VDI Zentrum Ressourceneffizienz

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VDI ZRE Publications: Brief analysis no. 31

Digital technologies for developing resource-efficient products and services

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The brief analyses of the VDI ZRE provide an overview of current developments in the field of resource efficiency in research and industrial practice. They contain a compilation of relevant research results, new technologies and processes as well as best- practice examples. The brief analyses thus provide an introduction to selected resource efficiency topics for a broad audience with business, research and administration background.

Editorial:

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Digital technologies for developing resource-efficient products and services

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LIST OF ABBREVIATIONS

AI	Artificial intelligence
AR	Augmented reality
CAD	Computer-aided design
CAx	Computer-aided x
CED	Cumulative energy demand
CO_2	Carbon dioxide
CPS	Cyber-physical systems
CRD	Cumulative raw material demand
ERP	Enterprise resource planning
FEM	Finite element method
HiL	Hardware-in-the-loop
HPC	High-performance computing
IoT	Internet of Things
IT	Information technology
KrWG	German Circular Economy Act (German: *Kreislaufwirtschaftsgesetz*)
LCA	Life cycle assessment
PDM	Product data management
PLM	Product lifecycle management
PPS	Production planning system
PSS	Product-service system
PVC	Polyvinyl chloride

PwC	PricewaterhouseCoopers
SME	Small and medium-sized enterprises
VDI	Association of German Engineers (German: *Verein Deutscher Ingenieure*)
VDI ZRE	VDI Zentrum Ressourceneffizienz GmbH
VR	Virtual reality
VPC	Virtual product creation

1 INTRODUCTION

Networking objects and people as part of Industrie 4.0[1] environment holds a wide range of opportunities, but it also generates and requires large quantities of information. Industrie 4.0 often provides engineers with data during the development of new products and services which, with the help of digital technology, can be recorded and processed in real time, allowing engineers to predict future behaviour or expand and add to existing databases with important additional information. The potential for improved efficiency for products, processes and services gained as a result is inherently very large and therefore very useful for increasing resource efficiency in the development of products and services. With the amount of information and potential for optimisation constantly increasing, however, Industrie 4.0 often goes hand in hand with a certain level of complexity, which one needs to get to grips with initially.

Digital technology refers to any (computer) hardware, software and networking-based technology, differing from traditional technology thanks to its flexibility and increased availability[2]. Often economically driven, measures for increased efficiency through new digital technology contain the potential to preserve natural resources and thus contribute to improving resource efficiency, e.g. due to increased efficiency in identifying the best possible solution or expected quality improvements. According to the *VDI-Richtlinie 4800 (Blatt 1)* guideline, resource efficiency refers to the relationship between a defined value or result and the resource usage required to achieve this.[3] To be resource-efficient, a company must be able to save materials and/or energy throughout the product's life cycle or increase its value in relation to its use. Ideally, products should be developed in a way that requires as few raw materials and energy resources as possible for the intended use, while still ensuring good maintainability/reusability. As the use of resources is still

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1 "Industrie 4.0 refers to the intelligent networking of machines and processes for industry with the help of information and communication technology." –Bundesministerium für Wirtschaft und Klimaschutz (2023).

2 Cf. Bundesministerium für Wirtschaft und Energie (2021), p. 8.

3 Cf. VDI 4800 Blatt 1:2016-02.

linked with greenhouse gas emissions, measures for improving resource efficiency can also make a significant contribution to climate protection.

The aim of this brief analysis is to identify digital technologies and related methods in product development and evaluate these in terms of resource efficiency. The analysis will also seek to determine the requirements for their implementation and outline these as part of a regulatory framework. A selection of practical examples will also show how other companies are currently already considering aspects of resource efficiency as part of product development.

To be able to better classify resource efficiency within the context of product development and Industrie 4.0, the following chapter shall serve as an introduction to the basics and explain the important terminology. Chapter 3 will then present some digital technologies that can be useful for improving resource efficiency as part of product and service development. Chapter 4 will look at a methodology on how businesses can drive forward the development of product-service systems (PSS) in terms of resource efficiency. Following on from the conclusion, chapter 6 will finally provide a look at possible technologies for which resource-efficient product development will play an important role going forward.

2 RESOURCE-EFFICIENT PRODUCT AND SERVICE DEVELOPMENT

The adaptation or new development of products and services is often the result of internal company changes, modified framework conditions (e.g. laws and technologies) or changes to customer requirements.[4] As well as advancements in digitisation, legal regulations such as the German Circular Economy Act (KrWG) paired with a general public demand for new functionalities and more environmentally friendly products are expected to drive forward the new and further development of resource-efficient products and services.

When it comes to developing products and services, the networking and communication of people and machines gives rise to new possibilities. While information was transferred for a long time in parallel to the steps of value added, with any subsequent product adjustments incurring high costs, the networking of more and more components now allows for both forwards and backwards communication and adjustment in all steps of value added.

A deeper networking in value added also facilitates the development of PSS and product-related services.[5] PSS involve the sale and linking of services to paired products. This can range from product-oriented services (e.g. supplemental training courses) and use-oriented PSS such as leasing models all the way to results-oriented PSS, which offer the end result exclusively instead of the product required to obtain this result.[6] As companies can often create a new, flexible revenue model by developing a PSS, we can expect to see an increasing number of these models in the future. The closer networking of company organisations also facilitates product-related services. The processing, analysis and forwarding of the arising data, primarily through the increase of information in all company organisations, are therefore attractive and should be considered from the point of view of resource-efficient product development.

[4] Cf. Scholz, U.; Pastoors, S.; Becker, J. H.; Hofmann, D. und van Dun, R. (2018), (Preface).

[5] We also speak of industrial product-service systems (IPSS) within the industrial context.

[6] Cf. Herzog, M.; Köster, M.; Sadek, T. und Bender, B. (2017), p. 8.

This brief analysis will consider product development as well as the development of product-related services and PSS. As, by extension, services are also products, the term “product” covers all three areas in this brief analysis, unless otherwise stated.

2.1 Basics of resource-efficient product and service development

In comparison to in trade, product development in small and medium-sized enterprises (SME) and large corporations differs due to the stronger networking of internal and external parties. The large number of interfaces with other departments (e.g. marketing, production or logistics) ensures that product development has the highest degree of networking among all the departments.[7] This means almost all information from other company departments can contribute directly or indirectly to the efficient development of products and services. Some examples include:

- Linking to production: problem areas in production, such as above-average processing times, are identified through the recording of production times and then rectified through product adjustments.
- Linking to customer management: analysed customer requirements lead more quickly to the development of satisfactory products with fewer adaptation cycles.
- Linking to infrastructure and logistics: logistically speaking, available machines, packaging types and transport options all limit the development of new products.

To promote resource efficiency in product development, regulations and standards in product development can be used as important guidelines in the first step (cf. Figure 1). Going further, it is useful to take into account the

[7] **Cf. Kirchner, E. (2020), p. 6.**

methodical approach in product development and as part of the process to determine resource usage.

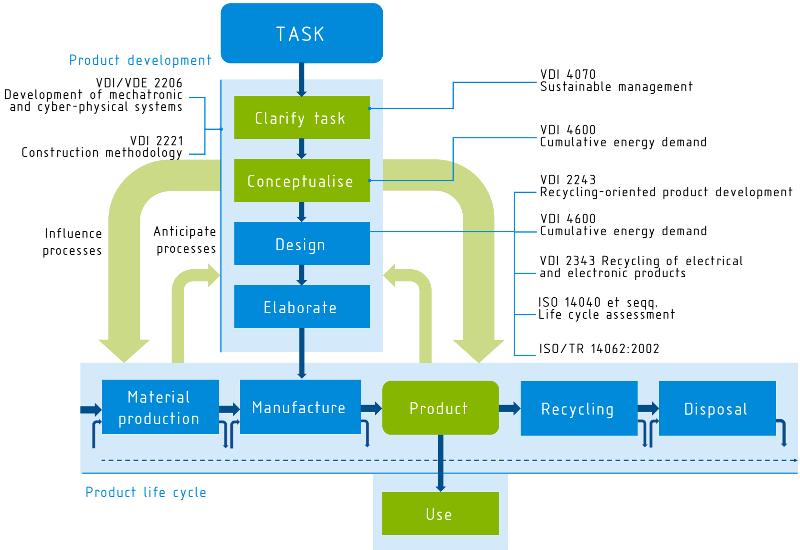
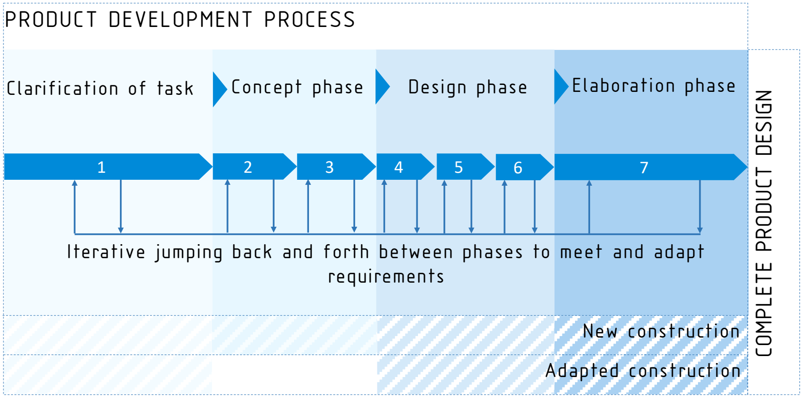


Figure 1: T model life cycle of a product and selected regulations and standards in the individual sections[8]

Many products are made up of mechanical, electrical, electronic, hydraulic and/or pneumatic subcomponents and offer additional immaterial services in the form of PSS. The product development phases outlined in Figure 1 (vertical steps) are therefore first considered in more detail under the term "integrated product development". Integrated product development is a target-oriented approach that considers organisational, methodical and technical measures.[9] The "leaps" between the individual phases shown in the figure below illustrate that product development increases in complexity as a result of the combination of objects and services outlined.

[8] Cf. VDI Zentrum Ressourceneffizienz GmbH (2022).
[9] Cf. Lange, U. und Oberender, C. (2017), pp. 13 – 14.



1 – Clarification and definition of task
2 – Determination of functions and their structures
3 – Search for solution principles and their structures
4 – Division into realisable modules
5 – Design of decisive modules
6 – Design of overall product
7 – Elaboration of specification for execution

Figure 2: Phases of the integrated product development process[10]

One option for overcoming this challenge is so-called simultaneous engineering. It involves shortening the product development time by running individual phases of the development process simultaneously or with overlap. This allows companies to improve adaptation cycles. Good coordination of the project teams in the individual stages is fundamental for this.

There is a wide range of methods and digital aids to promote the process of integrated product development. These are outlined in more detail in chapter 3. In general, the following factors help to ensure a successful integrated product development (cf. Figure 3):

[10] Own illustration based on Lange, U. und Oberender, C. (2017), p. 14.

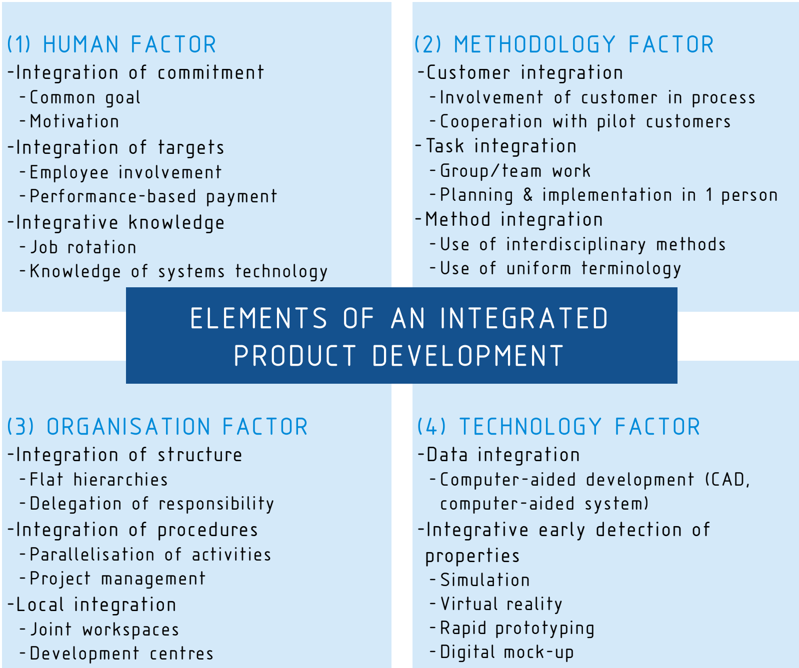


Figure 3: Elements of integrated product development[11]

Interdisciplinary teams are another important factor in integrated product development. Teams with members from various areas make a comprehensive view of product development more likely. Team members at the interface to suppliers or material management can, for example, identify potential for a circular economy more easily, while experts in production preparation can identify potential for optimisation in the subsequent production early on.[12]

To determine resource usage in the individual phases of product development (and in other value-added phases) and subsequently draw conclusions on resource efficiency, the expended raw materials and energy resources must be calculated. In doing so, the cumulative raw material demand (CRD) and cumulative energy demand (CED) make it possible to calculate resource

[11] Own illustration based on Lange, U. und Oberender, C. (2017), p. 15.
[12] Cf. Lange, U. and Oberender, C. (2017), p. 15.

usage for the entire life cycle.[13] However, the life cycle assessment (LCA) method is more common. This involves collecting the inputs and outputs of a process or product throughout the complete life cycle and converting them into comparable indicators using software. The carbon footprint is currently often used as an indicator for LCA.[14] In the area of product development, this allows businesses to determine how high material and energy usage were up until actual development. The life cycle inventory analysis can then be used to determine resource efficiency. For example, if a company determines that certain measures, such as the use of digital technologies, required lower material and energy usage up until the development of the desired product, these measures could be useful from both a business and a resource efficiency point of view.

To ensure that the development of resource-efficient products is successful, it is recommended to consider product development measures and the related standards and regulations, and take into account methods such as LCA, CRD or CED. By using balancing methods, companies can identify resource-intensive sections of the added value system and improve them with regard to resource efficiency and sustainability as part of the new or further development of products.

2.2 Product development in Industrie 4.0

Industrie 4.0 seeks to control and manage whole companies and their related networks digitally. However, to do so requires full digitisation of the indus-trial processes. Ultimately, Industrie 4.0 is no longer just the digital control of machines and production lines; it instead represents the effective interac-tion of all value-added processes, activities and services.[15] To keep up with this increasing networking and complexity from a product and service de-velopment point of view, changes in production following on from develop-ment in particular must be taken in account. Going forward, we can expect to see more dynamic and individual rescheduling of product orders and con-struction sequences (e.g. material availability or batch checks) as a result of

[13] Further information in VDI ZRE brief analysis no. 20.
[14] Cf. Scholz, U.; Pastoors, S.; Becker, J. H.; Hofmann, D. und van Dun, R. (2018), p. 27.
[15] Cf. Stark, R. (2022), p. 509.

data-controlled production processes.[16] For product development, however, this means considering aspects of modularisation (i.e. the division of individual components and objects) in future projects more seriously in order to meet the requirements for flexibility in production.

Due to the rise in networking, products may in future represent a subcomponent in a company's added value, the value of which will only become apparent in the system as a whole. The illustration below shows how the development of products can progress throughout the course of digitisation and general networking (cf. Figure 4). It is becoming more and more com-monplace for products to be equipped with digital components such as sen-sors, actuators and computers, allowing them to communicate with one an-other and other digital end devices. The future potential of such advances in networking can already be seen today in the mobility sector. While financing or sharing models have long since been important subcomponents of the mo-bility sector, complete industrial digital platforms and networked systems with a wide variety of information are expected to emerge in the future. In-terfaces to urban mobility or energy management could then, for example, help customers to avoid congestion or better coordinate the loading of bat-teries.

[16] Cf. Stark, R. (2022), p. 510.

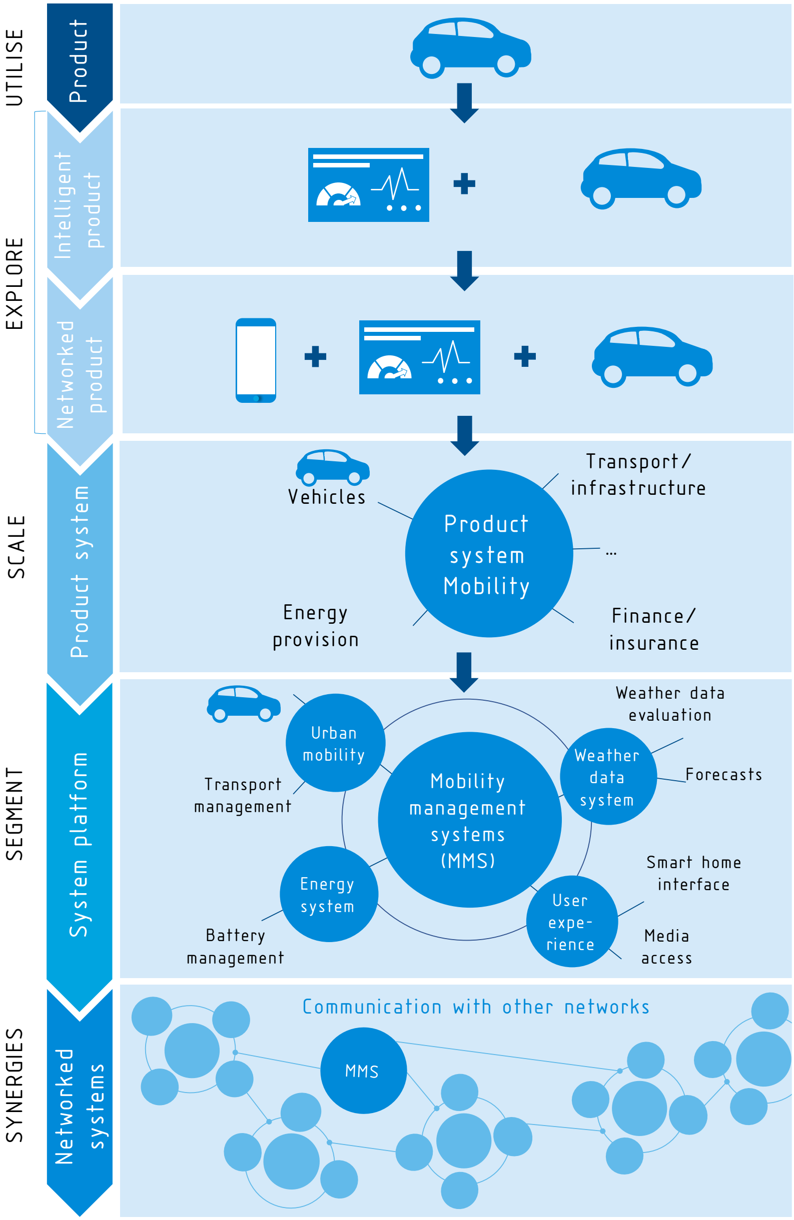


Figure 4: Vision of the product and service world (VDI ZRE illustration based on Unity Consulting[17])

Therefore, networking and the resulting possibilities to record and analyse large data quantities and use them for the purposes of improving efficiency is one of the main aims of Industrie 4.0. The following technical achievements and terminology are also essential for production development[18]:

Retrofitting

The retrofitting (also "digital retrofit") approach involves upgrading and modernising existing industrial facilities. Instead of completely replacing machines, this approach aims to establish a connection to the Internet of Things (see next section), in particular by subsequently adding sensors and communication technology. In addition to possible cost savings, retrofitting also saves resources and increases resource efficiency due to an extended service life of the product and the option for supplementary services such as predictive maintenance.[19] Retrofitting also shows developers that resource efficiency is not only gained through the design of new products; the further development of existing products also offers (resource efficiency) potential.

Cyber-physical systems (CPS) and Internet of Things (IoT)

CPS build on mechatronic or smart objects and consist of sensors, actuators, a user interface and functions that execute all data acquisition, processing and output tasks,[20] thus forming one of the main components of Industrie 4.0. CPS can be seen as a further development of programmable mechatronic systems (cf. Figure 5), largely characterised by their networking with the Internet of Things (IoT) and other services.[21]

The term IoT refers to a network of computer-aided objects that are able to communicate with one another. To some extent, the corresponding exchange

[17] Cf. UNITY Consulting & Innovation (2020).
[18] Further terminology that may be important as part of digital product development is listed in the appendix.
[19] Cf. Luber, S. (2018).
[20] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017), p. 28.
[21] Cf. VDI/VDE 2206:2021-11, p. 14.

between objects can be carried out without the human factor. The term "computer-aided", in turn, means that the connected devices themselves do not need to be computers and can instead have a different main function.[22]

CPS and IoT as overriding technologies are also very significant for product development. This way, the data collected in the manufacturing/usage phases, as well as the possibility of transferring this data, can be used to derive insights for product development – for example, by precisely determining the source of errors in predecessor products. However, new products must be equipped with the necessary sensors, actuators and computers to be able to implement the possibilities and potential of Industrie 4.0.

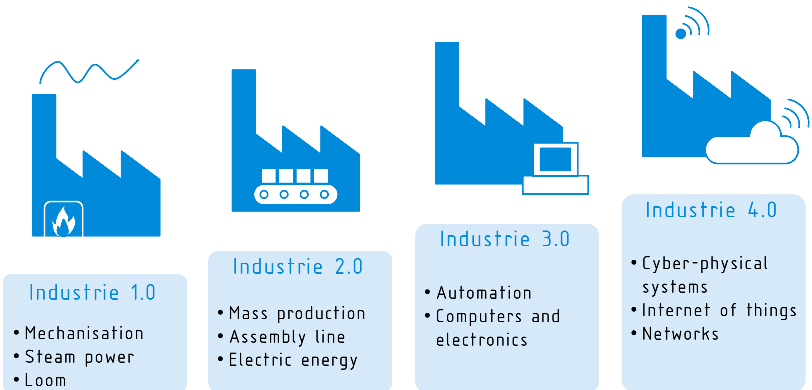


Figure 5: Progression of industry and the important related concepts (Differentiated by the four phases of the industrial revolution)[23]

[22] Cf. Stark, R. (2022), p. 532.

[23] Own illustraion based on Stark, R. (2022), p. 509.

<u>Big data and smart data</u>

The networking of people and machines gives rise to huge quantities of data, often in real time. The term “big data” refers to the collection and application of qualitatively and quantitatively diverse information. In the industrial realm, this often involves (real-time) data on processes, quality features, products and employees and their environment, all with the aim of improving processes and quality. The term “smart data” is also used as part of the correct processing of “big data”. Smart-data analyses can be used for more efficient production planning and more precise maintenance planning (so-called predictive maintenance).[24]

As outlined in the figure below, a wide range of information (e.g. about the product and production requirements) is required as part of the product de-velopment process (cf. Figure 6). For developers, the huge potential here lies both in the increased precision of data for the development process and in the expanded scope of data collection to include information that was previ-ously very difficult or impossible to measure. An example of this is the eval-uation of usage data in the automotive industry: engineers originally re-ceived information on the average service life of their cars – measured in years or mileage. However, using real-time data that can now be measured, such as braking behaviour, service life, average speeds or geo-coordinates, products or components in the future can be adapted to the corresponding requirements with a significantly higher degree of efficiency. This allows companies to gradually increase the service life of their vehicles which, in turn, improves resource efficiency.

[24] **Cf. Rank, R. (2017).**

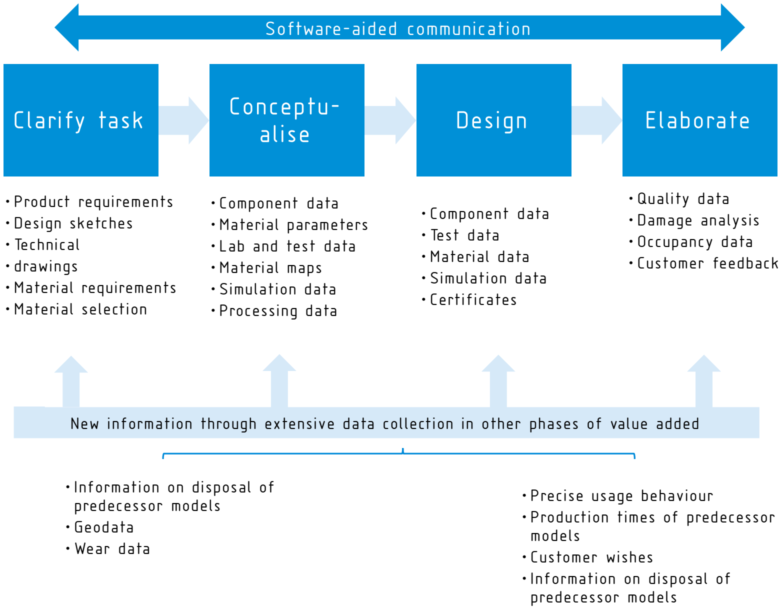


Figure 6: Selection of important necessary data in product development (VDI ZRE diagram)

High-performance computing (HPC)

Due to the large quantities of data in Industrie 4.0, high-performance computing (HPC) also plays a key role. These high-performance computers allow for parallel and efficient simulation and analysis of complex models, making it possible to find and implement software-based solutions. The enhanced networking and the related data increase are pushing current standard computers to their limits more and more frequently. This technology will therefore inevitably grow in significance going forward.[25] HPC also includes the use of so-called cloud computing and edge computing. Cloud computing refers to the real-time access to a computer via the network. Thanks to centralisation, this model allows businesses to keep administration effort and inter-

[25] Cf. Baden-Württemberg Stiftung gGmbH (2020).

action with service providers to a minimum while providing substantial computing power.[26] Due to the constantly increasing data quantities and transfers, cloud computing is now frequently also pushed to its limits which, due to latencies, is often to the detriment of the real-time factor that is so important for the technology. Edge computing can therefore be seen as an intermediary between sensors on end devices and the central computers or data centres. In simple terms, relevant data is collected and filtered at the place where it originates (e.g. on machines with sensors) using edge computing, and only important data is sent to a central computer.[27]

The resulting potential for product development is manifold. The precise provision of useable data (smart data) from downstream value-added chains allows companies to consider problems in production, in user behaviour or with regard to customer requirements in a more tailored way. HPC also offers complex calculations and fast, precise simulations (cf. section 3.2). This can have many positive effects from a resource efficiency perspective, e.g. the prevention of errors and fewer test and adaptation cycles.

[26] Cf. Stark, R. (2022), p. 540.
[27] Cf. Stark, R. (2022), p. 543.

3 PRODUCT DEVELOPMENT USING DIGITAL TECHNOLOGY

The range of technologies that have been created or which have enjoyed success as a direct result of digitisation is expansive. As a reflection of this closer networking of individual company organisations (and beyond), many digital technologies offer solutions to problems that do not clearly fit within the confines of any one company department, including product develop-ment. However, these technologies still promise users efficient solutions for operational challenges with opportunities to improve resource efficiency.

Due to the wide range of technologies, the following chapter outlines digital technologies that can take on an important role in resource-efficient product and service development both currently and going forward. The presented technologies are considered to be an overarching subject area. Possible char-acteristics and related topics are outlined in the respective organisational charts at the end of the chapter, and the important terminology is explained in more detail in the appendix. The digital technologies presented in section 3 focus on the development of physical products. However, they are also sig-nificant for service development due to the relevance of data acquisition, analysis and evaluations.

This chapter seeks to answer the following questions:

- Which digital technologies support efficient product development and the development of resource-efficient products?

- Which product development methods and approaches are related to the presented digital technologies?

- What data and information is particularly relevant for the implementation of digital technologies?

The digital technologies presented in this chapter also make it clear that the service character, with its typical features such as immateriality or frequent synchronicity of manufacturing and consumption of services, is also growing within engineering. The following technologies therefore form the basis for the themes presented in chapter 4 and chapter 6.

3.1 PDM systems in product development

Using digital technologies in product and service development requires a wide range of different forms of data to work with. Product data management (PDM) as a central “administrative body” can be seen as a basis for fully tapping into the potential of digital technologies outlined in the other sec-tions. Using PDM, product-specific data arising in product development can be recorded, managed and archived and then made available for downstream phases of the product life cycle. PDM therefore makes it possible to efficiently organise the increasing complexity of data. The starting point for PDM is creating a consistent concept for data management that can be used equally across all company departments. To do so, meta data, i.e. documents, files or databases, is managed in the PDM system and links are created to primary data in the production system.[28] PDM systems currently offered on the market can be divided into the following areas:[29]

- Traditional PDM system with focus on product structure and life cycle management

- CAD-oriented PDM system with focus on CAD model management for project teams and integration with CAD/digital mock-up

- Document-oriented PDM system with focus on the integration of cross-company documents and archive management

- PPS/ERP-oriented PDM system with focus on the integration of commercial product data

It should be noted that PDM solutions are always company-specific. Here, integration within the company is focussed on connections to the author systems used in the business (CAx system and word processing system) and the ERP systems. Integration with ERP systems is focussed primarily on the areas of work planning, procurement, purchasing and production planning.[30]

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[28] Cf. Syska, A. (2006), p. 104.
[29] Cf. VDI 2219:2016-09, p. 15.
[30] Cf. VDI 2219:2016-09, pp. 16 – 17.

The figure below (Figure 7) provides an overview of the different PDM system types and offers guidance for companies when implementing PDM systems.

Type	Turn-key PDM system	PDM toolbox	Configurable toolbox
Standard-adapted ratio	Adaptation Standard functions	Adaptation Standard functions	Adaptation Standard functions
Features	• Large amount of standard – Functions – Basic objects – Processes • Configurable application modules	• Development environment for customer-specific PDM solutions • Object-oriented tools and basic class libraries	• Industry-specific solutions based on a PDM toolbox • Generally offered by external partners of toolbox developers
Pros	• Low costs • Short-term use	• Increased flexibility • improved options for adaptation	• Medium degree of flexibility
Cons	• Partial adaptation of company organisation to PDM system structures	• Very high costs • High development effort • Long preparation	• Medium-level costs

Figure 7: PDM system types[31]

As well as deciding on the PDM system type, a gradual expansion and implementation with other systems and organisations used in the company is recommended (cf. Figure 8).

The introduction of PDM systems contains the potential to clearly shape work steps and changes for all groups of people within a company. The system also ensures that the generated data is kept up to date, meaning developer teams do not have to waste time searching and reconciling existing information, such as old CAD drawings or outdated requirements. At the same

[31] Own illustration based on VDI 2219:2016-09, p. 16.

time, the PDM system serves as a knowledge base for future product developments and other areas of the company organisation.

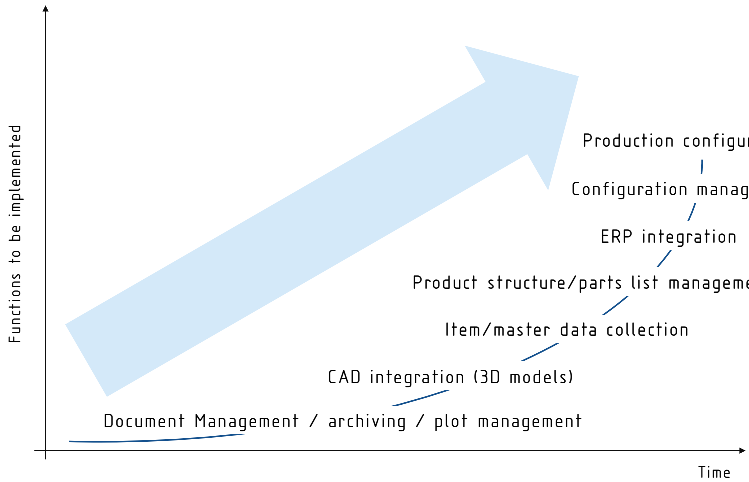

Figure 8: Possible implementation stages of PDM[32]

The potential for resource efficiency manifests itself primarily in the consideration of the product cost structure throughout the complete life cycle (cf. Figure 9). Here, it becomes apparent that the influence and assessment of costs is at the highest during the product design and development stage. With around 42% of the total costs, materials continue to represent the largest expense within the company.[33]

Measures for resource efficiency (e.g. error management) and increasing process efficiency have the biggest impact in the initial phases. However, these only (to an extent) become apparent in the next phases, such as the actual production or sale. If engineers are able to access a PDM system during product development, they are able, for example, to identify and adapt potential error sources and problems early on. The consistent data structure also ensures more efficiency in approval processes, revisions, and the like.

[32] **Own illustration based on VDI 2219:2016-09, p. 34.**
[33] **Cf. Statistisches Bundesamt (2019).**

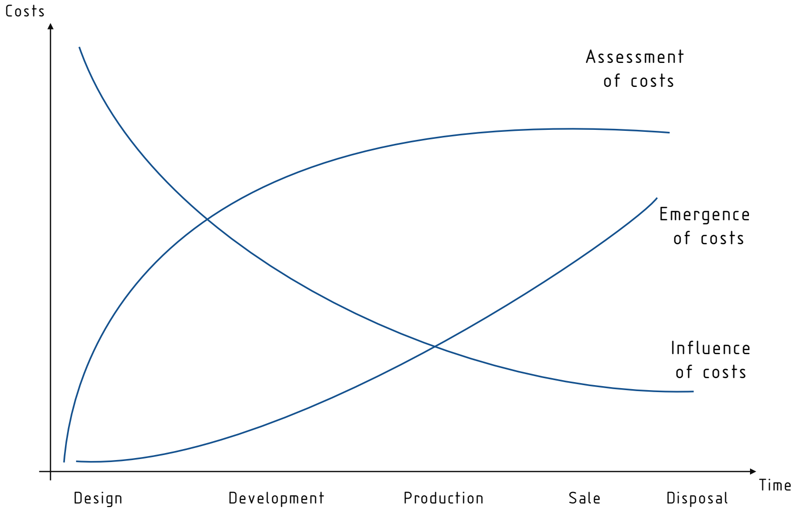

Figure 9: Assessment, actual emergence and influence of costs throughout the complete product life cycle[34]

Real life example: Drexler Automotive GmbH in Salzweg, Germany

Drexler Automotive GmbH develops and manufactures drive components for sports and race cars. The development of products involves large quantities of data in each step of the process. The data volume is constantly growing, and without sufficient management, it can become confusing. To avoid miscommunication as part of revisions and approvals and to prevent double workloads in construction and time-consuming searches for the necessary drawings and models, the medium-sized company established a universal solution consisting of 3D CAD, PDM and ERP. To do so, Drexler Automotive invested in a PDM and ERP system specially designed for SMEs within the manufacturing industry. A 3D CAD system was already introduced in 2006. The PDM system allows for a structured way of working with the latest data. There are no more outdated drawings and models. Data is kept synchronised in the event of changes, which in turn significantly reduces the error rate and allows the company to save resources.

[34] Own illustration based on Brecht, U. (2005), p. 105.

The company has also seen an improvement in cooperation within the team and an increase in product construction speed. The deciding factor for success for the company was the digital consistency of data to fully reproduce construction processes and changes.[35]

Real life example: Otto Zimmermann GmbH in Saarbrücken, Germany

With its team of approx. 45 employees, Otto Zimmermann GmbH specialises in machines and units for hydraulics, pneumatics and electronics. Construction employees have access to more than 5,000 components in the development and manufacture of hydraulic systems alone. The company's previous data management system was not particularly efficient and was prone to errors. Although the corresponding CAD data was saved on the server, employees had to search for commercial information such as item numbers, prices, suppliers and stocks for the necessary parts via an explorer each time. The company therefore decided to implement a PDM system that combined the construction data with an ERP system. A user-friendly interface for database management was also important here. The newly implemented system allows the company to file and search for product data in a structured way, and saved components can be quickly reused, making the exchange between item data and parts lists simple and effortless. Instead of automatically taking on inventory data, the company decided to create components piece by piece to update the database. Outdated or false data is removed as part of this process to avoid errors for future product developments and preserve resources. New components can be quickly and easily recorded based on existing parts of templates in the database. By implementing the PDM system, Otto Zimmerman GmbH is confident that it can increase its work speed threefold.[36]

[35] Cf. Tosse, T. (2020), p. 45 et seqq.

[36] Cf. Menke, R. (2020), pp. 50 – 51.

3.2 Digital prototyping

Prototyping is the executive activity that leads to the creation of a prototype.[37] In its digital form, prototyping can be seen as a subarea of the so-called virtual product creation (VPC). VPC involves all process steps and engineering activities consisting of digital applications, IT tool functions, software, algorithms, working methods and assessment/decision competencies,[38] illustrating individual or all planned product functions depending on the stage of development. Prototypes can therefore help to get a general understanding and feeling for the product in the early stage of product development.[39] The aim is to develop ideas so thoroughly that they can be implemented directly in reality. It is important to distinguish between physical and digital prototyping here. Digital prototyping is generally based on CAD models, calculations and simulations that are created on the computer and only exist in the digital realm.[40] In contrast to physical models, digital prototyping offers the following advantages:[41]

- Reduced development costs
- An unlimited number and parallel analyses of prototype variants
- Integration of other departments, customers and supplier companies into the product development process
- Fast adaptation and optimisation of prototypes and early identification of errors
- Clear presentation of future products for prospective customers and investors

The continuous growth of computing power and increase in cloud technology, open-source platforms and community software means that, today, digital prototyping goes far beyond mere digital imaging. The finite element

[37] Cf. Exner, K. (2019), p. 55.
[38] Cf. Stark, R. (2022), p. 48.
[39] Cf. Kirchner, E. (2020), p. 371.
[40] Cf. Kirchner, E. (2020), pp. 377 – 378.
[41] Cf. Scholz, U.; Pastoors, S.; Becker, J. H.; Hofmann, D. und van Dun, R. (2018), p. 199.

method (FEM), for example, is a process that is used as part of simulations for structural analysis and optimisation. FEM uses component areas to analyse the component's physical behaviour.[42] Virtual models facilitate and build on rapid prototyping (fast model construction) where CAD models and simulations are used in combination with additive manufacturing and/or 3D printers.[43]

When it comes to resource efficiency, in addition to avoiding physical prototypes and the related material use, digital prototyping provides insight into excess use of material which, in turn, allows companies to reduce weight and save raw materials. For example, this is the case where the FEM method is used to identify areas in components that would still meet the corresponding load requirements with reduced material use. Potential error sources can also be identified early on, meaning it is more unlikely that later adjustments are required.

In addition to the investment costs, one of the challenges is the correct training of the staff working on the digital prototyping. The aim of analysis and the data required for this must therefore be defined in detail, along with a description of the professional expertise necessary.

Digital prototyping does not end with the development of new products; it can also be used in production and manufacturing. For example, it can be used to simulate and optimise workflows in digitally mapped factories.

The following figure (Figure 10) is an overview of the important technologies and methods of digital prototyping in product development. It also shows which data is particularly important for integration into product development and what digital prototyping can do for resource efficiency. The terminology is explained in more detail in the appendix.

[42] Cf. Zwettler, M. (2020).
[43] Cf. Kirchner, E. (2020), p. 379.

Digital prototyping

Relevant technologies and methods

- Computer-aided Design (CAD)
- Computer-aided Engineering (CAE)
- Finite elements method (FEM)
- Flow simulation
- Augmented und virtual reality (AR and VR)
- Cloud computing
- High-performance computing
- Rapid prototyping
- Digital mock-up
- Simulation models

Important data and information

- Product requirements
- Technical drawings
- Material data
- Component data
- Material parameters
- Lab and test data

Possible contributions to resource efficiency

- Reduction of error rates
- Renunciation of physical products and sample tools
- Fast substitution test of sustainable materials
- Energy savings through reduced need for transport

Figure 10: Digital prototyping and the related themes (VDI ZRE illustration)

Real life example: Ottobahn GmbH in Munich, Germany

Founded in 2019, Ottobahn GmbH is developing a zero-emission, autonomous transport system. The system consists of a rail-mounted gondola cableway that moves five to ten metres above the road. Ottobahn engineers relied on data analysis, simulation and HPC solutions to determine the optimal chassis concept as early on as in the product development stage. Various concept models testing different vehicle dynamics and occurring forces were initially developed and compared using simulations. The company used the Altair start-up program for support, drawing on its various custom-made technology packages with professional consultation. To analyse the behaviour during track changes, Ottobahn carried out various multi-body simulations. This allowed engineers to quickly analyse the respective mechanics of the virtual prototypes, meaning the first results on the best vehicle models were ready to be presented after just one week. The early use of simulations in the development phase rendered physical prototypes redundant, while providing design engineers with a more extensive understanding of the system dynamics. This allowed engineers to make precise decisions early on in the development process. In addition, the use of external HPC solutions allows engineers to run highly complex simulations and calculations with high speed. The basis for this is provided by cloud services that offer an almost infinitely scalable computing capacity without requiring the company to have its own high-performance IT infrastructure. When combined with data analytics, companies can gain valuable insights from the processed data. Predictive analyses also allow companies to predict component deterioration or machinery failure, making it possible to ensure the best possible maintenance intervals and save resources.

Linking all three technologies has not only reduced development time, it also means products and systems can be developed in a more cost-efficient and sustainable/resource-efficient manner.[44]

Real life example: Sensitec GmbH in Wetzlar, Germany

Sensitec GmbH is a manufacturer of magnetoresistive sensor technology. The medium-sized company has used virtual prototyping as a core element of its development phase for over 15 years. Previously, the company had to manufacture multiple physical prototypes until it was able to meet the customer requirements. This is no longer necessary thanks to virtual product simulations. Today, the necessary sensor product samples are developed and simulated digitally using simulation software such as CAD and CAE. Any desired changes from the customer can be integrated into the simulation at any time prior to manufacturing the product sample. This reduces the number of prototypes required, saving both time and material/energy resources. The company implemented a PDM/PLM system to manage product data (incl. CAD data). This also allows data to be digitally exchanged with customers and suppliers, which helps to avoid potential error rates due to transfer errors or media disruptions.[45]

[44] Cf. Schneider, M. (2021), p. 36.

[45] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017), p. 110 et seqq.

3.3 Digital twin

Increased use of CPS and the integration of product development and productions into the IoT (cf. chapter 2.2) contains the potential to meet the need for increasing productivity, flexibility and configurability in industry. The promise of an adaptive and intelligent monitoring, control and influence of the physical world, however, also comes with a high level or complexity and significant challenges. One approach is the automation of the continuous synchronisation of the various digital components with the real-world counterpart. The digital components from the CPS with the described behaviour are called digital twins.[46]

In simple terms, a digital twin is the digital representation of a product instance (real devices, objects, machines or immaterial goods) with selected features, conditions and behaviour, which is then “fed” with real data.[47] However, the term “digital twin” can have different meanings both in practice and in science. A more precise distinction, for example, is made through the use of the terms “digital master” and “digital shadow”. Only together do these concepts make up a digital twin. The digital master refers to a digital geometry model or master data created at the start of development. The digital shadow, on the other hand, describes the data obtained and evaluated throughout the product’s life cycle.[48] For the purposes of simplification, this brief analysis does not explicitly differentiate between the terms.

In product development especially, the description of a digital twin overlaps with that of digital prototyping (cf. chapter 3.1). One core difference can be seen, for example, in the fact that a digital twin requires the existence of a real object. A digital twin can also be used in all phases of a product’s life cycle and developed at a later point for existing products. Other possible applications for a digital twin include:[49]

- **In product development:** digital product testing and simulations. Ideally, the digital twin can replace all physical testing, reducing development

[46] Cf. Klein, M.; Maschler, B.; Zeller, A.; Ashtari Talkhestan, B.; Jazid, N.; Rosen, R. und Weyrich, M. (2019), pp. 90 – 91.

[47] Cf. Wissenschaftliche Gesellschaft für Produktentwicklung (2020), p. 1.

[48] Cf. T-Systems International GmbH (2018).

[49] Cf. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft (2019), p. 26.

and implementation times. In this case, the technology can be consistent with digital prototyping. A digital twin can also serve as an interface to the customer, in the form of an exchange and testing platform for future functions, for example.

- **In production and supply chains:** simulation and improvement of production and supply processes. Ideally, processes can be simulated and calculated in real time or in advance as predictive simulations/calculations. In addition to digital product imaging, it is also useful to illustrate the production setting in the form of a digital factory. This makes it possible to identify potential error sources and faults in real processes at an early stage, increasing quality and efficiency and providing data for making strategic decisions.

- **For maintenance and disposal:** as a replica of a real product, the digital twin makes monitoring and maintenance easier. Ideally, a product's status (location, condition, performance, etc.) can be shown in real time. This information can then be used, for example, at the end of the use phase, to obtain information about the disposal or reusable components. A digital twin in the use and disposal phase can therefore form the basis for a PSS.

A comprehensive digital twin is most effective when created in parallel to the development of the physical product. Especially in the case of existing predecessor models, digital imaging can also be based on real data from installed sensors obtained as part of continuous analysis.[50]

A 2019 study by PricewaterhouseCoopers (PwC) was able to determine that digital twins are primarily used in the areas of product development and production. While 75% of the so-called digital champions in the surveyed group already use a digital twin, the number lies at 38% for so-called digital novices (cf. Figure 11). The study expected to see almost 60% of all surveyed companies using a digital twin within the company in 2021.[51]

[50] Cf. Grösser, S. (2018).

[51] Cf. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft (2019), p. 21.

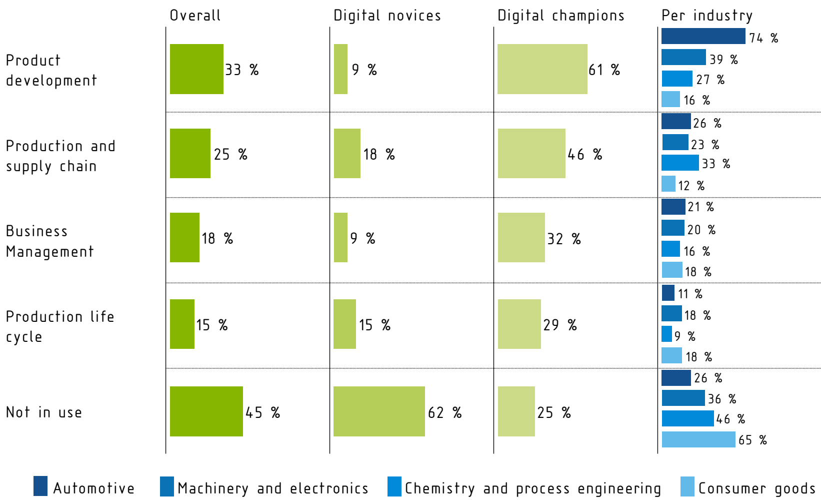

Figure 11: Use of a digital twin in various sectors[52]

From a resource efficiency standpoint, the advantages in product development often overlap with those of digital prototyping (chapter 3.1). The reason for this is the gradual transition from older sequences linked with material use towards more digital processes. In contrast to digital prototyping, however, digital twins can make use of a physical model. The hardware-in-the-loop process (HiL) is one possible form in product development. For HiL, components are integrated into a joint simulation environment with system models. This allows users to simulate an entire vehicle while only the control elements are physically connected, for example, reducing the need for time-consuming and complicated tests on the whole physical product.[53] Potential for resource efficiency comes from both the reduced need for physical prototypes (and related material use) and the ability to quickly identify areas of quality improvement or saving potential and save resources using simulations of future behaviour with aging or with certain material compositions.

[52] Own illustration based on PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft (2019), p. 28.

[53] Cf. Fraunhofer ITWM (2022).

Further potential for resource efficiency is also found in digital imaging as part of product development. However, they only become noticeable in the later phases of value added. As, ideally, a digital twin accompanies a physical product throughout the complete life cycle, these also make it easier to improve the product following the actual product development phase. The virtual accompaniment and simulation of a physical product allows for faster configuration on existing systems and quicker commissioning, for example.[54] Ongoing calculation of weak points and potential for optimisation in the use phase can also provide important findings for successor products and production processes retrospectively. And these “inherited” findings do not just help the development team; they can also give users indications of necessary maintenance, helping to increase the product service life and save resources.

Particularly complex simulations and calculations of digital twins require large quantities of (real-time) information here. Artificial intelligence (AI) therefore plays an important part in the use of digital twins and is simultaneously the biggest challenge for their implementation. Companies not only require the technical infrastructure along with extensive networking, computing power and consistent data management (cf. chapter 3.1), they also need specially trained staff to be able to tap into the potential. The role of AI in product development is looked at more closely in the next section (chapter 3.4).

[54] Cf. Klein, M.; Maschler, B.; Zeller, A.; Ashtari Talkhestan, B.; Jazid, N.; Rosen, R. und Weyrich, M. (2019), p. 91.

Digital twin

Relevant technologies and methods

- Digital shadow
- Internet of Things (IoT)
- Data analytics
- Machine data collection (MDC)
- Manufacturing execution system (MES)
- Augmented and virtual reality (AR/VR)
- Mix Sigma
- Prototyping
- Hardware-in-the-loop (HiL)
- Software-in-the-loop (SiL)

Important data and information

- Simulation data
- Material data
- Quality data
- Damage analysis
- Customer feedback
- Lab and test data
- Data on environment

Possible contributions to resource efficiency

- Fast calculation of potential error sources and potential for improvement
- Precise statements on actual behaviour throughout entire product life cycle
- Savings on physical prototypes and tools
- Tests of possible substitutes
- "Inheritable" knowledge for successor products
- Resource-efficient implementation of ideas due to digital test series

Figure 12: Digital twin in product development and the related themes (VDI ZRE illustration)

The above figure provides an overview of the important technical characteristics and methods associated with a digital twin. It also aims to show which data is important for integration into product development and what a digital twin can do for resource efficiency. The terminology is explained in more detail in the appendix.

Real life example: Veka AG in Sendenhorst, Germany

Based in North Rhine-Westphalia, Veka AG manufactures PVC profiles for window and door systems. A suitable tool must be constructed before a new profile can be produced. Traditional development methods for tool shapes are time-consuming and require a lot of resources. To develop optimal profiles with the desired quality, the company must test physically manufactured tool heads multiple times. Up to ten tonnes of PVC is used during the test phases. Although it is recycled, the recycling process itself is very energy-intensive. Using digital models in the form of a digital master can help here. For this purpose, the tool heads are virtually represented using CAD data of the real tool. It also gives the company the option to validate new concepts and ideas and understand process functions better using digital prototypes. In addition, lengthy test phases are eliminated as the product can be optimised on the computer using simulations, reducing the company's material use by 50% and saving 1,000 kWh annually. This equates to 408 kg CO_2 equivalents.[55]

Real life example: Knorr-Bremse Systeme für Schienenfahrzeuge GmbH in Munich, Germany

As a global supplier of braking systems for rail and utility vehicles, Knorr-Bremse Systeme für Schienenfahrzeuge GmbH has already tapped into the potential of Industrie 4.0 The company uses virtual tests to precisely simulate everything that would otherwise be tested on the test benches at the company's development centre in Munich – but with one crucial difference: the computer analysis is carried out using a digital twin. This is a significant component for identifying error sources and areas for saving energy and material early on in the development phase. Virtual testing with a digital twin also significantly reduces the number of tests that a product must go through on a test bench. The product optimisation makes it possible to use more lightweight components which, in turn, leads to cost and material savings.[56]

[55] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021a).

[56] Cf. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft (2019), p. 36.

3.4 AI in product development

The described networking in Industrie 4.0, established using sensors and actuators in new and existing products (cf. chapter 2), makes it possible to collect large quantities of data, and often in real time. These data quantities also come under the term “big data”. Big data can be seen as a resource that is automatically processed to obtain beneficial, fail-safe and high-quality “smart” data. The use of big data is on the rise in Germany and worldwide: in 2017, a fifth of German companies were already using big data in at least one company department. Smart data solutions are expected to generate 85 billion euros in revenue by 2025.[57]

The characteristics of big data, namely the volume, speed and diversity, quickly push traditional analysis methods to their limits. This is where artificial intelligence (AI) comes into play: using AI, application problems can be rectified using computer programs whereby the AI systems are able to self-optimise using algorithms and data. Typical task areas include classification, segmentation and regression. Through these tasks, companies can automate application fields such as cause analysis or text/image comprehension. AI thus offers the potential to fix certain problems that have only become pos-sible due to the provision of very large quantities of data.[58] A typical example of this is facial, object or voice recognition.

The implementation of artificial intelligence in industry can be considered one of the biggest tasks in the present and is promoted by the German Mit-telstand-Digital (English: *Digital SME*) network and the Federal Ministry for Economic Affairs and Climate Action. Even where implementation measures must be adapted to the respective circumstances, there are fundamental rec-ommended actions that can be useful when using AI:[59]

- Existence of a database and data processing systems (cf. chapter 3.1)
- Use of existing AI solutions

[57] Cf. Bundesministerium für Wirtschaft und Energie (2017), p. 3.
[58] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021b), p. 15.
[59] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021b), pp. 144-145.

- Expansion of IT infrastructure
- Demos or pilot projects for growing acceptance and building know-how
- Use of standardised interfaces and open-source solutions
- Completion of a feasibility study
- Development of a strategy/roadmap to implementation

In the VDI ZRE study entitled “Potential of weak artificial intelligence for operational resource efficiency” (German: *Potenziale der schwachen künstlichen Intelligenz für die betriebliche Ressourceneffizienz*), VDI was able to determine that companies already using AI are seeing benefits primarily in the areas of “error detection and prediction” (41.9% of companies surveyed), “production process optimisation” (38.7%), “product development process optimisation” (38.7%) and “product optimisation” (35.5%).[60] As motivation, the surveyed companies cite the reduction of costs (25.7%), improvement in quality (22.9%) and the incentive to design sequences more time-efficiently (20%). The increase in resource efficiency is often considered to be a positive secondary effect.[61]

The use of AI in product development also increases the potential to use material and energy resources more effectively and sustainably and reduce product development time. This, in turn, usually also results in increased resource efficiency. AI integrated into product development can obtain data using digital twins or prototypes, for example, and then use this to carry out calculations and simulations. The great potential for new and more efficient products lies largely in the ability to perform fast, simultaneous calculations of scenarios and the resulting recommended actions. The opportunities for resource efficiency created through digital prototyping (chapter 3.2) and digital twins (chapter 3.3) are therefore closely linked with the potential created through AI, relating largely to error prevention and quick decision-making through simulations.

[60] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021b), p. 48.
[61] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021b), p. 59.

The expected increase in AI in all areas of value added will also increase resource efficiency potential in product development. The further opportunities below can also be expected following the implementation of AI and can also have an impact on product development:

- **AI in communication:** AI has the potential to automatically record customer requirements and draw on conclusions from these. Development teams can use information from the use phase to help bring successor products to the market more quickly or make subsequent adaptations. Potential for resource efficiency also arises as a result of reduced development times, shorter test loops or, in the case of product adaptations, longer use phases as companies are able to implement customer requirements and demands with more precision.

- **AI and human intelligence:** In the long-term, we can expect to see AI becoming able to calculate and simulate more and more detailed human behaviour due to its ability to learn. For product development, this will give rise to new opportunities, in particular in the testing phases. This also means that the necessary safety tests in relation to human behaviour can also be calculated digitally in various scenarios going forward, even before any actual prototype is used. Potential for resource efficiency would arise here through reduction of material and faster error adaptation, for example.

- **AI in production and logistics:** Potential for efficiency through AI, such as automated production steps, adaptations or deliveries, requires sensor, actuator and computer interfaces. The resulting opportunities for resource efficiency, through the reduction of errors, for example, are therefore also closely connected to product development. This phase decides in which form and with which interfaces new products will interact in the Internet of Things.

AI in product development

Relevant technologies and methods

- Machine learning
- Predictive analytics
- Data analytics
- Internet of Things (IoT)
- Big data and smart data
- Cloud computing
- High-performance computing
- Fuzzy systems
- Artificial neural networks
- Metaheuristics
- Support vector machines

Important data and information

- Product requirements
- Component data
- Material data
- Use data
- Data on use environment
- Damage analysis

Possible contributions to resource efficiency

- Precise prediction of material behaviour
- Fast calculation of potential error sources and potential for improvement
- Precise statements on actual behaviour throughout entire product life cycle

Figure 13: Artificial intelligence in product development and the related themes (VDI ZRE illustration)

The figure above (Figure 13) provides an overview of important technical requirements and methods for AI in product development. It also aims to show which data is important for its implementation in product development and what AI can do for resource efficiency.[62] The terminology is explained in more detail in the appendix.

Real life example: BBM Maschinenbau und Vertrieb GmbH in Langenberg, Germany

BBM Maschinenbau und Vertrieb GmbH is a the medium-sized company that produces extrusion blow moulding machines for manufacturing vari-

[62] You can find basic information on AI and resource efficiency in the study entitled "Potential of weak artificial intelligence for operational resource efficiency" (German: *Potenziale der schwachen künstlichen Intelligenz für die betriebliche Ressourceneffizienz*). You can access the study (in German) using the following link: https://www.ressource-deutschland.de/publikationen/studien/

ous plastic hollow profiles such as cans, drums or even parts for the automotive industry. To increase plastic recycling, the extrusion systems are designed to enable increased use of recyclate material. For this purpose, the company utilises the advantages of artificial intelligence in combination with a digital twin. With the help of an IT company, the spiral distributor – the tool that mixes the recycled and new plastic together – is first simulated with a digital twin. AI is used to optimise the process in line with the evolutionary principle of “survival of the fittest”. Here, the AI software designs various different versions of spiral distributors in the first step. The manufacturing process is then simulated with each version. The top 30% of the versions that allow the most recycled material to be used are selected based on the simulations. These then form the “new generation”. The AI software analyses the construction of the selected versions and attempts to find regularities to explain why these versions are the best. This analysis is then used to create new digital twins for the spiral distributors. The process is repeated as many times as needed (usually around ten generations) until the optimal spiral distributor can be developed and put into practice. Using this principle, the company has been able to increase the amount of recyclate used in the development of new plastic drums to up to 85%.[63]

Real life example: it’s OWL technology network in Ostwestfalen-Lippe, Germany

The problem with artificial intelligence is that the lack of resources and expertise limit its use in producing companies. Solution providers, on the other hand, lack access to customers and the necessary specialised knowledge. In light of this, the it’s OWL technology network developed the so-called AI marketplace – a digital platform that allows customers, solution providers and experts to develop new AI solutions and exchange ideas. Even company-specific challenges can be solved together with suitable solution providers. The aim of the AI marketplace is to support medium-sized companies in particular in implementing AI in product creation in a way that’s profitable. For example, an agricultural machinery

[63] Cf. VDI Zentrum Ressourceneffizienz GmbH (2021a).

manufacturer can use the digital platform to integrate artificial intelligence in CAD applications with the aim of making product development more efficient. The project is funded by the Ministry for Economic Affairs, Innovation, digitisation and Energy (German: *Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie*) of the State of North Rhine-Westphalia.[64]

3.5 Agile product development tools

Agility in product development means moving away from linear processes towards more flexibility and proactive, anticipative action. From an academic standpoint, the aim of agile product development is to reshape existing organisations in the interest of gaining more competitiveness. Originally used in software development, this approach is gradually gaining traction in the manufacturing industry as part of the rise in digitisation. It is becoming more and more commonplace for more durable physical products to be sup-plemented with apps or software, particularly as part of PSS (cf. chapter 4), and these apps/software must be adapted at shorter intervals.[65] Advances in the area of communication with customers, where AI or VR technology also play an important role, mean that customers are becoming able to engage in the development process earlier and do so more effectively. In this case, agile tools can therefore be used to efficiently manage this exchange and the de-velopment process.

The fundamental challenge lies in the rethinking and adaptation of existing structures, concepts and systems for agile product development. This approach has led to the following findings:[66]

- Aspects such as quality, purchasing and management must be subordinate to the development process for a successful organisation.
- Product development is subject to various uncertainties and cannot be fully planned. Transparency and early error reporting are the foundation for agile product development.

[64] Cf. it's OWL Clustermanagement GmbH (2021).
[65] Cf. Welte, O. (2020), p. 50.
[66] Cf. Pfeffer, J. (2019), p. 30.

- Innovation comes from people and so processes must be oriented towards people. The continuous improvement of workflows creates the competitive edge.

Practical experience shows that any introduction to agile product development is best done gradually. It is therefore recommended to start with projects that can be isolated from in-house structures and hierarchies. The responsible team should have extensive skills to carry out the project from product planning all the way to marketing of the product. Value stream mapping must be carried out before agile development projects to analyse the previous development process. This analysis looks at all process steps and reviews their necessity and time requirements in order to minimise usual idle times. The aim here is for the team to create an initial usable prototype more quickly than before.[67]

Potential for resource efficiency from agile product development is largely indirect, with agile product development promising opportunities through faster target setting and risk minimisation. If the desired end results are achieved earlier, this can lead to resource savings, for example, as it allows for shorter test and adaptation cycles. This interactive approach can also minimise the risk of not taking into account the needs of the sales team and customers in the development process. Costly and resource-intensive adjustments to the end product can also be avoided.[68] A fast and continuous further development and modification of software on existing objects also contains the potential to increase the service life and thus save resources. For example, if software updates can be used to meet requirements that only arise later in the use phase, objects or components then need to be replaced less frequently.

Figure 14 summarises the important aspects of agile product development and shows how this can increase resource efficiency. The terminology is explained in more detail in the appendix.

[67] Cf. Welte, O. (2020), p. 50.
[68] Cf. Stüdemann, J. (2020).

Agile product development tools

Relevant technologies and methods

- Enterprise mobility management
- Open innovation framework
- Configure-to-order production
- Customer relationship management (CRM)
- Predictive analytics
- Fuzzy systems
- Artificial neural networks
- Metaheuristics
- Support vector machines
- Scrum in product development

Important data and information

- Product requirements
- Design sketches
- Material selection
- Target group feedback
- Quality data
- Damage analysis

Possible contributions to resource efficiency

- Resource savings thanks to faster target setting
- Resource savings thanks to fewer test and adaptation cycles
- Risk minimisation for subsequent resource-intensive adaptations of products

Figure 14: Agile product development tools and the related themes (VDI ZRE illustration)

Real life example: agile transformation for agricultural machinery manufacturers

The development of agricultural machinery is complex from both a technical and organisational standpoint. Due to some negative experiences in previous product development projects, an agricultural machinery company therefore chose to switch to the agile scrum method for the development of a new planting machine. Working together with a consultancy firm, as a first stage, the company held an internal “Agile Awareness Day” to create awareness of what impact the pilot project would have for the company and top management. Project teams were then put together and introduced to the iterative approach for scrum. In an additional step, modules and functional component groups were set up to simplify the project. As the development meant those involved had little time for other duties, a communication concept as also developed. Ultimately, the originally set deadline for completion only had to be delayed by six months. The company was also able to determine that project members identified with the project and the new way of creating the product much more than before due to agile working. Going forward, the company is therefore planning to continue to use agile methods and hybrid structures.[69] The reduced deviation from the actual deadline of the development project makes clear the potential for resource efficiency. It appears that, in the example presented, the project communication and modularisation in particular have led to more precise work instructions which, in turn, helped to avoid errors. Specifically the reduction of test and adaptation cycles as part of development also shows lots of potential for savings from a resource efficiency point of view.

Real life example: KION Group in Frankfurt am Main

The KION Group is a supplier of industrial trucks and provides the related services. To search for new ways of thinking and working for innovative solutions, the company opened a digital campus in Frankfurt am Main. The campus is a place for teams to work together across disciplines, combining agile development methods such as design thinking and digital technologies. The focus here is on creating the best possible value for the customer and ensuring the sustainability of the digital solutions. Agile solution approaches allow the company to be more adaptable, especially in times of constant change. To do so, data scientists, product managers and engineers analyse large quantities of product configuration data using data analytics, which has some decisive advantages in product development. For example, decisions can be made earlier in the development phase and requirements can be determined exactly, reducing the expense of unnecessary material use and increasing resource efficiency. Here, developers go one step further and make use of modern big data and analytics technology to predict operating costs for leased products, taking into account variant features and environmental impacts.

One of the first digital solutions developed is a chatbot app for service engineer staff that allows users to identify the cause of errors more quickly and more efficiently. The recorded error data also helps to optimise new products and design processes more efficiently.[70]

[69] Cf. Rosenkranz, C. (2021).
[70] Cf. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft (2019), p. 36.

4 DEVELOPMENT OF PRODUCT-SERVICE SYSTEMS

Product-service systems (PSS) combine physical products and services (cf. chapter2). This combination makes it possible for companies to expand their own portfolio and thus react to trends such as shorter product life cycles. Services integrated into a product not only create the desired added value for customers in the later use phase, they also act as a communication tool between the developer team and the customer. Digital technologies such as VR goggles or digital prototypes also allow customers to be integrated into the development process early on, making it possible to apply and implement wishes and suggestions for improvement more cost-efficiently than at a later point in time. From a resource efficiency standpoint, the added precision in this exchange allows for a clear definition and more effective implementation of these wishes in the product development, avoiding the need for later resource-intensive adjustments.

All digital technologies presented in chapter 3 require and generate information and can also serve as the basis for or a component of interaction with other technologies and tools. Services in the industrial sector are often linked with both the analysis and evaluation of data arising within the area of value added as well as the communication of company organisations with customers. The digital technologies used for this therefore often come from the areas of data analysis or involve (project) communication tools. The huge demand for information technology in companies is also reflected in the growth rates. Between 2010 and 2021, revenue grew from 69 billion euros (2010) to 101.8 billion euros in Germany alone.[71]

To be able to offer customers products for which supplementary services form a part of the value added, development teams must create physical products that combine information and software technology with mechanical components. Possible supplementary services include remote maintenance services, for example, or simple object user change/allocation (sharing models). The development of PSS therefore has many similarities to the development of cyber-physical systems (cf. chapter 2.2), meaning models for developing CPS can also serve as models for PSS. The *VDI/VDE Richtlinie 2206*

[71] Cf. Statista GmbH (2021).

guideline describes the systematic development of CPS systems. The outline of this is presented below with an additional note on the potential for resource efficiency.

Blending the various disciplines together adds another level of complexity to the development of CPS and PSS. The guideline presents a V model (cf. Figure 15) that can support interdisciplinary collaboration using the holistic methodical approach. The core idea of the V model involves breaking the system down into individual functions and then gradually integrating subsystems and elements with constant validation (question: “have we developed the right thing?”) and verification (question: “have we developed correctly?”). The guideline does not represent any single digital technology, although it can serve as a development methodology for coordinating those involved in product development and the digital technologies used. Instead, the guide-line seeks to provide guidance to help companies derive company-specific approaches for real-world tasks.

The V model outlined in Figure 15 has three strands. The outer strand represents the model design and system development that runs alongside the core tasks of product development. The middle strand outlines the core tasks of system development, and the inner strand represents requirements devel-opment. The starting point for the sequence is a customer need or the busi-ness model resulting from this need, or the development order. Following the decomposition (left side), implementation (bottom) and integration (right side) processes, system development ends with the handover. The six control points in the figure represent the progress of the system being developed and help the development team to reflect on the stage of development. The control points should not be seen as milestones or points in time in ap-proval.[72]

The important contents of the V model control points are summarised below. The aspects of resource efficiency can also be considered in the individual areas here.

[72] Cf. VDI/VDE 2206:2021-11, p. 24.

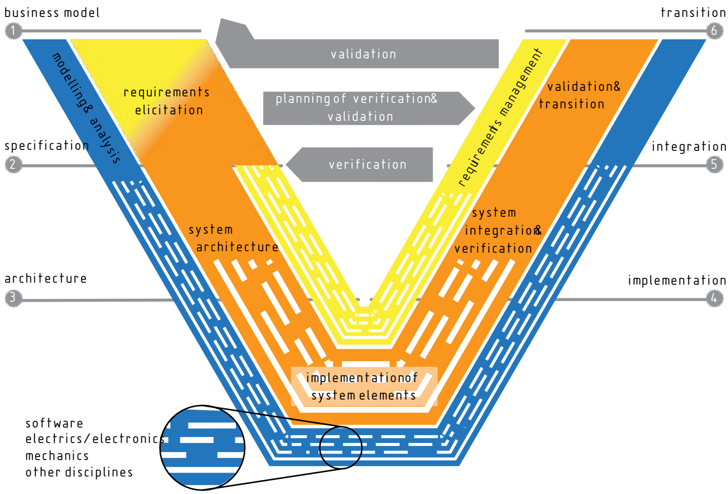

Figure 15: The V model as PSS development model[73]

(1) **Business model**: The creation of new values requires the inclusion of all company organisations. For development teams, the connection to strategic planning and both upstream and downstream chains should therefore be analysed in the first control point.[74] From the perspective of resource efficiency, this allows companies to check whether recycled materials or components from remanufacturing can be used for the product being developed, for example.

(2) **Specification**: The quality criteria for a specification are clarity, accuracy, completeness and consistency. For specifications, development teams should check to ensure that all requirements are formulated clearly and are complete and measurable.[75] Precision in specifications can also help to clearly define and communicate guidelines on resource

73 VDI/VDE 2206:2021-11, S. 22. Figure reproduced from [43] with permission of the Association of German Engineers (VDI e. V.)

74 Cf. VDI/VDE 2206:2021-11, p. 24.

75 Cf. VDI/VDE 2206:2021-11, p. 26.

efficiency (e.g. in acc. with VDI 4800 Blatt 1) and other ecological aspects.

(3) **Architecture**: This point should support users in reviewing the status of development. Significant questions therefore relate to interfaces and subsequent networking in the Internet of Things.[76] The potential for resource efficiency in this area comes primarily from networking. Using strategic interfaces in the Internet of Things (IoT) allows errors for future objects to be properly identified and communicated, minimising downtime and saving resources.

(4) **Implementation**: Questions relate to the correct implementation of system elements. Here, aspects such as the security of IT systems or the standardisation of exchange protocols are relevant.[77] The digital technologies outlined in chapter 3 are inherently associated with the area of implementation.

(5) **Integration**: This control point seeks to assess the technical implementation and quality of the system (e.g. queries about concrete implementation and completed tests in the system levels).[78] Questions and communication on the topic of error prevention and quality can also help improve resource efficiency.

(6) **Handover**: Here it is ensured that the entire system has been fully documented and an error-free handover can be guaranteed. The complete documentation can also form the basis for any offered training packages to ensure the system is used correctly later. This, in turn, prevents errors and preserves resources.

Further potential for resource efficiency can arise in PSS throughout the complete value-added chain. While services ranging from maintenance packages to sharing models all contain potential for an extended service life, for engineers, they also provide opportunities at the end of the use phase thanks to a clear recovery structure. If an object is returned to the manufacturer after

[76] Cf. VDI/VDE 2206:2021-11, p. 30.
[77] Cf. VDI/VDE 2206:2021-11, p. 32.
[78] Cf. VDI/VDE 2206:2021-11, p. 34.

use without the user needing to dispose of these, a large quantity of disposed objects of the same type can be expected. This simplifies both component recycling processes and reprocessing processes. From a product development point of view, companies can take advantage of the guaranteed recovery of objects and consider old components for new products to gradually use these parts up. Used components have already proven their suitability in practice which could potentially translate into a need for fewer test cycles when implementing these again. PSS can facilitate a circular economy in this way.

The following figure (Figure 16) provides an overview of important technologies and methods for developing PSS and the relevant data and shows the potential that PSS have for resource efficiency. Further development approaches and information on PSS can also be found on the VDI ZRE website.[79] The terminology is explained in more detail in the appendix.

Development of PSS

Relevant technologies and methods

- V model
- System map
- Blueprinting
- SWOT analyses
- Checklists

Important data and information

- Target group feedback
- Product requirements
- Usage behaviour
- Data from digital twins

Possible contributions to resource efficiency

- Offer of resource-efficient PSS revenue models
- Reuse of same-type products at EoL through recovery guarantee
- Long-lasting products through adaptation of integrated services without replacing product

Figure 16: Product-service systems and the related themes (VDI ZRE illustration)

[79] Further information on PSS available at: https://www.ressource-deutschland.de/themen/pss/

Real life example: Walther Flender GmbH in Düsseldorf, Germany

In addition to supplementary services offered in the use phase, services can also improve product development. This is the case, for example, when customers are more deeply involved in the development process.

Specialising in drive technology, Walther Flender GmbH has an extensive portfolio of motors, transmissions, clutches, belt drives and machine casings. The company also offers services through the entire product development process, allowing it to create customer-specific prototypes when designing tooth belt drives, for example. Here, the customer can have a say on what kind of prototype is made – from simple visual samples to functional prototypes that take into account tolerances. The company also offers a timing belt pulley online configurator that allows customers to design their own drive belts with a wide range of important parameters to choose from, including profile, division, number of teeth, width, material, drilling holes, etc. The end 3D CAD model and associated product data sheet can then be downloaded and used as a specification drawing as part of the enquiry. All of these measures remove the need for time-consuming, material test prototypes, reducing the consumption of resources and increasing efficiency.[80]

[80] Cf. Hochschule Pforzheim (2021), p. 6.

5 CONCLUSION

Digitisation and the subsequent networking of machines, people and company organisations will continue to increase in the coming years. The rise in complexity that this brings with it, paired with a general public demand for more environmentally friendly products and value-added chains, as well as an increased innovation pressure, will pose huge challenges for developers. Digital technologies offer the potential to stay on top of these challenges and also promise to increase resource efficiency (and overall efficiency in a more general sense) in product development.

Various advances in digitisation are leading to a diversified starting point with a wider, more diverse range of digital technologies available to use. The potential for efficiency that has grown as a result of this digitisation eco-nomically driven, but it can also have a positive impact from an environmen-tal point of view. The huge opportunities for resource efficiency come largely from the ability to record data more effectively and process this data in all phases of value added. This gives developers access to more precise usage behaviour, for example, and allows them to use these findings to create new products where objects are connected to one another via the Internet of Things. Technologies such as digital twins also allow developers to use data and information generated during the product development phase to achieve the desired result more quickly thanks to complex simulations. Fewer mate-rial test cycles, error prevention and more precise calculations on savings therefore represent the biggest opportunities for a greener industry.

In addition to the potential within product development, there are also tech-nologies, primarily in the area of services, that have a noticeable ecological impact throughout the entire value-added chain. So-called PSS offer services alongside physical products which, in turn, allows for a longer use phase and higher recovery rates. PSS, however, are not only attractive in an ecological sense – they can also help to expand a company's revenue model. More sta-ble recovery rates give development teams the chance to use tried-and-tested components in new products, paving the way for an improved circular econ-omy. Due to the complex interaction of various technologies and developers when creating a PSS, guidelines such as VDI/VDE 2206 can provide useful guidance.

When it comes to implementing digital technologies into product and service development, a gradual approach is recommended for companies. To start, businesses should clearly define which targets can be met by implementing digital technology. It is also important here to review the personnel and infrastructure requirements that need to be met. From both a business and ecological standpoint, it is therefore worthwhile for companies to gather, archive and manage all data relating to added value with as much precision as possible. These PDM systems are not only a helpful basis for the other technologies introduced; they can also serve as the foundation for an ecologically sensible digital product passport or PLM system (cf. chapter 6.1) that a company may want to set up in the future.

In addition to ensuring consistent data management, companies must also consider data security as the scope of data collection increases and the types of data become more diverse. Cooperation with external groups of experts can be beneficial with regard security issues and can help when it comes to analysing and evaluating the arising data. The interaction of the necessary infrastructure and available knowledge is vital for using the introduced technologies equally for the purposes of resource efficiency.

6 OUTLOOK

As outlined in the previous chapters, the networking of product and service development will become more and more commonplace as a result of digitalisation. The growing number of groups and company organisations that this potentially involves also increases the complexity, with the promise of all newly developed technologies also containing the promise of efficiency – something that is very appealing from a resource efficiency point of view. Only in rare cases should the digital technologies presented in this brief analysis be considered as standalone solutions. Instead, these technologies should be considered as subcomponents[81] of one joint network, with the aim of supporting developers to adapt and newly develop products.

As digitisation continues to advance and environmental issues grow in relevance, the redesigning of entire company systems and the resulting prod-ucts to achieve more efficiency on the path towards a circular economy and resource efficiency is becoming a more common aspiration. In conclusion, therefore, two examples (PLM systems and digital product passports) will be presented whose significance can be very relevant to developers.

6.1 PLM systems

Shortened product life cycles and constantly changing market situations lead to a constant pressure for change. Product lifecycle management (PLM) is a company-wide management approach that is used to manage processes, business systems, product data and all persons involved throughout the products entire life cycle. The aim of this approach is to manage and prepare all arising information centrally and consistently. This is achieved using IT solutions called PLM systems (cf. Figure 17).[82]

The idea of the PLM approach is ensuring that all information throughout the entire product life cycle is only entered into the system once with all com-putable information being generated automatically. Therefore, in practice the vision of a complete PLM system comes with some significant hurdles. The networking of all existing tools used within the company (from ERP systems

[81] Other useful digital technologies include tools for more efficient communication or project management tools, for example.

[82] Cf. Stark, J. (2015), p. 1.

and CAD to PDM) leads to an exponentially higher number of links, and this quickly becomes impractical. A more realistic goal, therefore, can be to gradually establish an in-house PLM landscape in order to get closer to the ideal state. It is useful to formulate an initial operative target at the start of the gradual introduction of a PLM. The following targets can be helpful:[83]

- Implementation of a database-driven requirements management system
- Introduction of a document management system
- Creation of open, standardised interfaces for important tools
- Implementation of a central CAD data management system

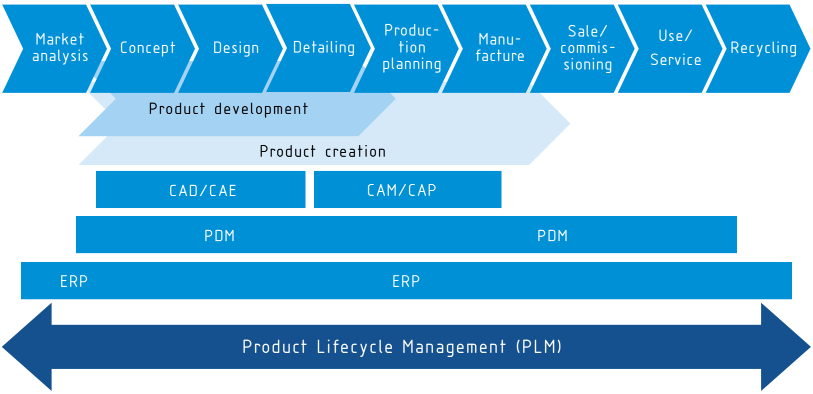

Figure 17: Integration of PLM in product life cycle and company IT landscape[84]

Ideally, new areas of implementation will arise as targets are implemented. In the case of the four named examples, this can be expanding the central CAD data management system to include configuration management.

As a basic principle, it should be noted that a PLM system must be created in line with the relevant circumstances in the company, similar to that of the development of PDM (cf. chapter 3.1). As implementing this fully in practice

[83] Cf. Digitized (2021).
[84] Own illustration based on VDI 2219:2016-09, p. 10.

is very complex, the potential contribution towards increasing resource efficiency can only be descriptive in nature. Possible tangible opportunities for a resource-efficient product development depend heavily on the respective connected digital tools within the PLM system. For example, if information from the LCA, such as CO_2 emissions for certain objects and processes, is provided throughout the entire system, this can make it easier to consider ecological factors in product development too. Working with the premise of only providing information once within the system and networking all stakeholders together, introducing PLM systems also promises to bring with it increases in efficiency due to the avoidance of errors and insufficient coordination between project teams and company organisations as described in the previous chapters. We can also expect to see companies using raw materials more efficiently and in a more targeted way as a result of better coordination.

Real life example: PLM approaches at Swedish company Electrolux

Electrolux is a global household appliance company. With lots of different customer requirements across more than 150 global markets, developing its products is not always easy. The company is able to rise to these challenges using various product development tools. By implementing an extensive PLM tool throughout the whole company, Electrolux was able to significantly increase efficiency in product development. Engineers can now exchange information with all Electrolux sites that are relevant for the development of products – from technical documentation and specifications to item acceptances, technical modifications and much more.

This basic technical framework with global and modular platforms helps the company to successfully translate product launches from one market to the next – with the necessary adjustments to fit the local preferences. Local engineers in each country can access digital images of Electrolux product models and convert these into specific models. Here, the digital images not only display all information on the physical properties of the product, they also contain information on any software that has been integrated into the product. Suppliers can also be integrated via the platform, meaning they get the latest information on all technical changes to keep them in the loop.

Electrolux is also working to develop the possibilities of this tool further. In addition to existing models for the product master, the company is also developing a prototype for a system that uses a "configurator" approach and creates a robust digital image that automatically replicates each warehouse unit. In doing so, this "super twin" can create an "overload" or "150% parts list" that can reflect all possible product variants and be directly fed into material requirements planning.

Because the described product images use the same PLM system as the digital twins from the Electrolux manufacturing sites, they can be seamlessly connected to the digital twins. This close integration increases efficiency in product development and production and helps the company to save costs while preserving resources.

According to the company's own estimations, these global and modular platforms can reduce the time from product development to the launch of a new product on the market by 20–30%. They also require 15–20% less investment. Electrolux believes that modular constructions allow for flexibility by giving designers and engineers the option to design products with a limited number of standard components in a way that ensures more individuality.[85]

6.2 Digital product passport

The digital product passport is a part of the digital agenda under new environmental policy and seeks to serve as a "digital CV". Digital passports are planned for all products and services with an initial focus on resource- and energy-intensive goods such as batteries. The aim is to create a dataset for every physical product that compiles all information on the components, ma-terials and chemical substances used as well as information on the product's repairability, replacement parts or proper disposal. To do so, just as for the PLM system, data must be collected from all stages of the life cycle so that it can be accessed when needed (cf. figure 18).

[85] Cf. PricewaterhouseCoopers GmbH Auditing firm (2019), p. 25.

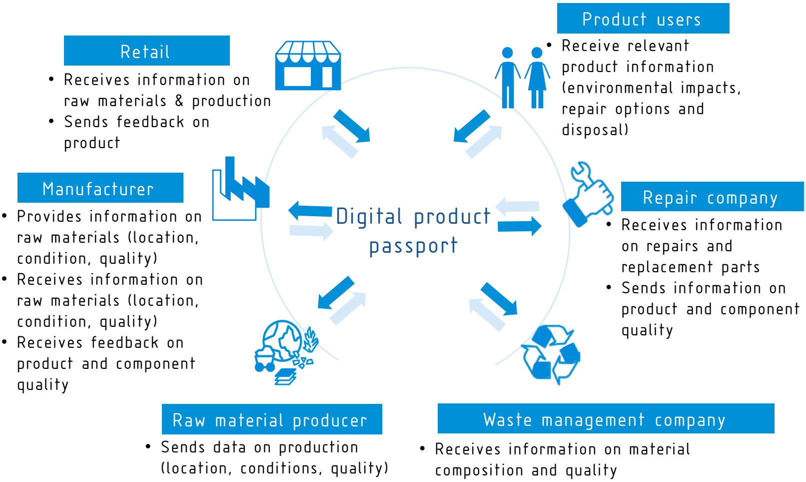

Figure 18: Concept of a digital product passport[86]

Structuring of environment-related data into a standardised, comparable format is intended to help all stakeholders in the value-added chain to promote a circular economy going forward. The resulting transparency should also allow for more sustainable purchasing decisions.[87,88]

Taking into account important interfaces for exchanging information using sensors, computers and a connection to the IoT ensures that future products meet the important requirements for establishing a digital product passport. From the perspective of sustainable product development, it is therefore important to recognise the future potential and significance of the digital product passport.

[86] Own illustration based on Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (2020).

[87] Cf. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (2020).

[88] Further information on the digital product passport can be found using the following link: https://www.bmuv.de/faqs/umweltpolitische-digitalagenda-digitaler-produktpass

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APPENDIX

Terminology	Description
ABC analysis	ABC analysis is a method for making decisions by grouping things into the categories "important", "less important" and "unimportant". The aim is to direct attention toward important points and set focus for further action.[89]
Advanced analytics	Advanced analytics involves a wide range of data processing tools that make it possible to predict future events. With advanced analytics, both structured and unstructured data can be evaluated automatically and projections can be modelled based on this data, allowing users to make decisions with increased precision and promoting proactive behaviour. This includes tools such as predictive analytics and machine learning, for example.[90]
Augmented reality (AR)	Augmented reality (AR) refers to the computer-aided imaging that combines real-world content and computer-generated virtual elements. The result for users is an "augmented reality". AR can be achieved using a smartphone, tablet, head-up display, holography system or AR goggles.[91]
Blueprinting	The service blueprint is a method designed for services which allows users to analyse, visualise and optimise service processes. The aim is to increase efficiency within the company by outlining the service to be rendered from the point of view of the customer, identifying needs for optimisation or allowing for a more customer-oriented design of new processes. A service blueprint is a process diagram that contains instructions for the interaction between customers, employees and various points of contact.[92]
Business Model Canvas	The Business Model Canvas, or BMC, is a template for visualising and structuring business models. It helps to condense the user's business model into one page by outlining the various areas of responsibility within a business model and listing the important issues for each area.[93]
Computer-aided x (CAx)	Computer-aided x (CAx) is a collective term for software applications that are used for various engineering tasks, e.g. modelling, calculations and simulations in product development. Here, the CA stands for computer-aided and the "x" is used as a placeholder for the different letters specifying the particular area of activity.[94]
Computer-aided engineering (CAE)	Computer-aided engineering (CAE) refers to the use of software to calculate, analyse and simulate products.[95]

[89] Cf. Gabler Wirtschaftslexikon (2022a).
[90] Cf. Gabler Wirtschaftslexikon (2022b).
[91] Cf. Gabler Wirtschaftslexikon (2022c).
[92] Cf. Finanzen.net (2022a).
[93] Cf. Existenzgründungsportal des BMWK (2022).
[94] Cf. Finanzen.net (2022b).
[95] Cf. Siemens.com (2022a).

Configure-to-Order (CTO)	CTO is a construction method where products are configured using a selection of predefined options. This means products are no longer developed on an entirely order-specific basis but are instead configured using all theoretically possible components or options.[96]
Chatbot	A chatbot is a digital dialogue system that is able to recognise text and voice messages and respond to them. It seeks to find suitable answers by searching through databases or on the internet or, alternatively, refers the user to the correct point of contact within the company.[97]
Co-creation	Co-creation refers to the integration of the customer into the product development/creation process.[98]
Customer journey map	A customer journey or user journey refers to the visualisation of the customer's path to their desired goal, containing all direct and indirect interaction points with the company. Customer journey mapping, in turn, shows the documentation process that a company goes through to visualise this journey. The aim is to develop an understanding of the customer's wishes and needs.[99]
Customer relationship management (CRM)	Customer relationship management (CRM) refers to the comprehensive and systematic approach to planning, managing and executing all interactive processes with the customer in order to achieve optimal orientation towards the target group.[100]
Design thinking	Design thinking is a concept of creative problem-solving. The aim is to draw on various experiences, opinions and perspectives to find a solution. The first step involves collecting data on a target group. The goal here is to generate ideas from this data that can be used to quickly create and test prototypes. To start, the focus is much less on being perfect, instead encouraging users to experiment to gain new insights.[101]
Digital mock-up	A digital mock-up (DMU) is the creation of a virtual prototype in the CAD system that can be used to carry out various tests, simulations or animations.[102]
Ecodesign	Ecodesign is a design approach that seeks to reduce the environmental impact of a product throughout its entire life cycle through an optimised product design.[103]
Enterprise mobility management (EMM)	Enterprise mobility management (EMM) is used to manage mobile devices and mobile applications throughout the company as a whole. The aim is to integrate end users more productively into business processes, regardless of their location or device.[104]

[96] Cf. Siemens.com (2022b).
[97] Cf. Gabler Wirtschaftslexikon (2022d).
[98] Cf. Gabler Wirtschaftslexikon (2022e).
[99] Cf. Gabler Wirtschaftslexikon (2022g).
[100] Cf. Gabler Wirtschaftslexikon (2022f).
[101] Cf. Gabler Wirtschaftslexikon (2022i).
[102] Cf. MB CAD GmbH (2020).
[103] Cf. Lexikon der Nachhaltigkeit (2015).
[104] Cf. Vogel Communications Group (2020).

Enterprise resource planning (ERP)	The enterprise resource planning system (ERP system) is an interdisciplinary software solution that can be used to efficiently manage and plan all business processes within a company – from procurement, material requirements planning, production, development and HR to accounting and controlling.[105]
Finite element method (FEM)	The finite element method (FEM) is a computer-assisted process that numerically calculates the physical structure and behaviour or objects. The object is divided into finite and mathematically determinable elements or forms. This allows engineers to approximate even complex bodies with as much precision as needed. Connected to one another via nodes, the elements are given certain properties (physical parameters) for analysis. This allows engineers to then simulate the object's behaviour under various load conditions and boundary conditions. The FEM is used largely for stress and deformation analyses on solid bodies.[106]
Fuzzy systems	The basic idea of fuzzy systems lies in expanding the traditional two-valued modelling of concepts and properties such as 'big', 'fast' or 'old' in the interest of a gradual fulfilment. In concrete terms, it means that, for example, a person is no longer seen as big or not big. Instead, the person is allocated any real number between 0 and 1 as a quantification of size. While in the past vague, imprecise or uncertain information was rated negatively and attempts were made not to include such information as part of modelling where possible, fuzzy systems consciously make use of this information, leading to a generally more simple, easier-to-manage modelling that is more akin to human thinking.[107]
Cyber-physical systems (CPS)	CPS build on mechatronic or smart objects and consist of sensors, actuators, a user interface and functions that execute all data acquisition, processing and output tasks. They are therefore a core component of Industrie 4.0. For product development, the ability to record (real-time) data in the manufacturing or use phase provides findings on potential for product adjustments, for example by analysing problem areas or concrete usage behaviour.[108]
Kanban	Kanban is an agile working method developed by automotive manufacturer Toyota. It seeks to ensure a consistent rhythm for the production process, primarily helping to provide an overview of multiple tasks, some of which run simultaneously. This is achieved using a column form which originally featured three columns: to-do, work-in-progress and done.[109]

[105] Cf. Gabler Wirtschaftslexikon (2022j).
[106] Cf. Vogel Communications Group .
[107] Cf. Spektrum der Wissenschaft Verlagsgesellschaft mbH (1995).
[108] Cf. Gabler Wirtschaftslexikon (2022h).
[109] Cf. Dahler, J. (2019).

Artificial neural network	"Artificial neural networks are algorithms modelled on the human brain. This abstracted model of interconnected artificial neurons makes it possible to solve complex tasks from the areas of statistics, computer science and business using computers. Neural networks are a very active area of research and form the basis for artificial intelligence."[110]
Lean development	Lean development (also lean product development) refers to the application of lean principles (defining target group added value, identifying value stream (process optimisation), implementing flow principle (ConWIP), introducing pull principle, striving for perfection (Kaizen and/or continuous improvement process (CIP)) to product development as a precursor to lean production (see also Toyota production system). Lean development therefore involves the product creation process (PCP) directly upstream from production.[111]
Machine learning	Machine learning is a subarea of artificial intelligence (AI). It allows IT systems to identify patterns and contexts using databases and algorithms and use these to develop solutions. This automatically generates "artificial knowledge" from experience (data). The knowledge gained from the data can be applied to new, unknown datasets to make projections and optimise processes.[112]
Manufacturing execution system (MES)	A manufacturing execution system refers to an IT system used in a technical production process. Contrary to similar production planning systems (enterprise resource planning systems), an MES is directly connected to distributed systems of the process control system and allows users to manage, steer, monitor and control production in real time. This involves traditional data recording and processing, such as the recording of operation, machine and personal data, as well as all other processes that have a timely effect on the technical production process.[113]
Machine data collection (MDC)	Machine data collection (MDC) registers product and process data from a production machine automatically. The recorded information can then be further processed by the ERP, controlling or other systems.[114]

[110] Wuttke, L. (2022).
[111] REFA AG (2022).
[112] Cf. Gabler Wirtschaftslexikon (2022k).
[113] Cf. Siemens.com (2022c).
[114] Cf. GFOS mbH (2022).

Metaheuristics	"Metaheuristics are general (i.e. problem-independent) process concepts that draw on a subset of problem-specific heuristics that are managed based on intelligent principles in the search for almost optimal solutions within the solution space of a given problem." The "intelligent" attribute refers to the fact that the process obtains information about the solution space as part of the search and utilises the knowledge gained from this for further searches. By using metaheuristics, users seek to overcome the weaknesses of conventional heuristics, e.g. getting stuck in local optima. However, a metaheuristic only provides a problem-independent framework procedure to start with that must be fleshed out for use on a certain class of optimisation problems by embedding problem-specific components.[115]
Mix Sigma	Mix Sigma is an innovative method that combines statistical process analyses with new data processing and tracking technologies. The aim here is to provide all data on the exact state of individual components and ensure a supplementary assignment of a suitable counterpart. This allows users to optimise process steps and reduce production costs.[116]
Open innovation	The term open innovation is used to describe the "opening of the innovation process" in product development through coordination between the company and target groups. Open innovation seeks to integrate the customer into the idea generation and prototype development process.[117]
Predictive analytics	Predictive analytics is a forward-looking analysis method that creates projections of future events using historical data combined with statistical models. This allows companies to identify opportunities and risks in future business decisions.[118]
Rapid prototyping	Rapid prototyping converts objects from the CAx system into physical objects using additive manufacturing. The most important aspects of the process include: stereolithography, laminated object manufacturing, 3D printing, fused filament fabrication, selective laser sintering.[119]
Support vector machine	A support vector machine (SVM) is a mathematical method from the realm of machine learning. Using linear and non-linear object classification, SVMs make it possible to quickly analyse large quantities of data. A typical application for this is pattern recognition in machine learning procedures for computer programs.[120]

[115] Cf. Stickel, M. (2006), S. 63.

[116] Cf. Deutsche Gesellschaft für Qualität (2018).

[117] Cf. Gabler Wirtschaftslexikon (2022l).

[118] Cf. Gabler Wirtschaftslexikon (2022m).

[119] Cf. TWI Ltd (2022).

[120] Cf. scikit-learn developers (2022).

SWOT analysis	SWOT, an abbreviation of *strengths, weaknesses, opportunities and threats*, is an analysis of a company's internal activities. The results are first compiled in the form of an opportunity-threat catalogue and then compared with the strengths/weaknesses profile from the internal analysis.[121]
System map	A system map shows all the various parties involved in providing a service as well as their mutual connections (e.g. material, energy, information, money, document flows, etc.). This map makes it clear how various different service components and roles are interlinked and highlights important values.[122]
Virtual reality	Virtual reality (VR) creates a computer-generated and interactive virtual environment in real time that users can experience using VR goggles or other digital end devices.[123]

[121] Cf. Gabler Wirtschaftslexikon (2022n).
[122] Cf. Servicedesigntools.org (2007).
[123] Cf. Gabler Wirtschaftslexikon (2022o).

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