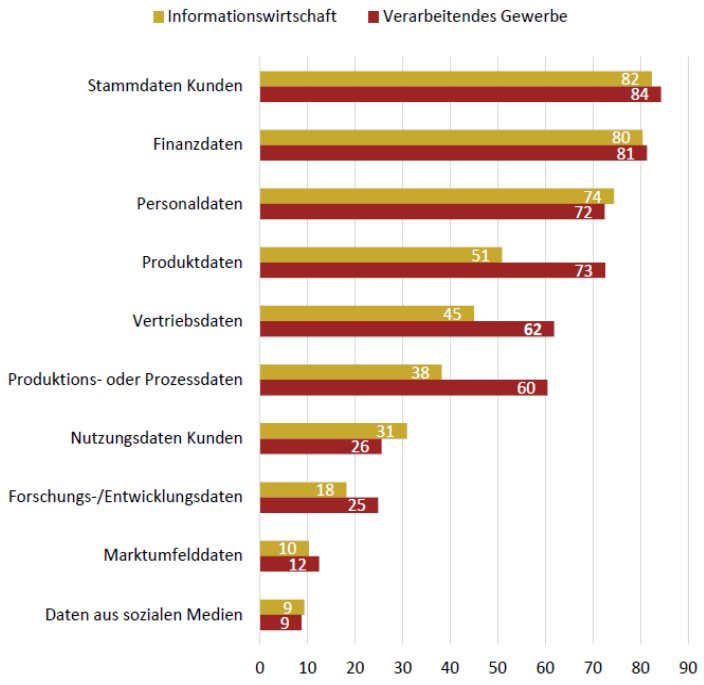


Figure source: (Konjunkturumfrage Informationswirtschaft Dezember 2021, January 2022)

`*Types of data systematically stored in digital form, by sector*`

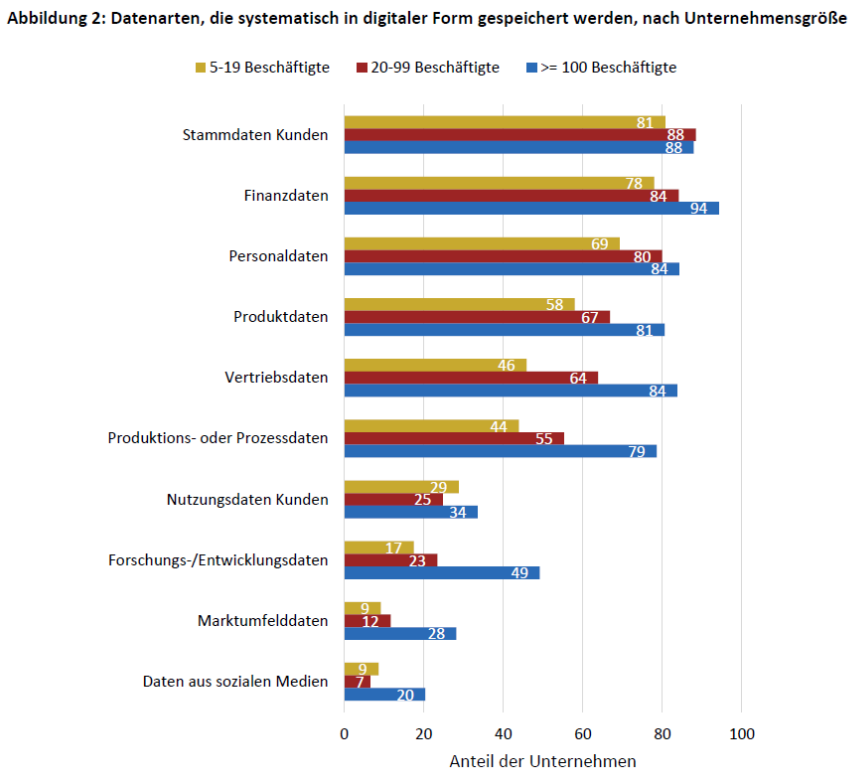


Figure source: Konjunkturumfrage Informationswirtschaft-ZEW December 2021, January 2022

`*Types of data that are systematically stored in digital form, by company size*`

2.5.1 Challenges in the Integration of Data Management

It is the era where data-driven technologies have become integral because it is important to be aware of the economic use of data for the creation of new value-creation opportunities in this era. The economic utilization of data enables manufacturers to gain deeper insights, make informed decisions, and discover innovative pathways to add value to their products, services, and processes.

Manufacturing is an extremely important economic sector for Germany, making a contribution of 26.6 percent to the overall gross value added in 2021 (Statistisches Bundesamt, 2021). While Germany is leading in industrial and manufacturing sectors, there may be room for growth and enhancement in terms of data economy.

The essential requirement to initiate the digitalization process is the presence of data in digital format. A survey conducted by IW Consult GmbH between June 2021 and October 2021 among

425 companies in Bavaria, Germany, examined ten different data categories (including product data, customer data, customer purchasing behavior, order backlog, inventory data, supplier data, employee master data, financial data, process descriptions, and workforce planning data) within these companies, with a specific focus on the availability of inventory data in digital form. The results indicate that approximately 18 percent of Bavarian companies (or 22.5 percent of all German companies) have fully digitized inventory data in at least one of these categories. However, only 1.4 percent of Bavarian companies (as opposed to 1.3 percent of companies across Germany) claim to have almost all their data available digitally across all ten subject areas. Specifically, the most significant obstacle identified by these companies (92%) is the fear or worry that unauthorized third parties might gain access to their data, therefore, legal obstacles come as the first problem. (Digitalisierung der Unternehmen in Bayern, vbw 2022)

The research study also acknowledges a well-established fact supported by various previous studies (for example, one by ZEW et al. in 2020) that most companies are still in the early stages of adopting digital technologies and strategies in their products, operations, and overall business models. Therefore, there is a clear imperative for ongoing and intensive efforts to address and further advance the level of digitalization in both Germany and the specific region of Bavaria. (Schmitz, E. & Lichtblau, K., 2019)

Since data-driven business processes become more complex, companies encounter a multitude of challenges that are currently lacking practical solutions and support from existing information systems. These challenges extend beyond mere quantity, and it is about data diversity or "heterogeneity." The knowledge of how to analyze, clean, and integrate data is very critical. Companies need to use innovative tools to treat data as an asset, essential for ensuring sustained profit and competitiveness in the dynamic landscape of modern business.

In the survey conducted by the Institut der Deutschen Wirtschaft which was carried out among German companies from the 1.002 industrial sector and industry-related service providers in autumn 2021, 81% of participating companies were asked about the aspects responsible for creating barriers to data sharing across businesses. The survey revealed that a substantial 68 percent of the surveyed companies identified **legal barriers** (referred to as **rechtliche Hemmnisse**) as the most significant challenge impeding the facilitation of data sharing. This observation underscores the considerable reluctance among companies to engage in data sharing with other entities, as they are more likely to be in the role of data recipients rather

than data providers. Even after the establishment of the European General Data Protection Regulations, legal barriers continue to be a prominent concern for data sharing, driven by the companies' uncertainty regarding the application of data protection rules. The study suggests that providing clearer information about data protection regulations can help in resolving this hurdle. Another issue is that the European General Data Protection Regulations primarily focus on personal data protection, which may not align with the predominant focus of companies on shared data management. (Büchel, Jan / Engels, Barbara, 2022)

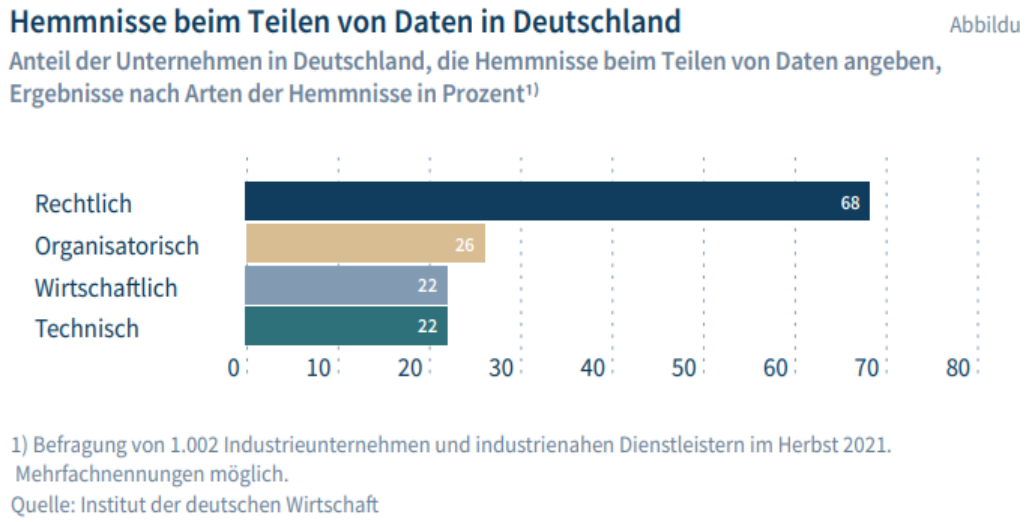


Figure source: Büchel, Jan / Engels, Barbara, 2022, IW.

`*Proportion of companies in Germany that indicate barriers to sharing data, results by type of barrier in percent*`

The next major challenge that companies face relates to organizational barriers, a concern that has been cited by 26% of the surveyed companies. The most prominent obstacle is the lack of organizational knowledge necessary for efficient data utilization. Companies don't often mention unclear roles or responsibilities as a significant issue within their organization. Additionally, when companies mention a lack of organizational knowledge, it's not always easy to separate it from technical challenges. The main problem is often the absence of proper data governance, which results in data being disorganized or not well-structured within the company.

Economic and technical barriers were both mentioned by 22 percent of companies. The most significant economic challenge is the uncertainty about the benefits of shared data management.

Companies are not sure what advantages they will gain from sharing data with others. Companies are also worried about how sharing data might impact their overall success. They want to ensure that sharing data is a beneficial move for their business. Many companies do not find a strong economic motivation to explore shared data management or look for new ways to use data more effectively. It doesn't seem financially necessary for them. Additionally, one of the economic challenges is the absence of a business model that outlines how data sharing should work in a way that is profitable and sustainable. What exacerbates the situation is the difficulty companies face in determining the value of their data to others and setting an appropriate data price. Only a small fraction of companies (around one-tenth) are willing to provide their data to others for a fee, whether with a profit margin or as a cost reimbursement. To fully benefit from shared data management, there's a need for experimentation and innovation. Companies need to try out different approaches and ideas to unlock potential advantages through collaboration.

The most significant challenge related to technology is the absence of standardized practices for managing shared data, which is a concern for 67 percent of companies. Standards are like agreed-upon rules that make it easy for digital systems to communicate and exchange information. Establishing these standards can often take a lot of time. To address this issue, there is an initiative called Gaia-X that aims to find a solution. This initiative is working on creating standards for data sharing. Interestingly, the lack of standardized practices for shared data management is a big technical challenge for many companies, but other technical aspects are not a major concern. Therefore, the focus should be on addressing challenges in non-technical areas of data management. (Büchel, Jan / Engels, Barbara, 2022)

In addition to descriptive analyses, chi-square tests were conducted in extensive research conducted by the Institut der Deutschen Wirtschaft in 2021. The key finding of the research is that as companies express a greater interest in working with data, they tend to see more challenges or obstacles related to this. In simpler terms, when companies want to use data more, they become more aware of the difficulties or issues they might face. That means companies that are well-prepared or "data economy ready" are particularly good at identifying the obstacles or difficulties they might encounter in this regard.

To tackle these obstacles head-on, the "DEMAND - Data Economics and Management of Data-driven Business" initiative in Germany is actively crafting pragmatic remedies. Through

collaborations with several companies, it guides them in data governance and information architecture.

When a company underestimates the potential advantages of data utilization, potentially lucrative investments are probably overlooked and not pursued. Therefore, understanding these challenges in German manufacturing is important for enhanced operational efficiency, innovation, and competitive advantage within the industry, positioning German manufacturing companies on the path to sustainability and growth.

Chapter 3 The Transition Journey: Data-Driven Smart Customization

Over the course of three decades, from the early 1990s to 2020, the concept of mass customization has witnessed a significant transformation, as depicted in the graph. Initially, it primarily aimed to fulfill customer demands for products that were 'good enough.' However, as time progressed, it evolved into providing an array of product variations to cater to a broader customer base. The shift continued towards offering individualized products, where customers had the option to tailor specific aspects of their purchases to meet their unique preferences. Furthermore, the highest level of mass customization emerged, involving custom design involvement, allowing customers to actively participate in the design and creation process. Concurrently, information technology played a pivotal role in this evolution. The adoption and advancement of technologies such as wireless communication, internet connectivity, the Internet of Things (IoT), and big data analytics empowered companies to enhance their mass customization strategies. Manufacturing strategies also adapted to this changing landscape, shifting from traditional flow and line production methods to more flexible, agile, and even virtual manufacturing approaches, reflecting the ever-evolving nature of mass customization in response to customer and technological trends.

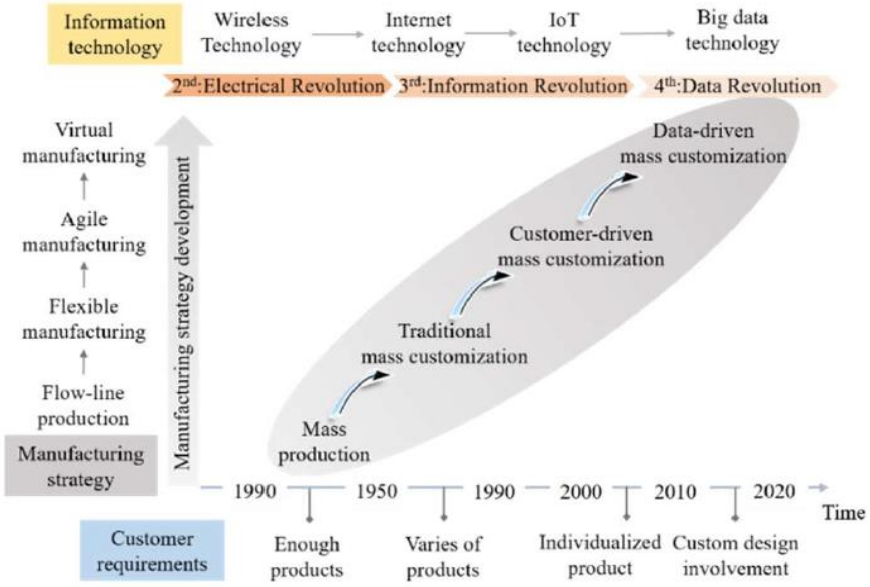


Fig. 1. The evolution of mass customization.

Figure source: Zhang, Cheng & Chen, Daindi & Tao, Fei & Liu, Ang. (2019). Data-Driven Smart Customization

The transitions from traditional manufacturing to virtual manufacturing models are underpinned by data-driven insights. This shift is driven by insights derived from data. This data comes from various sources, including how consumers behave, trends in the market, and the capabilities of production. The data serves as the foundation for creating flexible production processes that are modular and adaptable. This means that they can be easily adjusted to accommodate individual customization requests. With the aid of machine learning algorithms, predictive analytics, and real-time monitoring, manufacturers can fine-tune products on the fly, aligning them with customer desires. If a customer wants a product tailored to their specific preferences, the production process can adapt to make that happen. To make this all work, manufacturers use advanced technologies like machine learning and predictive analytics. These tools help in making real-time adjustments to meet customer desires.

3.1 The Evolution of Customization in German Manufacturing

The history of customization within German manufacturing is a testament to the country's innovative and adaptive spirit. Rooted in a tradition of craftsmanship, German artisans were celebrated for their meticulous attention to detail and their ability to tailor products to meet the unique needs and desires of individual customers (Pine & Gilmore, 1999).

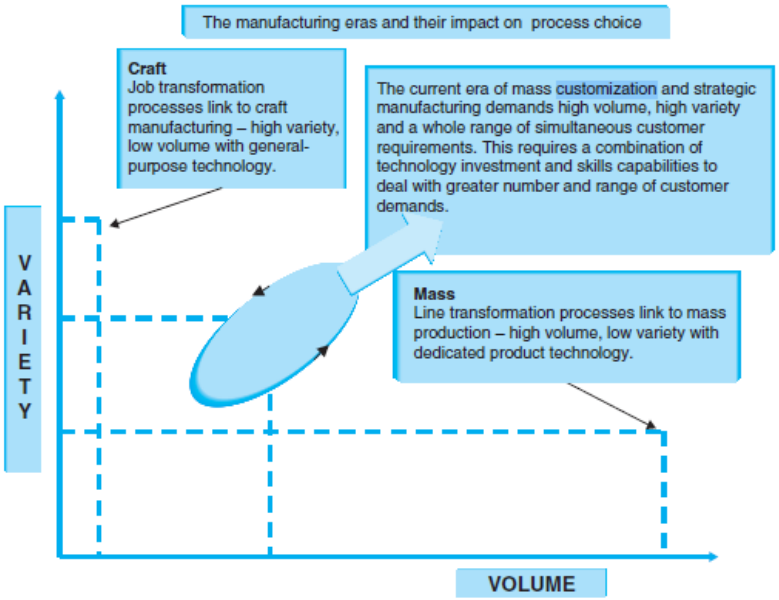


Figure source: Brown, S. (2005). Strategic Operations Management (page 119)

This artisanal approach was prominent in sectors such as watchmaking, where precision and personalization were paramount. However, as the Industrial Revolution swept through Europe, including Germany, the landscape of manufacturing underwent a significant transformation. This historical context sets the stage for a deeper examination of how German manufacturing evolved to meet changing market dynamics and customer expectations.

3.1.1 The Artisanal Era

In the pre-industrialization era, German craftsmanship thrived, characterized by skilled artisans who painstakingly crafted products ranging from timepieces to textiles.

This system originated in Europe and was closely tied to how skills were cultivated. It followed a progression from apprentice to journeyman and ultimately to master, with individuals gaining expertise through this process. This system led to the formation of skilled guilds that aimed to control the supply of their skills, concentrating expertise within specific segments of society. For instance, skills were passed down from one generation to the next, like from a father to his son. Craft manufacturing and shop delivery were particularly suited for products that had low production volumes but high variety, with workers being highly skilled, and a strong emphasis on quality and attention to detail, as the artisan or craftsman focuses on creating a product that precisely matches the customer's preferences. This system was well-matched for serving primarily national markets with minimal imports and exports. While this traditional craft manufacturing has declined, it still exists today in niche markets where unique or highly desirable products and services can effectively control demand. (Brown, S.,2005)

3.1.2 Mass Production Era

The second major era, known as mass production, emerged primarily in North America and was driven by the need to meet the demands of an expanding economy. Mass production aimed to address three key requirements: the need to export goods, provide jobs for a largely unskilled workforce, and establish global influence. This system represented a significant departure from

traditional craft production and played a pivotal role in changing global working and buying practices in the early 20th century. Mass production was characterized by high volume and low product variety, with a notable emphasis on standardization, exemplified by Henry Ford's famous quote ` A customer can have a car painted any color he likes if it is black!'. Branding became a critical tool for differentiation in this era. However, by the 1990s, brands faced new challenges, including market fragmentation, shorter product life cycles, and increased customer sophistication, which diminished the power of advertising. That is why effective operations management is now a central and critical component of strategic thinking for achieving success in the modern business landscape. (Brown, S.,2005)

It is described in the book 'Customization 4.0' (2017) as follows: 'mass production (when the products were designed and produced mainly for the average consumer but pushed on the market before the consumer could even see the product – Ford Model T). (Hankammer & Nielsen & Piller & Schuh & Wang (ed.), 2018, p. 244)

3.1.3 Mass Customization Era

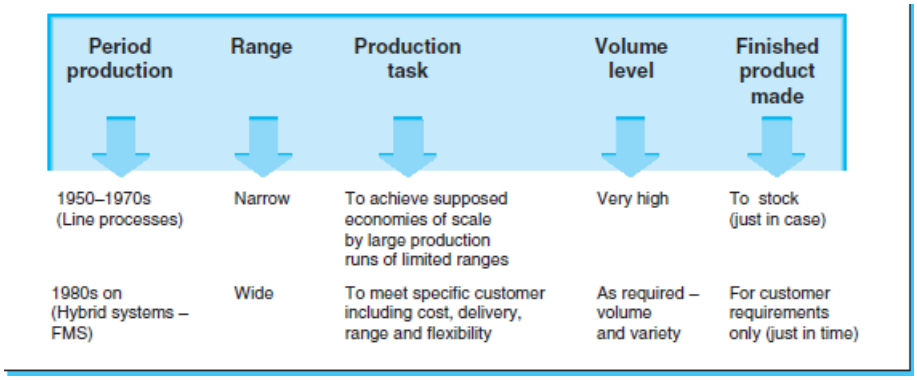
The shift from the industrial society to the information society is the underlying reason for the development of customer-specific mass production. There happened many changes in the way societies operate, where information and data play a central role, have given rise to this new approach in manufacturing. (Gräßler, I., 2004)

The term "mass customization" was introduced to the literature in 1987 (in German: kundenindividuelle Massenproduktion / maßgeschneiderte Produktion). According to Davis (1987, p.169), it is defined as follows: "Mass customization of markets means that the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously they can be treated individually as in the customized markets of pre-industrial economies." (Davis, S.M., 1987)

Mass customization is a production approach that blends the benefits of mass production (making a large quantity of the same product) and one-off production (making unique, individual products). It's like finding a middle ground between these two approaches. It also aims to avoid the downsides of both mass and one-off production. For example, mass production can lack

personalization, while one-off production can be very expensive and time-consuming. Mass customization seeks to strike a balance. The main idea is to cater to the unique needs of each customer. It's about offering products that are tailored to what each customer wants or needs. Importantly, while tailoring products to individual customers, the aim is to keep the prices competitive. In other words, it's about providing personalized products at prices that are similar to what you might pay for mass-produced standard products. It's worth noting that mass customization doesn't always mean making each product entirely from scratch for each customer. It can involve various levels of customization, from minor adjustments to unique products. (Filler, F. T. (2020))

This approach allows businesses to blend the benefits of mass production, where economies of scale lead to lower costs, with the advantages of individual production, where products are tailored to each customer's unique requirements. The result is a kind of "customized mass production" that aims to deliver personalized products without the high costs traditionally associated with individual customization. (Schenk, M., Seelmann-Eggebert, R.,2002)



Period production	Range	Production task	Volume level	Finished product made
1950–1970s (Line processes)	Narrow	To achieve supposed economies of scale by large production runs of limited ranges	Very high	To stock (just in case)
1980s on (Hybrid systems – FMS)	Wide	To meet specific customer including cost, delivery, range and flexibility	As required – volume and variety	For customer requirements only (just in time)

Figure source: Brown, S. (2005), Strategic Operations Management (Page 120)

Da Silveira et al. (2001) offer a comprehensive summary of the essential prerequisites for successfully implementing mass customization strategies. These requirements encompass the existence of a customer base desiring variety and personalization, the alignment of market conditions, preparedness within the value chain, the availability of relevant technology, the adaptability of products for customization, and the dissemination of essential knowledge. These factors collectively contribute to the effective execution of mass customization initiatives in

businesses seeking to meet the evolving demands of their customers and provide tailored solutions in a competitive marketplace.

3.2 Customer-centricity in Smart Customization

3.2.1 Understanding Customer Needs

Understanding customer needs during customization in the manufacturing industry is a foundational pillar of successful business operations. It entails a comprehensive exploration of customer preferences, expectations, and specific requirements, aiming to align product or service offerings with individual desires. This critical process involves not only listening to customer feedback but also proactively anticipating their evolving needs. Manufacturers conduct comprehensive research to gain a deeper understanding of both the market and their customers, which includes studying consumer trends, analyzing competitors, and examining market dynamics. This information can be collected through various methods, with the most common being feedback and surveys. They employ data analysis techniques to extract valuable insights from the data they have collected, enabling them to identify patterns and trends in customer behavior. A better understanding of their customers not only allows manufacturers to enhance customer satisfaction but also to cultivate long-term customer loyalty. This customer-centric approach empowers manufacturers to decipher the factors influencing their customers' choices and adapt their products or services accordingly. Consequently, it drives innovation and bolsters their competitiveness in the continually evolving manufacturing industry. (Schenk, M., Seelmann-Eggebert, R. (2002)

In the paradigm of smart customization, placing the customer at the center is not merely a strategy; it is an imperative. German manufacturing, renowned for precision and innovation, has embraced this ethos by deeply understanding customer needs as a foundational pillar of its customization strategies (Pine & Gilmore, 1999).

3.2.2 Customer-Centric Mindset

Manufacturers have recognized that effective customization starts with a deep understanding of each customer's unique preferences, behaviors, and expectations. This understanding goes beyond just surface-level recognition. It involves a systematic process of gathering and analyzing data from various points of interaction with customers, including online interactions, purchase history, and feedback. By collecting and using data-driven insights, manufacturers gain a comprehensive understanding of what influences customer decisions and how they can create personalized solutions to meet individual needs and desires.

Even though there are some profound changes that a company must undergo when transitioning from traditional mass production to customer-specific, or customized, production, the role of the customer became significantly more important and central in this transition compared to their role in traditional mass production, where products are standardized. This shift towards customization leads to increased complexity in both internal and external logistical processes. (Eggebert, Schenk, 2001)

Customer needs are inherently subjective, forming a highly personalized landscape influenced by a multifaceted interplay of internal and external factors, each distinctive to the individual. This subjectivity underscores the uniqueness of every customer's perspective, making it challenging to generalize preferences and requirements. The internal factors include personal preferences, experiences, and cognitive processes that shape how a customer perceives and values a product or service. Meanwhile, external factors encompass a broad spectrum, ranging from cultural influences and social norms to marketing messages and peer recommendations. Recognizing this subjectivity is essential for businesses seeking to excel in customization because it highlights the necessity of tailoring offerings to cater to the diverse and ever-evolving needs of their customer base.

3.2.3 Data-Driven Insights

In a data-driven manufacturing cycle, data is visualized, helping individuals involved in manufacturing to see and understand the data more effectively, and enabling insightful decisions in the data analysis step The final layer is the decision layer, where the knowledge obtained from the previous step is utilized to make informed decisions, which may also including predictions

about future trends, simulations of manufacturing processes, and other actions that support smart and data-driven manufacturing practices.

To ensure that all steps, from receiving a customer's order to delivering the final product, occur smoothly and without delays, it's essential to have a well-coordinated process. The efficient flow of information is the key to achieving this. The system collects a range of data, including customer-specific details like their contact information, delivery address, preferred payment methods, and specific delivery instructions. It also involves information about the product itself, such as its characteristics and any customization options. When collected in a company, this data must be distributed or divided among different departments or tasks. (Eggebert, Schenk, 2002)

3.3 Data Harmonization: Improving German Manufacturing

Manufacturing companies must question their current operations according to how they manage their data and what new potential this can unleash for staying competitive in the market. The foundation lies in the comprehensive collection and seamless integration of data from various sources. It is important to understand the intricate process of sourcing and collating data for customization efforts.

The study "Produktionsarbeit der Zukunft - Industrie 4.0" (2013) by Fraunhofer IAO which is a prominent research institute in Germany, is a very valuable source on this topic. It is founded on a comprehensive research effort, initially surveying 661 German manufacturing companies, and supplemented by interviews with 21 prominent experts in German production, including representatives of innovative production and high-tech companies, and esteemed scientists specialized in production work and Industry 4.0. his study provides significant insights into the crucial role of data management about operational flexibility, particularly within customer-centric cycles. (Produktionsarbeit der Zukunft - Industrie 4.0. Fraunhofer)

Professor Dieter Spath, Director of the Fraunhofer Institute for Industrial Engineering IAO and one of the authors in the study, "Produktionsarbeit der Zukunft - Industrie 4.0" (2013) emphasizes that the use of real-time data in Industry 4.0 production offers a significant improvement in decision-making quality compared to traditional experience-based and instinctive reactions from production personnel. This **enhanced decision-making capability allows for more reliable and**

flexible responses to customer requests, all while still considering important economic factors.

Dr. Wieland Holfelder, Engineering Director & Site Lead at Google Germany GmbH, emphasized in an interview conducted by the Fraunhofer Institute for Industrial Engineering IAO that digital data is often likened to the "oil" of the 21st century. Those who understand how to effectively utilize digital data such as data protection, computing, and storage capacities will gain a significant competitive advantage in the future. Consequently, manufacturing companies are expected to require a growing number of skilled data analysts to harness this potential.

Dr. Stefan Ferber, Director for Communities & Partner Networks at Bosch Software Innovations, also highlights the significance of Industry 4.0. He notes that it's not just about achieving a minor five or ten percent improvement within the system. Instead, it involves preparing for a substantial shift, akin to tectonic plate movements. This shift focuses on differentiation through services, data utilization, and increased agility in the manufacturing sector. Dr. Ferber underscores the significance of having well-prepared and appropriately visualized data rather than just an exponentially growing data volume. This aspect is expected to gain more importance in the future, leading to an increased demand for competent data analysts. Additionally, he emphasizes the need to integrate various data streams, including private data, a process that poses technical complexities and raises data protection concerns. Dr. Ferber notes that the expertise required for this task may currently be lacking within medium-sized companies.

In the same study, Professor Gunther Reinhart, head of the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich highlights the necessity for enhanced mobile assistance to facilitate more effective interaction with production control systems and machines. This, in turn, allows for more efficient and rapid data evaluation, which is essential for making informed decisions. His prediction suggests that the increase in mobile assistance is a crucial step towards enabling people to interact effectively with production control systems and machines.

3.4 Data Sources and Acquisition for Customization

The practice of customization, whether in product design, marketing, or service delivery, depends on the availability of accurate, timely, and diverse data sources that offer insights into individual

customer preferences and behavior. Businesses today draw data from an array of sources, including customer final product transactions, online purchases or feedback, social media activity, and IoT devices.

Traditionally, customer data has been sourced from internal databases, sales records, and customer feedback surveys. While these sources remain valuable, the advent of digitalization has exponentially expanded the range of potential data sources. For instance, e-commerce platforms can collect data on user behavior, including browsing history, product views, and purchase patterns. Social media platforms offer a wealth of unstructured data in the form of posts, comments, and likes, which can provide valuable insights into customer sentiment and preferences. Additionally, IoT devices and sensors in various industries yield real-time data, enabling businesses to respond to customer needs and preferences with unprecedented agility.

The methods of data acquisition for customization practices span a spectrum ***from conventional data collection techniques***, such as surveys and questionnaires***, to advanced technologies*** like machine learning models and natural language processing for sentiment analysis. Advanced technologies for data collection are presented in section 3.6. For instance, recommendation engines, powered by machine learning algorithms, are commonly used in e-commerce for personalized product suggestions based on historical user behavior and preferences. German e-commerce giant Zalando leverages user browsing and purchase history to deliver highly personalized fashion recommendations, transforming every visit to their online store into a tailored shopping experience. This personalized approach not only drives customer engagement but also bolsters sales and customer loyalty.

As stated in the IEEE conference paper (2014) authored by G. Shao, S.-J. Shin, and S. Jain, "*Manufacturing big data originate from various sources, including machines and equipment equipped with sensors for automatic monitoring and collection of operational status and performance data, as well as from radio-frequency identification and barcode readers, financial transactions, market statistics, design images, the internet, social media, and insights from Subject Matter Experts (SMEs).*"

Modern manufacturing systems are equipped with **advanced sensors.** These sensors are responsible for collecting data from different physical events or aspects of the manufacturing process. When taken individually, each piece of data collected by the sensors may not have a high

intrinsic value and may not provide much insight or usefulness. However, when all these individual data points are considered together as a collective dataset, they can provide significant value. (Xu, K., Li, Y., Liu, C., 2020)

For instance, in the realm of German manufacturing, companies like Volkswagen and Siemens employ data gathered from sensors embedded in production machinery to monitor real-time equipment performance and predict maintenance of machines. These insights not only enhance operational efficiency but also offer invaluable data for customizing product offerings based on the performance and maintenance history of these machines. Siemens will serve as the integration partner for Volkswagen's Industrial Cloud, enabling improved data transparency and analysis to enhance productivity in Volkswagen plants. This partnership will also extend benefits to connected suppliers and machinery producers by leveraging the potential of production data even more effectively. (Siemens Press, n.d.)

3.4.1 Data Preprocessing and Cleaning

Data is a fundamental component of operations and decision-making in many organizations. Merely possessing data, whether in small or large quantities, doesn't inherently add value to a company. In other words, raw data, on its own, doesn't provide benefits or a competitive edge. The real added value comes from how you utilize the data. It's when you analyze the data, extract meaningful insights from it, and use those insights to enhance and inform your business processes that you create value. This often involves making data-driven decisions that lead to improved efficiency, better products or services, and a more competitive position in the market. To achieve this, the data must be accurate, complete, and free from errors or inconsistencies. Poor data quality can result in incorrect or misleading insights. Achieving data quality can only be realized through appropriate data curation. Data curation involves processes such as data cleaning, validation, and transformation. It ensures that data is in a format that is suitable for analysis and decision-making (Engels, B. & Schäfer, C., 2020)

Furthermore, data preprocessing in the German manufacturing sector involves the normalization of data to bring it within a standardized range, ensuring that disparities in data units or scales do not compromise the accuracy of subsequent analytical models. As German manufacturers

increasingly adopt smart customization to tailor products to individual customer preferences, this preprocessing step plays a crucial role in ensuring the reliability of the data used to guide customization decisions.

In parallel, data cleaning becomes imperative to identify and rectify anomalies, errors, or inconsistencies within the datasets. In the context of German manufacturing, where precision and quality are non-negotiable, data cleaning ensures that any aberrations in the data, whether they stem from sensor inaccuracies on production lines or data entry errors in customer orders, are promptly addressed. Only by achieving data integrity through preprocessing and cleaning can manufacturers confidently rely on data-driven insights to make informed decisions regarding product customization.

This intricate process of data preprocessing and cleaning in German manufacturing aligns with the principles of Industry 4.0, where the integration of advanced technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) enables the collection and analysis of vast datasets. To put this into perspective, the work of Westkämper et al. (2016) on "Industrie 4.0 and Smart Manufacturing - A Review of Research Issues and Application Examples" underscores the significance of data preprocessing in the context of Industry 4.0, a framework closely intertwined with the evolution of German manufacturing.

In conclusion, the transition toward smart customization in German manufacturing relies heavily on the rigorous processes of data preprocessing and cleaning. These processes are the cornerstones that ensure the reliability of data, enabling manufacturers to navigate the complexities of customization while upholding the industry's renowned precision and quality standards. Consequently, German manufacturers must continue to invest in robust data preprocessing and cleaning techniques to fully realize the potential of smart customization and remain at the forefront of innovative manufacturing practices.

3.5 Customer-related Data Security and Ethical Considerations

Ensuring robust data security measures are in place is not only a legal requirement but also an ethical obligation to protect its data from unauthorized access and cyber threats. Manufacturers are dedicated to secure data handling throughout its lifecycle, including data storage,

transmission, and disposal because data security is one of the hot topics in Germany which is widely discussed, prioritized, and a matter of considerable attention in the country.

According to the findings of a survey conducted by the DEMAND project in 2020, which involved 13 German companies representing various industries and sizes, 'The majority of companies believe that ensuring data security in the future will become more challenging. The increasing number of internal and external interfaces and partnerships, along with the continued trend of digitalization, pose additional challenges for data security.'

Data security which includes protecting the confidentiality, integrity, and availability of data, is a top priority among German companies. Efficient data governance is suggested to enhance data security. Data governance serves a dual purpose. On the one hand, it helps in tracking instances of data misuse. On the other hand, data governance also functions to prevent data misuse. It sets rules, policies, and access controls that deter individuals or systems from misusing data. Based on the survey results, implementing data governance is justified by the fact that it leads to more efficient and effective data security. (Engels, Barbara / Schäfer, Christin, 2020- DEMAND)

Customer Trust and Confidence

Building and maintaining customer trust and confidence represent the bedrock of successful smart customization practices. German manufacturers grasp the growing concern customers have regarding the privacy and security of their data. Trust, once established, can lead to long-lasting brand loyalty and positive word-of-mouth. Conversely, the erosion of trust due to data mishandling can have severe consequences. Therefore, safeguarding customer data is not only a legal obligation but a fundamental ethical responsibility that German manufacturers prioritize.

The ethical obligation to protect customer data is underscored by the stringent data protection laws, notably the General Data Protection Regulation (GDPR), within the European Union. German manufacturers are acutely aware of the legal and ethical imperative of complying with these regulations. The GDPR, which went into effect in 2018, not only mandates strict data protection measures but also enforces hefty penalties for non-compliance. Ensuring compliance with GDPR and similar data privacy regulations is both a legal requirement and an ethical commitment to preserving customer data integrity.

Beyond data privacy, and ethical considerations permeate the landscape of smart customization within German manufacturing. This section delves into the ethical dimensions surrounding the responsible use of customer information.

3.6 Data Integration Technologies and Processes

In the realm of data-driven smart customization, the effective integration of data from diverse sources is paramount to unlock the true potential of personalized experiences.

SAP SE, a leading German-based technology company, offers a range of data integration solutions, with "SAP Data Intelligence" as a prominent example. SAP Data Intelligence serves as a comprehensive data management and integration tool, allowing organizations to seamlessly discover, connect, enrich, and orchestrate data from various sources. It also provides robust metadata management capabilities, integrating machine learning and AI for data classification and matching. (SAP Data Intelligence Cloud , n.d.)

Contemporary technological advancements have provided the means to shift from mass production to mass customization. The technologies listed play pivotal roles in facilitating this transition:

• Virtual reality for design

• Robotics and automation for production

• 3D printing for manufacturing

• Smart factory or factory 4.0 for logistics and control

• Smart city for integration

(Hankammer S., Nielsen K., Piller F., Schuh G. and Wang N., p(249))

All data integration technologies and strategies enable organizations to create a unified data ecosystem. By understanding these technologies and strategies, companies can navigate the complex terrain of data integration, ensuring that the data collected from various sources is seamlessly harmonized, ultimately driving the intelligent and customized experiences that define the era of smart customization.

The following subsections specifically address data management and technologies related to customization processes. They explore the role of various technologies in collecting, analyzing, and using data for customization and personalization in manufacturing.

3.6.1 Computer-Aided Design (CAD)

Computer-aided design (CAD) software plays a crucial role in gathering and storing data. When designing a product, CAD tools can record and save information about the product's characteristics, dimensions, materials, and more. This data can be invaluable for future reference, quality control, and analysis. Furthermore, CAD software can connect with other data collection systems, such as sensors and measurement devices, to capture real-time data during the manufacturing process. This real-time data collection is essential for ensuring product quality and optimizing the manufacturing process.

CAD is instrumental in customization as it allows manufacturers to tailor products to meet individual customer requirements. Designing custom components or variations of a product is made more efficient with CAD tools. For example, in German manufacturing, CAD software is used to create customized automobile features, from unique vehicle designs to personalized interiors. This customization ensures that products meet the specific needs and preferences of customers, enhancing customer satisfaction.

Features such as parametric design have become standard, allowing engineers to create product models with adaptable features that can easily accommodate changes in design or customization preferences. CAD is not only a tool for designing customized products but also for collecting and managing data related to the product design and manufacturing process. It serves as a bridge between customization and data collection, ensuring that customized products meet high standards of quality and precision (Bi, Z., & Wang, X., 2020).

3.6.2 Product Configuration Software for Personalization

A product configurator, which is a tool that enables customers to customize a product according to their preferences and needs without requiring specialized knowledge. Customers can adjust various aspects of the product, such as its color, material, shape, features, and functions, and they can also view a 3D representation of the product from all angles to better understand how it will

look. This interactive process allows customers to virtually experience and visualize the product before making a purchase, and they can do so from the comfort of their own home using a computer or device. In simpler terms, a product configurator is a user-friendly tool that empowers customers to personalize a product, ensuring that the final configured product aligns with their specific desires and expectations. (Produktkonfigurator für Ihre Umsatzsteigerung, n.d.)

By enabling customers to personalize their products, manufacturers enhance customer satisfaction by providing precisely what the customers desire. Simultaneously, the software used for customization gathers data on customers' preferences and choices, benefiting not only the customers but also the manufacturers themselves. This data is invaluable to manufacturers as it offers insights into customer preferences, enabling them to improve future product development and enhance marketing strategies. This, in turn, helps manufacturers meet customer demands more effectively and increase the number of satisfied customers, ultimately boosting the likelihood of increased purchases.

3.6.3 The Internet of Things (IoT)

With the advent of IoT (Internet of Things) and cloud computing technologies, information systems have transcended their previous confines within individual departments or organizations. Instead, they have migrated to the cloud, a centralized and accessible platform. This shift facilitates the seamless exchange and sharing of data among various departments and even across distinct organizations, effectively eliminating the information gap that previously separated them. This newfound accessibility and integrated data flow promote a more collaborative and agile approach to customization, ensuring that customer demands for personalized products can be efficiently met. Various forms of customer information, such as search records, transaction history, and product reviews, are combined and analyzed. This data can provide insights into customer preferences and behavior. Additionally, the cloud's scalability readily adapts to the increasing demand for customization, and its built-in data security measures provide essential protection for sensitive customer information. (Zhang, C. & Chen, D. & Tao, F. & Liu, 2019).

Moreover, IoT-enabled predictive maintenance strategies have emerged as a game-changer in the realm of German manufacturing. By remotely monitoring product performance and wear, IoT

devices can detect potential issues, allowing for scheduled maintenance or replacement before a breakdown occurs.

3.6.4 Machine Learning and AI in Customization

Machine Learning (ML) and Artificial Intelligence (AI) are at the forefront of the smart customization revolution within German manufacturing. This section delves into the profound impact of ML and AI in revolutionizing customization strategies.

The use of data is a fundamental requirement for the effective application of artificial intelligence. AI is expected to bring about improvements in efficiency and cost reductions. It is particularly valuable in situations where processes are automated or can be automated. In such cases, AI can optimize operations, reduce human labor, and ultimately save costs. (Engels, Barbara, 202; p12)

German manufacturers are harnessing the immense potential of ML and AI to exploit the high potential for improvement at all stages of value creation. By analyzing extensive datasets capturing customer behaviors, preferences, and historical interactions, ML algorithms can uncover intricate patterns and trends that human analysts might overlook. The use of ML is stated as follows by the Fraunhofer research members:

"*We use machine learning in production processes to generally generate "knowledge" from "experience" - learning algorithms develop a complex model from example data that is as representative as possible. This model can then be applied to new and unknown data of the same type. Whenever processes are too complicated to describe analytically, but there is enough sample data available, e.g. sensor data or images, machine learning comes in handy*". (Maschinelles Lernen. eine analyse zu kompetenzen, Forschung und Anwendung. Fraunhofer, p (8))

This capability empowers manufacturers to deliver highly relevant product recommendations and configurations, thereby significantly enhancing the customer experience.

ML and AI algorithms excel at predicting customer needs and preferences. Through advanced predictive modeling, German manufacturers can anticipate individual customer requirements and proactively offer customized solutions. For instance, in the automotive sector, predictive AI can

suggest vehicle features and configurations based on a customer's previous purchases, driving habits, and lifestyle. This approach not only streamlines the buying process but also fosters a more intuitive and personalized customer journey.

3.6.5 Big Data Analytics in Customization

Big Data Analytics has emerged as a pivotal force in the landscape of mass customization, significantly influencing German manufacturing, renowned for its engineering precision and innovative practices. At the core of this transformation lies the capacity to handle vast amounts of data.. Big Data Analytics enables manufacturers to harness this data deluge, organizing, processing, and deriving actionable insights from it. This capability offers an invaluable understanding of customer preferences, market trends, and production processes, allowing German manufacturers to navigate the intricate balance between personalization and cost-effective mass production.

In the context of intelligent manufacturing, industrial big data characterized by its volume, variety, and velocity plays a crucial role. It not only enables companies to accurately perceive changes within their internal and external environments enabling them to stay aware of developments within their systems. but also facilitates in-depth business analysis and decision-making, leading to optimized production processes, reduced costs, and improved operational efficiency. The sheer volume of data gives rise to new business models, such as mass customization and precision marketing, which significantly impact social development and economic growth. As a result, big industrial data is seen as a valuable production tool driving the progress of intelligent manufacturing, revolutionizing manufacturing practices, and contributing to both economic development and societal advancement. (Wang, Xu , Zhang, 2022)

3.7 Enabling Technologies for Customization in Manufacturing

This section discusses various technologies such as computer-aided manufacturing, robotics, automation, supply chain management systems, and additive 3D technology that facilitate the

customization process. These technologies play a crucial role in the practical implementation of customization in manufacturing.

3.7.1 Robotics and Automation in Mass Customization

Robotics enables more customized manufacturing processes, particularly as robots become increasingly adaptable, programmable, and autonomous through artificial intelligence. Industries that experience rapidly changing market demands and evolving consumer preferences can derive significant benefits from the use of robots, especially when compared to the alternative of offshoring production to distant suppliers. In such offshoring scenarios, products may not consistently meet the required specifications, resulting in quality issues and extended delivery times. The deployment of robots in these industries can expedite the introduction of new products to the market, providing a valuable competitive advantage.

These technologies have enabled manufacturers to realize flexibility in production, particularly in response to varying customer demands. By integrating robotics into flexible production processes, German manufacturers can quickly reconfigure production lines to accommodate customization requests without extensive retooling, significantly reducing changeover times.

Automation streamlines the entire process from the initial sale or order placement to the final delivery of the customized product. This high level of automation ensures that tasks are executed quickly and efficiently, reducing lead times and speeding up the production and delivery process. Automation systems often include data integration capabilities, enabling seamless information exchange between different stages of the production and delivery process. This integration ensures that customer preferences and order details are accurately communicated and implemented throughout the process. A high level of automation contributes to a seamless and consistent customer experience. It allows customers to place orders, track their progress, and receive their customized products without unnecessary delays or complications. This positive experience can lead to higher customer satisfaction and loyalty. Manufacturers that embrace automation in customization can gain a competitive edge. They can deliver customized products more efficiently and at a competitive price point, making them a preferred choice for customers seeking tailored solutions.

The impact of robotics and automation on efficiency and cost-effectiveness in German manufacturing is profound. Automated processes minimize errors, reduce labor costs, and ensure consistent product quality. Moreover, the ability to accommodate customization requests without major disruptions to the production line enhances operational efficiency, allowing for seamless transitions between standard and personalized products.

3.7.2 Supply Chain Management Systems for Agile Customization

One key component of SCMS is Just-in-Time Manufacturing, a practice that has become synonymous with German manufacturing excellence. This approach emphasizes efficient inventory management, reducing waste, and aligning production with customer demand. In this way, Just-in-Time Manufacturing facilitates rapid response to customization requests, ensuring that resources are deployed precisely when needed.

When manufacturers in traditional mass production predict the demand for their products, they often make mistakes. Sometimes they end up producing too many items that customers don't want. This leads to a problem of excess inventory, as they're left with large quantities of unsold goods that nobody is buying. On the other hand, supply chain-enabled mass customization is a different approach. It involves using data and technology to quickly respond to the specific needs and desires of individual customers. Firms adopting this strategy collect real-time data about what customers want and what they have in stock. Effective supply chain planning can help reduce the lead time it takes for suppliers to provide necessary components or materials. When supplier lead times are shorter, the company can respond more quickly to customer orders, especially for customized products. This means that the company can fulfill customization requests in a more timely manner. By doing so, companies practicing mass customization can serve specific groups of customers more efficiently and effectively because they're closely aligned with what customers actually want. This will indeed create long-lasting loyal customer relations. (Liu,.G., & Deitz, D.G. (2011))

3.7.3 3D Printing in Customization

The utilization of data serves as a fundamental prerequisite for the effective implementation of artificial intelligence (AI). Data not only provides the essential building blocks for the creation and development of AI applications but is also instrumental in their execution. Diverse datasets are essential for AI technology, which relies on them to learn, adapt, and make informed decisions. The capability of AI to analyze, recognize patterns, and perform tasks is severely limited without data. Therefore, data plays a significant role in empowering AI technologies to fulfill their potential and adapt more flexibly to fluctuations in demand. (Engels, Barbara, 2023)

The MULTIMATERIAL Center Augsburg stands as a prominent emblem of additive manufacturing advancement, representing one of the most extensive projects of its kind not only in Germany but also across Europe. This pioneering initiative not only showcases the cutting-edge capabilities of additive manufacturing but also underscores its potential to revolutionize the landscape of smart, multifaceted components. Within the framework of this ambitious project, notable achievements have been made through the collaborative efforts of esteemed German companies, including industry giants such as Siemens, MAN Energy Solutions, and Schunk, among others. (Multimaterial Center Augsburg, 2023)

3D printing allows German manufacturers to offer on-demand customization with unprecedented operational flexibility. Instead of relying on traditional manufacturing methods that require costly tooling and setup, 3D printing can produce complex and customized parts directly from digital designs. This capability enables manufacturers to swiftly respond to individual customer requests, minimizing lead times and reducing waste. It is great tool in producing components with intricate geometries that were previously challenging or impossible to manufacture. This capability is particularly advantageous in industries like aerospace and healthcare, where customized, complex components are essential.

Mass customization aims to provide products that are tailored to individual customer preferences, often involving a level of co-design where customers have input into the product's specifications. What makes 3D printing particularly valuable in this scenario is that it combines the best of both worlds: the ability to cater to individual customer needs while maintaining the efficiency of mass production. Traditionally, individualized products were crafted in small workshops, which were not well-suited for mass production due to their limited capacity and labor-intensive processes. However, 3D printing offers a flexible and efficient manufacturing method that can adapt to the

specific requirements of each customer. It bridges the gap between traditional mass production, which offers limited customization, and small-scale individual production, which is often not scalable. In essence, 3D printing allows manufacturers to efficiently produce customized products on a larger scale, striking a balance between mass production and individual customization. (Feldmann, C., Gorj, A. 2017)

3.8 Benefits and Outcomes of Data-Driven Smart Customization

The adoption of data-driven customization not only improves customer satisfaction but also engenders efficiency gains throughout the value chain. In the realm of German manufacturing, data-driven smart customization has emerged as a transformative force, reshaping how companies design, produce, and deliver products to meet the dynamic demands of customers. This chapter explores the multifaceted advantages and outcomes of adopting smart customization strategies, providing insights into how German manufacturers leverage data to enhance customer satisfaction, operational efficiency, and competitive advantage.

The benefits and outcomes of data-driven smart customization in German manufacturing are profound and multifaceted. By embracing smart customization strategies, German manufacturers position themselves at the forefront of Industry 4.0, delivering tailored solutions that meet both customer demands and the imperatives of a sustainable future.

3.8.1 Personalized Experiences

By leveraging data insights to tailor products according to individual preferences, German manufacturers foster a profound connection with their clientele, leading to higher levels of satisfaction and loyalty.

The manufacturer gathers and consolidates data from all of its customers. When this customer data is analyzed and processed, it forms what is referred to as "customer know-how." This is essentially a deep understanding of the customer base, their needs, and their interactions with the company. Customer know-how plays a crucial role in enhancing the entire value chain of the

company. The value chain includes all the processes involved in creating and delivering a product or service, from suppliers to customers. (Piller, F. T., 2020)

Bosch Smart Home exemplifies how German manufacturers are offering personalized, IoT-driven solutions for consumers, allowing them to tailor their smart home experience to their lifestyles and needs. Bosch Smart Home provides a comprehensive ecosystem of connected devices for home automation. (Bosch-Home website)

3.8.2 Increased Operational Efficiency

Efficiency improvements are a distinguishing feature of data-driven customization in German manufacturing. This means that by harnessing customer data, companies can optimize their production processes and operations. In addition to cost reduction, the focus is on producing not in excess but precisely what is demanded in the market and from the customer's perspective. This approach minimizes resource consumption and waste generation, thus contributing to environmentally responsible practices.

The key idea here is that, through mass customization, companies can avoid overproduction or the creation of products that might not be needed or wanted by customers. Instead, they produce only what is necessary to fulfill specific customer orders. Mass customization plays a role in promoting sustainable business development. It achieves this by addressing potential waste before it is even produced. (Hankammer S., Nielsen K., Piller F., Schuh G. and Wang N., 2018, p(244))

3.8.3 Enhanced Competitive Advantage

Market Differentiation

In addition to customizing the product itself, companies can set themselves apart from competitors through individual additional services or the communication of experiences. Businesses can convey not just the features of a product but also the experiences and enthusiasm associated with it. This emotional connection can greatly influence customers' perceptions and preferences. An example is provided with Mercedes-Benz, where customers can use a computer

program to create an individualized vehicle on a screen. This includes a virtual reality system to visualize the customized vehicle. This goes beyond just providing information; it creates the emotional Experience of virtual shopping as an important differentiation tool. Achieving high customer loyalty is important in building a unique market position. (Piller, F. T. (2020); p119)

German companies that effectively leverage data-driven customization establish themselves as leaders in their respective industries, differentiating themselves from competitors and attracting a loyal customer base.

Agility and Innovation

Agility and innovation have become synonymous with data-driven smart customization in German manufacturing. BMW's use of data analytics to enhance vehicle performance, creating increasing added value for continuous improvement in the production system, stands out as one of the prime examples among German manufacturers. (BMW Group PressClub. (n.d.))

Customization fosters further innovation by consistently improving current products or services and by exploring new possibilities. Data management is an indispensable tool on this journey. By swiftly adapting products to changing customer needs in the highly competitive manufacturing landscape, most German manufacturers maintain their agility in volatile markets, particularly in the auto industry.

3.9 Achieving Balance Between Customization and Mass Production

As Zawadzki and Krzysztof (2016) pointed out (as cited in the book "Customization 4.0," 2018), the creation of products tailored to individual customer preferences and needs may not be efficiently or inexpensively achievable through traditional mass production methods. The concept of the smart factory combines the principles of Industry 4.0, emphasizing the integration of advanced manufacturing technologies, with recent advancements in intelligent and automated production systems. The overarching aim of the smart factory is to enhance operational efficiency and reduce production costs. In essence, although customization and mass production may initially seem incompatible within a traditional factory environment, the smart factory, powered

by modern technology and automation, aims to bridge this gap by enabling the efficient and cost-effective manufacturing of customized products.

German manufacturers, renowned for their engineering excellence, have become exemplars in **achieving the delicate equilibrium between personalization and mass production through the strategic utilization of data-driven customization**.

Achieving the delicate **equilibrium between personalization and mass production** is critically important for several reasons:

Resource Efficiency: Mass production is efficient for producing identical or highly similar products in large quantities. However, it can lead to overproduction and excess inventory. Smart manufacturing in Germany often utilizes data-driven insights to optimize production, ensuring that both mass-produced and customized items are made in the right quantities, minimizing waste, and conserving resources.

Enhancing Customer Satisfaction: Balancing between mass production and mass customization is essential for enhancing customer satisfaction by meeting the diverse needs of consumers. While some customers prefer cost-effective, off-the-shelf products, others seek personalized solutions tailored to their unique requirements. Striking this balance enables companies to offer tailored, high-quality products that cater to individual preferences, resulting in improved customer satisfaction. Providing customization options also grants a competitive advantage by differentiating the company from rivals and engaging customers in the design process, fostering brand loyalty. Moreover, the ability to adapt to evolving market demands and efficiently allocate resources ensures long-term customer satisfaction and business success.

Competitive Advantage: Striking the right balance between personalization and mass production can give German manufacturers a competitive edge. For instance, Adidas employs smart manufacturing techniques to offer customizable sportswear through its "mi Adidas" platform. This not only attracts consumers but also allows the company to compete effectively with both high-end boutique brands and lower-cost alternatives.

Flexibility and Adaptability: Achieving this equilibrium makes manufacturing processes more adaptable. German companies, such as Siemens, are using Industry 4.0 principles to enable quick reconfiguration of production lines. This agility allows them to shift seamlessly between mass

production and personalized manufacturing based on market demand and changing customer preferences.

Data-Driven Decision-Making: Smart manufacturing in Germany relies heavily on data analytics to understand customer preferences and market trends. This data-driven approach enables manufacturers to anticipate demand for personalized products and adjust their production, accordingly, reducing the risk of underutilized resources.

Global Market Reach: With the ability to efficiently produce both standardized and customized products, German manufacturers can target global markets more effectively. They can cater to local preferences while leveraging economies of scale for core components.

In summary, finding the right balance between personalization and mass production is essential for German smart manufacturing. It enables companies to meet diverse customer needs, optimize resource usage, enhance customer satisfaction, maintain a competitive edge, and stay adaptable in an ever-evolving market. German manufacturers like BMW, Adidas, and Siemens showcase how this equilibrium can be achieved, contributing to their success on the global stage.

3.9.1 Strategic Approaches: Product Modularity and Family Architecture

According to Seelmann-Eggebert (2001, as cited in Von der Massenproduktion zur Mass Customization, 2002), customers desire products customized to their specific preferences without lengthy delays. Research indicates that customers are willing to pay a premium of 10 to 15% for such customized offerings compared to standard products. However, the demand for quick delivery remains unchanged. To address this challenge of delivering customized products as swiftly as standard ones, efficient coordination of information logistics is essential. In addition to efficiently managing information flows, companies must also challenge themselves with the traditional issue of ensuring the timely availability of materials and spare parts at the right locations (material flows). Thus, minimizing end-user waiting times is crucial for capitalizing on sales and market opportunities in both customized mass and series production, often requiring close geographical proximity between manufacturers and suppliers.

Mass customization leads to an ever-increasing volume of data due to a progressively higher frequency of generating "new configurations.". While traditional orders involve making multiple products for anonymous customers, mass customization requires producing personalized items for specific customers, resulting in increased data diversity, including customer names and addresses linked to each order. The implementation of Customer Relationship Management (CRM) unlocks greater customization potential by managing customer data for personalized marketing and service. To handle the increased data load effectively, suitable IT systems must be chosen, capable of intelligent information logistics to manage the entire information flow. (Schenk, M., Seelmann-Eggebert, R. (2002), p256)

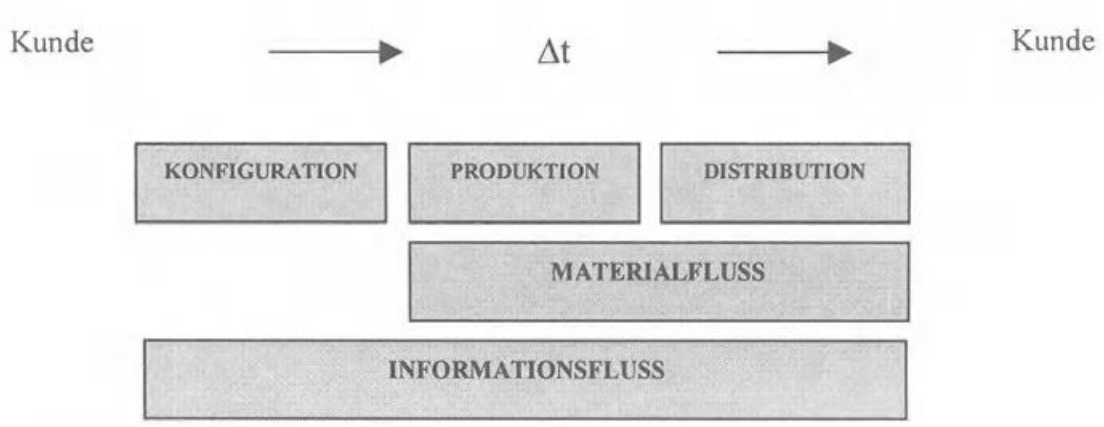


Figure source: Schenk, M., Seelmann-Eggebert, R. (2002). Von der Massenproduktion zur Mass Customization. P(257) *`Material and Information Flow`*

Figure 2 depicts the material and information flow (Materialfluss und Informationfluss) within the value chain across three production phases: **configuration** (configuration-deciding how a product will be made), **production** (production-actually making the product), and **distribution** (distribution-getting the product to the customer). A time interval called "**At**," measures how long it takes from when a customer (Kunde) places an order until they receive their customized product. The shorter this time (At) is, the better, especially when implementing customized mass production. The goal is to make the time it takes to get a customized product to the customer almost as fast as it would be with traditional mass production and its associated sales channels.

To achieve this goal, the study suggests that several things need to be improved, including technical processes (how the product is made), logistics (the way materials and products are moved around), and information systems (how data is managed and used). These improvements are necessary to make customized mass production more efficient and competitive.

Achieving economies of scale are of paramount importance, allowing companies to optimize production processes, reduce costs, and remain competitive in their respective industries. However, this pursuit of efficiency must also align with the ever-evolving and diverse needs of customers and the dynamic shifts in market trends. To strike this delicate balance, manufacturing companies have turned to innovative strategies. Among these, the concepts of **product modularity** and **product family architecture** have emerged as effective approaches. These methodologies empower manufacturers to maintain economies of scale while tailoring their offerings to meet individual customer requirements, adapting swiftly to changing market dynamics, and ultimately ensuring they remain at the forefront of their industry. Standardizing product elements and the manufacturing process through a uniform modularization approach is crucial for cost reduction. Tseng, M.M., Wang, Y., Jiao, R.J. (2017) used the fundamental rule for that traditional rule "**The more standard, the lower the costs**". Therefore, the authors stress that this long-standing rule remains valid and relevant, even in the context of modern manufacturing practices.

Product family design is a strategic approach in product development and manufacturing that focuses on creating a group or family of related products that share common elements or components while allowing for variations to meet specific customer needs or market demands. The key idea is to design a product family with a common platform or architecture, which serves as a foundation for multiple product variants. For example, smartphone manufacturers often use product family architecture. The core design and components of a smartphone can remain consistent across different models, with variations in features and specifications to cater to various customer segments. According to Robertson and Ulrich(1998) ,(as cited in Jiao, J., Simpson, T. W., & Siddique, Z., 2007), many companies are implementing product family development strategies to provide a diverse range of product variations to meet various market demands while simultaneously capitalizing on the cost efficiencies offered by effective and comprehensive manufacturing capabilities.

In essence, product family design is a strategy that strikes a balance between standardization and customization, enabling companies to optimize production processes while meeting individual customer requirements.

A product platform, as described by Meyer and Lehnerd (1997), (as cited in Jiao, J., Simpson, T. W., & Siddique, Z., 2007), comprises a collection of subsystems and interfaces meticulously crafted to establish a shared framework, enabling the efficient development and production of a continuous stream of derivative products.

Tseng and Jiao (2001) highlight the concept of a product family architecture as crucial in the context of designing products for mass customization. This architecture essentially involves creating a group of related products that share a common platform or foundation while allowing for variations to meet individual customer preferences. The significance of this approach lies in its ability to balance customization and efficiency. By having a common platform as a base, manufacturers can streamline their production processes and utilize shared components, which is more cost-effective and efficient compared to developing unique products for each customer. Furthermore, Tseng and Jiao stress the importance of distinguishing between two types of product variety: customer-perceived variety related to functionality (e.g., features, capabilities) and technical variety (e.g., different technical components). Understanding these distinctions is vital because it allows manufacturers to comprehend what aspects of a product matter most to their customers. In other words, it helps them grasp how customers perceive and value different attributes of a product. For instance, some customers may prioritize certain features or functionalities, while others may focus on the technical components of a product.

Two prominent approaches have gained recognition in the topic of product family architecture which are *scalable product family design* and *configurational product family design*, as noted by Jiao et al. in 2007 and Jiao in 2011.

Scalable product family design centers around the concept of creating a product family with a scalable architecture, allowing for flexibility and adaptability to meet varying customer needs and market demands. This approach emphasizes the ability to efficiently adjust and extend the product family as requirements evolve. On the other hand, **configurational product family design**, also called module-based product family design (Ulrich, 1995), focuses on developing a family of products with various configurable features and options. Customers can then tailor the

product to their specific preferences within predefined parameters. Both approaches offer strategic advantages, and the choice between them depends on the nature of the products, the target market, and the desired balance between customization and standardization. This approach is also referred to as module-based product family design. Configurational product family design centers on creating a family of products with modular components and features. These modular elements can be flexibly combined and configured to meet the specific needs and preferences of individual customers. By using a module-based approach, manufacturers can offer a broad range of product variations without the need for extensive reengineering, resulting in a cost-effective and efficient method for delivering customized solutions. This approach aligns with the principles of mass customization, where flexibility and choice are pivotal to meeting diverse customer demands while optimizing production processes. As an example, in the automotive industry, modular design is commonly used for engines, transmissions, and other components. Car manufacturers can use the same engine module in various models, making production more efficient and cost-effective.

3.9.2 Sustainability: Lean Data Management & Additive Manufacturing

The increasing preference of consumers for customized products has led to intense competition among companies aiming to fulfill unique customer demands. While these organizations are trying to adjust to this changing business landscape, they are also faced with the responsibility of managing their operational capacity in a manner that aligns with sustainable practices. This involves addressing issues related to resource conservation and reducing the generation of waste. On the surface, the challenge of meeting individual customer preferences while also promoting sustainability may appear to be quite challenging.

Thanks to transformative technologies facilitated by Industry 4.0, it is becoming increasingly achievable across a variety of manufacturing companies in Germany.

Fraunhofer ISI has developed an Industry 4.0 Readiness Index and showed whether lean principles are fundamentally compatible with the idea of smart Industry 4.0 production. This project also proved that when smart and lean principles meet and are linked, there is also far-reaching potential for operational performance increases. The current research unequivocally

demonstrates that 73 percent of companies are actively engaged in this emerging management framework, effectively intertwining the principles of lean production with those of smart manufacturing. Companies that do not embrace Lean 4.0 practices tend to exhibit performance levels below the manufacturing industry average. (Press release. Fraunhofer Institute for Systems and Innovation Research; 2021)

Increasing demand for customer-specific products, shorter product lifecycles, and cross-location/company production networks required a rethinking of the current manufacturing processes for the companies. On the one hand, customers demand more innovative, individually tailored products of high quality at a competitive price. On the other hand, companies are faced with the challenge of shorter life cycles, which leads to a shorter payback period for investments in machines and tools.

In response to this tension, 3D printing, also known as additive manufacturing, emerges as a promising solution. Often heralded as a "breakthrough innovation," 3D printing holds the potential not only to revolutionize manufacturing processes by reducing material and resource consumption but also to transform entire industries and their intricate supply chains and value-added networks. Data acquisition and processing is one of the main parts of layer-by-layer-based printing.

The integration of Lean Manufacturing (LM) and Additive Manufacturing (AM) holds the potential to provide a significant competitive advantage in the face of ever-evolving market dynamics and complexities. This strategic combination allows companies to excel through two primary avenues: product differentiation and service enhancements. By leveraging LM principles for efficient production processes and coupling them with the innovative capabilities of AM, businesses can develop unique, high-quality products that set them apart in the market. This differentiation not only attracts a broader customer base but also positions the company as an industry leader. Additionally, integration enables the provision of enhanced services, such as rapid prototyping or customized product offerings, further solidifying customer loyalty. In essence, the synergy between LM and AM equips businesses with the agility and creativity required to not just adapt to but thrive in the ever-changing market landscape.

Chapter 4 Case Study: Piezosystem Jena - High Precision Piezo Motion Solutions

4.1 Rationale for Choosing Piezosystem Jena

The selection of Piezosystem Jena as the subject of this case study is driven by its pivotal role in exemplifying the convergence of data-driven smart manufacturing and customization, both integral components of achieving operational flexibility in modern manufacturing. Piezosystem Jena's prominence in the field of high-precision piezo motion solutions positions it as a compelling case study for several reasons.

Firstly, the company's commitment to leveraging cutting-edge technology, including the integration of smart manufacturing and data-driven processes, aligns with the central theme of this thesis. By closely examining their adoption of data management systems and their interface with smart manufacturing technologies, this case study will shed light on how Piezosystem Jena optimizes its operational flexibility. Secondly, within the broader context of the thesis, which explores how data-driven strategies enhance flexibility within manufacturing processes and customization, Piezosystem Jena serves as a pertinent example of how an innovative manufacturer navigates the era of Industry 4.0.

Studying their approach to data utilization, data-driven customization, and their response to market dynamics will provide valuable insights into how companies can adapt to the digital age, achieve operational flexibility, and efficiently deliver highly customized products. Therefore, the choice of Piezosystem Jena as the case study subject holds the promise of offering practical lessons and empirical evidence that align with the overarching thesis goal of enhancing operational flexibility through data-driven smart manufacturing and advanced customization strategies.

Image source: Company website

4.1.1 Industry Significance

Piezosystem Jena, a leading entity in the realm of high-precision piezo motion solutions, stands as a significant player within the broader manufacturing landscape. The selection of Piezosystem Jena as a case study subject is underpinned by its profound impact on several key aspects of modern industry, making it a pertinent subject for in-depth investigation.

"Established in 1991, piezosystem jena offers piezo nano-positioning and metrology solutions to the semiconductor, aerospace, photonics, microscopy and synchrotron communities."(Company website)

- **Advanced Precision Engineering:** One of the core reasons behind the industry significance of Piezosystem Jena is its pioneering role in advanced precision engineering. The company specializes in the design and manufacturing of piezo-based motion solutions, a technology renowned for its exceptional precision and reliability. These solutions find application in an array of industries which are *aerospace, semiconductor, photonic applications, material testing*. The semiconductor, photonic applications, and material testing industries are critical in manufacturing due to their contributions to safety, precision, and technological advancements across various sectors, fostering innovation and ensuring product quality and reliability. Conversely, the industries Piezosystem Jena serves often demand a substantial number of custom-manufactured products. By delving into Piezosystem Jena's operational practices and technological advancements, this case study provides a unique opportunity to specifically learn more about German high-precision manufacturing.

- **Adoption of Smart Manufacturing Technologies:** Piezosystem Jena's dedication to embracing Industry 4.0 principles is another point of its industry significance. In an era marked by the integration of smart manufacturing technologies, data-driven processes, and the Internet of Things (IoT), Piezosystem Jena exemplifies how a forward-thinking manufacturer adapts to these transformative shifts. *Optical inter satellite links, microscopy, micro manipulation, spectroscopy, shaker system, shock testing systems, lithography, wafer positioning, auto focus device* are among the applications listed in the Piezosystem Jena's website. Several are closely related to advanced smart manufacturing

technologies. Optical Inter Satellite Links benefit from cutting-edge data communication and information exchange methods for satellite networks. Microscopy relies on precision manufacturing techniques to enhance imaging and diagnostics. Micro Manipulation leverages smart robotic systems and automation for intricate tasks. Spectroscopy involves advanced sensors and data analysis for precise material analysis. Shaker Systems and Shock Testing Systems require smart controls and data collection to simulate real-world conditions. Finally, Lithography, Wafer Positioning, Auto Focus Device, and Pixel Shift are essential in semiconductor manufacturing, utilizing automation, data analytics, and precision control for efficient production processes in the semiconductor industry.

- **Customization as a Competitive Edge:** Customization, a key aspect of the thesis theme, plays a vital role in Piezosystem Jena's industry significance. The ability to tailor products and solutions to the unique needs of clients has become a defining feature of modern manufacturing. Piezosystem Jena's adeptness at data-driven customization, as observed in its product offerings, showcases how customization can be a potent competitive edge in today's market. They offer customized solutions to fit their customers` special requests. This case study will scrutinize how the company navigates the fine balance between customization and mass production, revealing valuable lessons for other manufacturers seeking to provide highly customized solutions while maintaining operational efficiency.

"With more than 30 years of experience, piezosystem jena is a worldwide developer and manufacturer of incredibly precise piezo actuators and piezo stages. As a privately owned company, there is ***a strong focus on creating customized solutions*** *for industrial and research applications."* (Company official website)

- **Global Market Reach:** The global reach of Piezosystem Jena is a testament to its industry significance, and the company also maintains a branch in North America. Piezosystem Jena GmbH has knowledgeable and skilled representatives for their piezo technology products working in more than 25 countries. These representatives are likely responsible for promoting, selling, and providing support for the company's piezo technology products in their respective regions or countries. The company's products are

distributed worldwide, serving diverse industries in various regions. As such, the case study offers insights into the challenges and strategies associated with operating in a global context. Piezosystem Jena's approach to supply chain management, logistics, and adaptation to different regional demands is an area of particular interest.

In essence, the industry significance of Piezosystem Jena lies in its advanced precision engineering, embrace of smart manufacturing technologies, adeptness at data-driven customization, and its reach in a global market. By delving into these aspects, this case study promises to provide a comprehensive understanding of how a modern manufacturer achieves operational flexibility aligns with Industry 4.0 principles, and leverages customization as a strategic advantage within the competitive manufacturing landscape.

4.1.2 Relevance to the Thesis

Piezosystem Jena's prominence and approach to manufacturing hold a profound relevance to the central themes of this thesis, which primarily explore operational flexibility, data-driven smart manufacturing, and the role of customization in modern industrial practices. This section elucidates the specific facets of Piezosystem Jena's operations that align with the thesis's core objectives.

- Operational Flexibility: Operational flexibility, a central focus of this thesis, is inherently intertwined with Piezosystem Jena's practices. As a manufacturer dealing with intricate, high-precision solutions, the company navigates the complexities of producing tailor-made products for diverse industries. This case study is poised to unveil the strategies and technologies employed by Piezosystem Jena to enhance operational flexibility while maintaining the high precision required for its products. Doing so will provide a nuanced understanding of how operational flexibility can be achieved in manufacturing contexts where customization and precision are paramount.

- Data-Driven Smart Manufacturing: The integration of data-driven smart manufacturing practices stands as a defining characteristic of Piezosystem Jena's operational model. The

company effectively utilizes digital tools, automation, and data analytics to optimize its production processes, aligning with Industry 4.0 principles. By examining the specifics of Piezosystem Jena's data-driven approach, this case study offers valuable insights into the practical implementation of smart manufacturing in a precision engineering context. Researchers will gain an understanding of how data collection, analysis, and utilization are leveraged to improve efficiency, quality, and customization.

- Customization as a Competitive Advantage: Piezosystem Jena's proficiency in data-driven customization is of particular relevance to the thesis's exploration of customization as a competitive advantage. The company tailors its solutions to the specific requirements of clients, showcasing how customization can be a powerful differentiator in today's manufacturing landscape. By dissecting Piezosystem Jena's approach, this case study illustrates the strategies and technologies used to balance mass production efficiency with highly customized solutions, addressing a key theme of the thesis.

- Technological Integration and Adaptation: The company's capacity to remain at the forefront of technological advancements and its adaptability to changing market dynamics align with the thesis's focus on how manufacturers can stay relevant and agile in the digital age. By examining how Piezosystem Jena integrates advanced technologies, adapts to market demands, and operates on a global scale, this case study provides valuable lessons for manufacturing entities seeking to thrive in a dynamic, technology-driven environment.

In summary, Piezosystem Jena's operational practices, marked by operational flexibility, data-driven smart manufacturing, customization as a competitive advantage, and technological integration, perfectly mirror the core themes of this thesis. By scrutinizing the company's approach, this case study offers practical insights that can inform and enrich the broader discussion on how modern manufacturers can navigate the digital age, achieve operational flexibility, and effectively leverage data-driven practices to remain competitive in an evolving industrial landscape.

4.2 Design of the Case Study

The case study of Piezosystem Jena, facilitated by an interview with Malik Javadov, Lead Software Engineer at Piezosystem Jena GmbH and Doctoral Researcher at the Friedrich-Schiller University of Jena, has been meticulously designed to provide a comprehensive exploration of the critical aspects of the company's operations. This section delves into the overarching design, the methodology for data collection, and the objectives of the case study.

4.2.1 Data Collection

- **Primary Source:** The primary source of data for this case study is the extensive interview conducted with Mr. Malik Javadov. As a Lead Software Engineer at Piezosystem Jena GmbH, Mr. Javadov plays a pivotal role in the company's data-driven practices, automation systems, and technological integration. His dual role as a Doctoral Researcher at the Friedrich-Schiller University of Jena further enriches the insights provided in the interview. The primary data collected from this interview forms the cornerstone of the case study, offering firsthand knowledge of the company's strategies, challenges, and successes in the domains of operational flexibility, data-driven smart manufacturing, and customization.

- **Secondary Sources:** The company`s official website and its articles were used as a secondary source.

4.2.2 Objectives and Scope

The primary objectives of the case study are to illuminate the operational flexibility, data-driven smart manufacturing, and customization strategies adopted by Piezosystem Jena. The case study seeks to delve into the following specific aspects:

Operational Flexibility: To uncover the methodologies and technologies employed by Piezosystem Jena to enhance operational flexibility while maintaining high precision in its manufacturing processes. This includes an examination of the company's production processes, response to market demands, and flexibility in addressing diverse client requirements.

Data-Driven Smart Manufacturing: To elucidate how Piezosystem Jena leverages data analytics, automation, and Industry 4.0 principles to optimize its production processes. This encompasses insights into data collection, analysis, utilization, and the resultant impact on efficiency and product quality.

Customization as a Competitive Advantage: To explore how Piezosystem Jena balances mass production efficiency with highly customized solutions. The case study will shed light on the company's data-driven customization strategies, showcasing how they provide a competitive edge in the precision engineering landscape**.**

Technological Integration and Adaptation: To examine how Piezosystem Jena remains at the forefront of technological advancements and adapts to evolving market dynamics. This includes insights into the integration of smart manufacturing technologies, the management of digital tools, and the strategies for operating on a global scale.

The scope of this case study encompasses the operations, practices, and strategies employed by Piezosystem Jena, with a specific focus on the role of Malik Javadov, Lead Software Engineer,

and Doctoral Researcher. The study seeks to provide a holistic understanding of how Piezosystem Jena embodies the themes central to this thesis – operational flexibility, data-driven smart manufacturing, and customization. It is anticipated that the insights gained from this case study will contribute significantly to the broader discussion on these critical facets of modern manufacturing.

4.2.3 Research Questions

The interview with Mr. Malik Javadov, Lead Software Engineer at Piezosystem Jena GmbH and Doctoral Researcher at Friedrich-Schiller University of Jena, aimed to address several key research questions pivotal to this case study:

Data Management and Customization: How does Piezosystem Jena manage data, and how does this align with customization strategies in product manufacturing?

Data Sources and Data Quality: What data sources and sensors are used in manufacturing for custom production, and how does Piezosystem Jena ensure data quality and accuracy in its processes?

Success Stories and Optimization: What are successful data-driven customization initiatives at Piezosystem Jena, and what factors contribute to their success in optimizing production and product quality?

Market Adaptation and Flexibility: How important is it for Piezosystem Jena to adapt to evolving market conditions and changing customer demands? How does the company prioritize flexibility within its industry?

Advanced Technologies: What roles do advanced technologies like IoT, AI, and machine learning play in Piezosystem Jena's data-driven customization efforts in manufacturing and product development?

Data Security and Protection: How does Piezosystem Jena manage data security and protect data collected from precision machinery and sensors for customization in manufacturing?

Challenges and ROI: What challenges or obstacles has Piezosystem Jena encountered in implementing data-driven customization, and how have these been addressed in the production environment?

Future Vision: What is Piezosystem Jena's vision for the future of data management and customization in manufacturing, both within the organization and the industry as a whole?

4.2.4 Data Analysis Approach

The data analysis approach for this case study is founded upon a qualitative research framework. In this methodology, data obtained from the interview with Mr. Malik Javadov serves as the primary source, offering valuable firsthand insights into Piezosystem Jena's data management, customization, and smart manufacturing practices. These insights will be analyzed and contextualized, shedding light on the interplay between data management and the achievement of operational flexibility in the context of customization in precision engineering.

Secondary sources, including academic literature and industry reports, are employed to provide a broader context. They corroborate the insights gleaned from the primary interview and underpin the theoretical and practical foundation of this research. These secondary sources guide the interpretation of primary data and contribute to the overall comprehensiveness of the case study.

4.2.5 Ethical Considerations

Ethical considerations are of utmost importance in conducting this case study. Respecting ethical principles, confidentiality, and privacy, as well as ensuring that data is used responsibly and without harm, are fundamental tenets of this research. The interviewee, Mr. Malik Javadov, provided informed consent for participation in the interview, and his responses were treated with confidentiality and anonymity. All data is handled in compliance with data protection regulations and ethical research standards. The case study aims to provide an informative and insightful exploration of Piezosystem Jena's practices while ensuring the protection and ethical treatment of all involved parties.

4.3 Results and Findings

The interview with Mr. Malik Javadov, Lead Software Engineer at Piezosystem Jena GmbH and Doctoral Researcher at the Friedrich-Schiller University of Jena, unveiled several key findings and insights into the relationship between data-driven smart manufacturing, customization, and operational flexibility. These findings provide a deeper understanding of the interplay between data management and the pursuit of operational flexibility in manufacturing.

4.3.1 Overview of Findings

(All answers were recorded, and this information was conveyed to the interviewee.)

Data-Driven Customization in Manufacturing: The findings reveal that data-driven customization is fundamental to Piezosystem Jena's manufacturing practices. Advanced data systems are employed to collect and analyze data from precision manufacturing equipment. This data-driven approach allows the company to tailor its products to the specific needs of its customers, enhancing precision and reducing production costs.

Answer by Mr. Javadov: “At Piezosystem Jena, our data management approach is integral to our product customization strategies. We use advanced data systems to collect and analyze data from our precision manufacturing equipment. This data informs our customization strategies, allowing us to tailor products to the specific needs of our customers.”

Data Sources and Quality Assurance: Piezosystem Jena relies on various sensors, including precision sensors integrated into their piezo equipment, ensuring data quality and accuracy through rigorous calibration and maintenance. Data validation procedures are fundamental in maintaining data reliability.

Answer by Mr. Javadov: “In our manufacturing processes, we rely on various sensors, including precision sensors integrated into our piezo equipment. Data quality and accuracy are maintained through rigorous sensor calibration, regular maintenance, and a commitment to precision engineering. Our data validation procedures are crucial to ensuring the reliability of our customization processes.”

Market Adaptation and Flexibility: The interview underscores the importance of adapting to evolving market conditions and changing customer demands. Piezosystem Jena's commitment to adaptability and flexibility enables them to remain responsive and relevant in a dynamic business landscape.

Answer by Mr. Javadov: “At Piezosystem Jena, we consider it very important factor to adapt to quickly changing market conditions, changing customer demands, and prioritize flexibility within our industry. This approach enables us to remain responsive and relevant in a dynamic business landscape. Our commitment to adaptability and flexibility allows us to tailor our products and services to meet the specific needs of our customers, keeping us at the forefront of innovation and customer satisfaction. By continuously monitoring market trends and customer feedback, we ensure that our solutions align with current requirements, positioning us for sustained success and growth.”

Role of Advanced Technologies: Advanced technologies, including AI and machine learning, play a central role in data-driven customization efforts. These technologies are used to analyze customer requirements and optimize piezo actuator configurations, contributing to enhanced customer satisfaction and manufacturing efficiency.

Answer by Mr. Javadov: “Advanced technologies, such as AI and machine learning, are central to our data-driven customization efforts. We employ these technologies to analyze customer requirements and optimize piezo actuator configurations. For example, AI-driven algorithms predict optimal actuator settings based on historical data, enhancing both customer satisfaction and manufacturing efficiency.”

Data Security and Protection: Data security is having great importance, and Piezosystem Jena implements robust cybersecurity measures, employee training programs, and encryption techniques to safeguard sensitive data throughout the manufacturing process.

Answer by Mr. Javadov: “Data security is a top priority at Piezosystem Jena. We implement robust cybersecurity measures, including encryption, intrusion detection systems, and regular security audits. Employee training programs emphasize data security awareness and compliance. These efforts ensure the protection of sensitive data throughout the manufacturing process.”

Challenges and ROI:

Answer by Mr. Javadov: “We utilize various KPIs to assess the impact of our data-driven customization initiatives, including actuator precision, production costs, and customer satisfaction scores. By analyzing these metrics alongside production expenses and revenue, we calculate the ROI of our initiatives. This data-driven approach guides our ongoing efforts to enhance precision and efficiency.”

4.3.2 Analysis of Data

The analysis of the data and insights gathered from the interview with Mr. Malik Javadov underscores the significance of data-driven customization in achieving operational flexibility within manufacturing. The data analysis approach incorporates a qualitative research framework, providing a comprehensive understanding of how data management is intricately linked with customization strategies. The utilization of advanced data systems and the integration of precision sensors were identified as key practices for achieving data quality and accuracy in precision manufacturing. The results highlight the critical role of adaptability, flexibility, and the integration of advanced technologies in responding to market dynamics and customer needs while optimizing manufacturing efficiency. Furthermore, the importance of data security and the measures taken to protect sensitive data emerged as a vital aspect of the data-driven manufacturing landscape.

4.3.3 Key Insights

Key insights from the interview with Mr. Malik Javadov suggest that data-driven customization serves as a catalyst for operational flexibility. The ability to collect, analyze, and apply data in real time enables precision engineering that optimizes product quality and reduces production costs. Moreover, the adoption of advanced technologies like AI and machine learning contributes to a dynamic and responsive approach to manufacturing.

4.3.4 Implications for the Thesis

The findings and insights from this interview present compelling implications for the thesis, which explores achieving operational flexibility through data-driven smart manufacturing and customization. The case study on Piezosystem Jena elucidates the symbiotic relationship between data management, data-driven customization, and operational flexibility. These implications provide valuable contributions to the thesis's overarching goal of understanding how data-driven approaches enhance operational flexibility and customization within the manufacturing industry.

Conclusion

In conclusion, this research underscores the significant role of data management technologies and customization in shaping the future of the German manufacturing industry within the context of Industry 4.0. The thesis integrates existing research findings from top research institutes in Germany to better understand the data readiness levels of manufacturing companies and the challenges they face. The study provides a comprehensive understanding of how data management and customization play pivotal roles in shaping the future of the German manufacturing sector, offering valuable guidance to both researchers and industry stakeholders.

Germany is renowned for its exceptional ability to manufacture technically advanced and high-quality products. Based on previous research, there is still room for improvement, especially in achieving full data readiness. On the other hand, mass customization is a current focal point, revolving around the strategic coordination of planning, design, production, and service delivery to cater to a broader spectrum of customer requirements and adapt to changing market demands, all while preserving the advantages of economies of scale. In essence, it involves a significant restructuring of business models with a predominantly customer-centric approach.

Chapter 1 delved into the evolution of German manufacturing from traditional to smart manufacturing models, addressing the driving forces and challenges of traditional methods and the transition to mass customization. The distinctive advantages of mass customization were discussed based on theoretical studies by previous researchers.

Chapter 2 focused on the evolving significance of data as an asset for manufacturers. It explored the symbiotic relationship between data management and Industry 4.0, emphasizing the critical roles of being both data providers and recipients to maintain the competitiveness of the German manufacturing industry. The emergence of data ecosystems offers a powerful means to enhance both internal and external collaborations. By bringing all facets of the value chain under one digital roof, these ecosystems facilitate rapid information exchange. The concept of data economy readiness among German manufacturers was unveiled, along with the challenges faced during data management integration, categorized as legal, organizational, economic, and technical. The research revealed that the most significant barrier to becoming data-ready among German manufacturers is legal, primarily related to data security.

Chapter 3 formed the crux of this thesis, titled the transformative journey toward data-driven smart customization. It traced the historical evolution of customization in German manufacturing, covering the artisanal, mass production, and mass customization eras. The chapter highlighted the paradigm shift toward customer-centricity in smart customization, emphasizing the understanding of customer needs, cultivating a customer-centric mindset, and harnessing data-driven insights. It delved into various data integration and enabling technologies that facilitate customization in manufacturing. The chapter also discussed the benefits and outcomes of data-driven smart customization and emphasized the importance of achieving an intricate balance between mass customization and mass production. Strategic approaches and the sustainability approach of lean data management and additive manufacturing were explored.

In Chapter 4, the case study of Piezosystem Jena, a high-precision piezo motion solutions company, brought these concepts to life with real-world applications. The selection of this company was that its pioneering role in advanced precision engineering. Through an exhaustive analysis of data, key insights and implications emerged, demonstrating the pivotal role that data management and customization played in the company's success. It played as a rich source of insights in high-precision German manufacturing for researchers seeking to understand how such technologies can be effectively employed to enhance operational flexibility.

This thesis serves as a comprehensive guide to understanding the critical interplay between data management and customization, providing a roadmap for the future of German manufacturing in the Industry 4.0 era. It emphasizes the transformative potential of data management and customization for the German manufacturing industry, fostering innovation, customer satisfaction, and operational efficiency.

As German manufacturing grapples with multifaceted challenges, particularly the issue of data security and concerns about data sharing across businesses, it becomes increasingly important to address these challenges and understand the underlying reasons. Nowadays, the German manufacturing industry poses significant challenges, including volatile markets, global competitors, custom product demands, and complex production processes. On the other hand, maintaining high levels of productivity and quality is another important factor for many companies. This required more adaptable and responsive production systems and trained employees. Becoming a data-ready business has evolved into a competitive differentiator, offering a powerful means to enhance both internal and external collaborations. Therefore,

comprehending data-driven management capabilities in customization practices is instrumental in a company's pursuit of sustained success in today's dynamic business landscape.

References

A. Immonen, M. Palviainen and E. Ovaska, "Requirements of an Open Data Based Business Ecosystem," in IEEE Access, vol. 2, pp. 88-103, 2014, doi: 10.1109/ACCESS.2014.2302872. Available in: https://ieeexplore.ieee.org/abstract/document/6730652

ATTARD, J., ORLANDI, F., AUER, S. (2016): Data Value Networks: Enabling a New Data Ecosystem. In: IEEE/WIC/ACM International Conference on Web Intelligence (WI), S. 453–456.

Basistabelle Bruttowertschöpfung: Produzierendes Gewerbe. Statistisches Bundesamt. (2022, July 25). https://www.destatis.de/DE/Themen/Laender-Regionen/Internationales/Thema/Tabellen/Basistabelle_IndWertschoepfung.html

Bi, Z., & Wang, X. (14 February, 2020). Computer Aided Design and manufacturing | wiley online books. https://onlinelibrary.wiley.com/doi/book/10.1002/9781119667889

Büchel, Jan / Engels, Barbara, 2022, Datenbewirtschaftung von Unternehmen in Deutschland, in: IW-Trends, 49. Jg., Nr. 1, S. 73-90: https://www.iwkoeln.de/studien/datenbewirtschaftung-von-unternehmen-in-deutschland.html

Büchel, Jan / Engels, Barbara, 2022, Branchentrends beim Data Sharing. Status Quo und Use Cases in Deutschland, IW-Report, Nr. 53, Köln. https://www.iwkoeln.de/studien/jan-buechel-barbara-engels-status-quo-und-use-cases-in-deutschland.html

Carsten Feldmann, Anneliese Gorj (2017), 3D-Druck und Lean Production Schlanke Produktionssysteme mit additiver Fertigung. Springer Fachmedien Wiesbaden. ISBN 3658184078, 9783658184070

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G., & Thiede, S. (2015). Direct digital manufacturing: Definition, evolution, and sustainability implications. Journal of cleaner production, 107, 615-625. https://doi.org/10.1016/j.jclepro.2015.05.009

Christy, D. P. (1993). Mass Customisation: The New Frontier in Business Competition by B. Joseph Pine II, 1993 (Boston, Harvard Business School Press) US$29.95, hardback, pp.xxi + 333. Australian Journal of Management, 17(2), 271-283. https://doi.org/10.1177/031289629301700206

Cui, Y., Kara, S., & Chan, K. C. (2020). Manufacturing big data ecosystem: A systematic literature review. Robotics and Computer Integrated Manufacturing, 62, 1-20. https://doi.org/10.1016/j.rcim.2019.101861

Da Silveira, G., Borenstein, D. and Fogliatto, F.S. (2001) Mass customization: literature review and research directions. International Journal of Production Economics, 72, 1–13.

Data Economy: STATUS QUO DER DEUTSCHEN WIRTSCHAFT & HANDLUNGSFELDER IN DER DATA ECONOMY. DEMAND-Projekt. (2019). https://demand-projekt.de/paper/DEMAND-DataEconomicsAndManagementOfDataDrivenBusiness(WhitePaper).pdf

Demary, Vera / Fritsch, Manuel / Goecke, Henry / Lichtblau, Karl / Schmitz, Edgar, 2019, Bereitschaft der deutschen Unternehmen für die Teilhabe an der Datenwirtschaft, Gutachten im Rahmen des BMWi-Verbundprojektes DEMAND – DATA ECONOMICS AND MANAGEMENT OF DATA DRIVEN BUSINESS, Köln. https://www.iwkoeln.de/studien/vera-demary-manuel-fritsch-henry-goecke-alevtina-krotova-karl-lichtblau-edgar-schmitz-bereitschaft-der-deutschen-unternehmen-fuer-die-teilhabe-an-der-datenwirtschaft.html

Demary, Vera; Fritsch, Manuel; Goecke, Henry; Krotova, Alevtina; Azkan, Can; Krote, Tobias et al. (2019): Readiness Data Economy. Bereitschaft der deutschen Unternehmen für die Teilhabe an der Datenwirtschaft.

Digitalisierung der Unternehmen in Bayern - vbw. (January, 2022). https://www.vbw-bayern.de/Redaktion/Frei-zugaengliche-Medien/Abteilungen-GS/Wirtschaftspolitik/2022/Downloads/Studie-Digitalisierung-der-Unternehmen-in-Bayern_final_CI.pdf

Discover the world of piezosystem Jena. High Precision Piezo Motion Solutions – Piezosystem Jena. (n.d.). https://www.piezosystem.com/

Engels, Barbara / Scheufen, Marc, 2020, Wettbewerbseffekte der Europäischen Datenschutzgrundverordnung – Eine Analyse basierend auf einer Befragung unter deutschen Unternehmen, IW-Report, Nr. 1, Köln. https://www.iwkoeln.de/studien/barbara-engels-marc-scheufen-wettbewerbseffekte-der-europaeischen-datenschutzgrundverordnung.html

Engels, Barbara, 2023, Mit Daten nichts am Hut?. Datennutzungspotenziale für Unternehmen, IW-Policy Paper, Nr. 8, Köln. https://www.iwkoeln.de/studien/barbara-engels-datennutzungspotenziale-fuer-unternehmen.html

Engels, B. (2017, May 25). Befunde auf basis des IW-Zukunftspanels: Bedeutung von standards für die Digitale Transformation. Institut der deutschen Wirtschaft (IW). https://www.iwkoeln.de/studien/barbara-engels-bedeutung-von-standards-fuer-die-digitale-transformation-339509.html

Data sharing fundamentals: Characteristics and definition - ieds. (n.d.-c). https://ieds-projekt.de/wp-content/uploads/2023/04/HICSS_DataSharingFundamentals.pdf

Demary, Vera / Fritsch, Manuel / Goecke, Henry / Lichtblau, Karl / Schmitz, Edgar, 2019, Bereitschaft der deutschen Unternehmen für die Teilhabe an der Datenwirtschaft, Gutachten im Rahmen des BMWi-Verbundprojektes DEMAND – DATA ECONOMICS AND MANAGEMENT OF DATA DRIVEN BUSINESS, Köln

Erdsiek, Daniel and Rost, Vincent, (2022), Datenbewirtschaftung in deutschen Unternehmen: Umfrageergebnisse zu Status-quo und mittelfristigem Ausblick, No 22-09, ZEW Expert Briefs, ZEW - Leibniz Centre for European Economic Research, https://EconPapers.repec.org/RePEc:zbw:zewexb:2209.

F. Kitsios, N. Papachristos and M. Kamariotou, "Business Models for Open Data Ecosystem: Challenges and Motivations for Entrepreneurship and Innovation," 2017 IEEE 19th Conference on Business Informatics (CBI), Thessaloniki, Greece, 2017, pp. 398-407, doi: 10.1109/CBI.2017.51.

Fraunhofer Institute for Software and Systems Engineering ISST. (n.d.-d). https://www.isst.fraunhofer.de/content/dam/isst-neu/documents/Publikationen/Datenwirtschaft/ISST-Report/Fraunhofer_ISST-Report_Data-Strategy-Praxis-Report.pdf

Franke, N., Piller, F.T.: Key research issues in user interaction with configuration toolkits, in: International Journal of Technology Management (IJTM), 2003, pp. 578-599.

G. Shao, S. -J. Shin and S. Jain, "Data analytics using simulation for smart manufacturing," Proceedings of the Winter Simulation Conference 2014, Savannah, GA, USA, 2014, pp. 2192-2203, doi: 10.1109/WSC.2014.7020063.

Gilmore, J. H. and Pine, B. J. (1997); “The Four Faces of Mass Customization,” Harvard Business Review 75(1), 91-101.

Gilmore, J.H. and Pine, J. (1997) Beyond goods and services. Strategy and Leadership, 25(3), 10–18.

Green, D. (2023, July 11). The P-F curve: All you need to know!. Click Maint CMMS. https://www.clickmaint.com/blog/p-f-curve

Gräßler, I. (2004). Kundenindividuelle Massenproduktion. SpringerLink. https://link.springer.com/book/10.1007/978-3-642-18681-3

Jiao, J., Simpson, T. W., & Siddique, Z. (2007). Product family design and platform-based product development: A state-of-the-art review. Journal of Intelligent Manufacturing, 18(1), 5-29. https://doi.org/10.1007/s10845-007-0003-2

Junliang Wang, Chuqiao Xu , Jie Zhang (January 2022, Pages 738-752). Big Data Analytics for Intelligent Manufacturing Systems: A Review. Journal of Manufacturing Systems. https://www.sciencedirect.com/science/article/pii/S0278612521000601

Kagermann, H., Wahlster, W., Helbig, J., Hellinger, A., & Karger,R. (2012). Im Fokus: das Zukunftsprojekt Industrie 4.0: Handlungsempfehlungen zur Umsetzung. Bericht der Promotorengruppe Kommunikation. Forschungsunion.

Piller, Frank & Schubert, Petra & Koch, Michael & Moeslein, Kathrin. (2004). From mass customization to collaborative customer co-design. Proceedings of the European Conference on Information Systems (ECIS). 1497-1509.

Rahmenkonzept “forschung für die produktion von morgen.” (Bonn, September 1999). https://www.ibbnetzwerk-gmbh.com/media/ibb/news/BMBF_-_Rahmenkonzept_Forschung_fuer_die_Produktion_von_morgen.pdf

SCHROEDER, W. (November 2016).Germany’s Industry 4.0 strategy: Rhine capitalism in the age of digitalisation. Friedrich Ebert Stiftung. Available in : https://uk.fes.de/fileadmin/user_upload/publications/files/FES-London_Schroeder_Germanys-Industrie-40-Strategy.pdf