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Challenges of the integrative product and production system development

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Abstract

Shorter product lifecycles and a shift from mechatronic to cyber-physical systems are leading to greater product complexity. This complexity can be addressed by more intensive cooperation between product and production system development. Despite intensive development in recent years, these process models have not been able to establish themselves in corporate practice. Therefore, this paper analyses the existing integrative product and production methods to identify the reasons for their lack of use in practice. The analysis has shown that there are nine barriers.

Keywords: integrative development, production design, product development

1. Introduction

Continuous technological progress leads to the desire for increasingly shorter innovation cycles in the industry. (Dumitrescu *et al.*, 2021; Gausemeier *et al.*, 2019) At the same time, the products being developed are shifting from established mechatronic systems to complex cyber-physical systems. This results in a rising complexity in the product creation process. (Gausemeier *et al.*, 2019) The competitive pressure of the globalised market further intensifies these trends. This leads to different lead or test times between software and hardware, which is another challenge in the development process. To remain competitive, shorter product development times are needed to bring innovations to market faster. (Eversheim *et al.*, 2005)

The aforementioned challenges can be met through intensive collaboration between product and production system development. (Stoffels and Vielhaber, 2015) By conducting product and production system development in parallel and in close coordination, it is possible to achieve optimal development results that meet the requirements. (Gausemeier *et al.*, 2012; Stoffels *et al.*, 2021; Stoffels and Vielhaber, 2015) Parallelizing processes reduces development time, which can help counteract ever-shorter innovation cycles. (Eversheim *et al.*, 2005; Petersen *et al.*, 2014)

Due to their complexity, the processes of product and production system development are carried out using methodical procedures. (Gericke *et al.*, 2021b) This has been the background to the development of integrative approaches over the last couple of decades. In these approaches, the development of products and production systems is considered in close coordination with each other or as a holistic process. (Sinnwell, 2020)

However, these approaches have not yet taken hold in industry. Instead, product and production system development are still largely sequential and independent. (Ehrlenspiel and Meerkamm, 2017; Steimer and Aurich, 2016; Schäfer *et al.*, 2023)

This paper therefore analyses the reasons for the failure of integrative development approaches for product and production systems. To this end, the research design is first presented (chapter 2). This is followed by a more detailed discussion of the problem (chapter 3). Subsequently, selected literature review methods are presented (chapter 4). The reasons for the failure of integrative methods in practice are then presented (chapter 5). Finally, a conclusion is drawn and the need for further research is discussed (chapter 6).

2. Research design

The research design for this study is divided into two parts: an ***overarching*** and a ***specific research methodology***. The paper follows the ***overarching research methodology*** of the Design Research Methodology (DRM) according to Blessing and Chakrabarti. (Blessing and Chakrabarti, 2009) The research methodology is divided into four phases (1. research clarification, 2. descriptive study I, 3. prescriptive study, 4. descriptive study II). The first phase of the DRM has already been conducted as part of a systematic literature review (SLR) to identify various challenges of integrative planning. (Disselkamp *et al.*, 2023) The following research question was derived from the research clarification:

> ***What are the reasons for the lack of use of integrative methods in industrial product and production development?***

This paper presents the second phase of the DRMs, the first descriptive study, to gain a better understanding of the issues. Therefore, the existing literature will be analysed to answer the research question. The paper thus represents the first type of DRM.

The Webster and Watson approach was selected as the ***specific research methodology*** for the literature review. (Webster and Watson, 2002) A structured selection was conducted of literature on product development, production system development and integrative product development. A total of 25 sources were analysed as part of the literature review (some of the sources are presented in chapter 4). The papers were then analysed to identify the reasons for the lack of success of integrative approaches to product and production system development. The filtered challenges were enriched by expert interviews. The results of this analysis are presented in chapter 5.

3. Definition of terms

A definition and delimitation of terms is provided at the beginning of the paper. The product and production system development process are then described in more detail. Finally, the paper discusses collaborative working in the design process and describes integrative engineering. In the literature there are different definitions of the exact beginning and end of the product development process. In some publications the product idea is mentioned as the start of the product development process. (Abele and Reinhart, 2011; Ehrlenspiel and Meerkamm, 2017; Gausemeier *et al.*, 2012) Other Authors refer to product planning as the first process step. (Verein Deutscher Ingenieure e.V., 2019; Bender and Gericke, 2016) All references share the understanding that product development and production system development are both considered as part of the product creation process. Therefore, for the purpose of this paper, the product creation process will be understood as a combination of both product development and production system development.

3.1. Product development

In VDI 2221 of the Association of German Engineers (VDI), product development is defined as a process in which a marketable product is developed in iterative steps on the basis of defined requirements and objectives. (Verein Deutscher Ingenieure e.V., 2019) Bender and Gericke describe this in terms of systems theory: the requirements as an input variable provide a product model or prototype as an output variable. (Bender and Gericke, 2016)

The product model contains the product characteristics, which are generally determined through the generation and processing of information. (Bender and Gericke, 2016; Verein Deutscher Ingenieure e.V., 2019) The classic activities of product development include the calculation and design of individual components, the overall development of assemblies and systems and the development of services. (Gericke *et al.*, 2021a) Development goals defined in advance, such as cost minimisation, a

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special focus on lightweight construction or the fulfilment of a specific function, must be taken into account. (Verein Deutscher Ingenieure e.V., 2019)

3.2. Production system development

In general, the term production system development encompasses the processes for designing production systems. (Gausemeier *et al.*, 2012) In some publications, production system development is also referred to as production system planning.

Various definitions of the term production system exist in the literature, as well as different views on which processes production system development comprises in detail. This paper is based on the definitions of Gausemeier and Plass as well as Cochran et al. (Cochran *et al.*, 2001; Gausemeier and Plass, 2014) Accordingly, the development of production systems includes the planning of workflows, workplaces and work equipment as well as production logistics and material flow planning. (Gausemeier and Plass, 2014) Consequently, the selection and arrangement of the physical components as well as the design of the work processes and material flow is the task of production system development. (Cochran *et al.*, 2001)

Thus, production systems include various elements and processes that transform knowledge and materials as inputs into the required products and residual materials as outputs. (Heinen *et al.*, 2008) Production system development is a subset of factory planning. This essentially includes building and site planning. (Sinnwell, 2020) The term factory planning is frequently used in the literature and is described in detail, for example, in VDI Guideline 5200 Sheet 1. (Verein Deutscher Ingenieure e.V., 2011)

3.3. Co-design and collaboration - Integrative development

The processes involved in product and production system development are generally highly complex. (Gericke *et al.*, 2021b; Helbing *et al.*, 2018) To meet this challenge, the development processes are carried out in an integrated manner using different methodological approaches. The collaboration between product and production system development has changed from a sequential to a parallel approach in the form of simultaneous engineering. This partial parallelisation of product and production system development shortens the time to production or time to market. (Bullinger *et al.*, 1995; Eigner and Stelzer, 2009)

Today, there are a large number of integrative methods that offer clear advantages over the sequential approach. (Sinnwell, 2020) However, various publications show that these have not yet been adopted in industrial practice. (Ehrlenspiel and Meerkamm, 2017; Steimer and Aurich, 2016; Schäfer *et al.*, 2023) Instead, the sequential approach or partial parallelisation in the context of simultaneous engineering is predominant. (Gräßler *et al.*, 2017; Graner, 2015) Thus, the development of products and production systems is performed independently by different specialist departments. Nevertheless, coordination between the disciplines is necessary because the product concept and the selected production processes influence each other. (Eversheim *et al.*, 2005; Gräßler *et al.*, 2017) The challenge is therefore to find out why the existing approaches are not being used in industrial practice. This helps to answer the question of how to organise collaboration between departments.

The difficulties that can arise when a non-integrative approach is used in the product development process are illustrated by Albrecht and Anderl. The development of a complex sheet metal structure is described in their paper. To cope with the complexity, the structure was mathematically optimised. The requirements and information from the production system development could not be considered in the algorithm used, which is why the sheet metal structure did not initially meet the requirements. Only after extensive iteration was it possible to adapt the sheet metal structure to meet the requirements. (Albrecht and Anderl, 2016)

4. Existing integrative development methods

A selection of the methods examined is presented below. A complete overview of the methods investigated is presented in Chapter 5.

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4.1. Simultaneous and concurrent engineering

Simultaneous engineering and concurrent engineering are two similar approaches. (Stoffels and Vielhaber, 2015) The idea of simultaneous engineering is to carry out two different processes in parallel and/or to overlap them. These processes can be, for example, product and production system development. Concurrent engineering, on the other hand, involves several people or departments working on individual, extensive tasks in parallel rather than entire processes. (Verein Deutscher Ingenieure e.V., 2019) Successful application of the methods leads to time and cost savings, which result on the one hand from parallelisation and on the other hand from the fact that fewer iteration loops and changes are required. (Ehrlenspiel and Meerkamm, 2017)

The main challenge in parallel work is the coordination and exchange of information between all parties involved. If the work is carried out in parallel, assumptions must be made about the product concept that has not yet been finalised. If the work only partially overlaps, it must be estimated when the product concept is sufficiently detailed to start designing the production system. (Verein Deutscher Ingenieure e.V., 2019) Successful coordination between the parties involved is therefore essential for the success of the processes and the prevention of errors that are costly to correct. (Ehrlenspiel and Meerkamm, 2017; Verein Deutscher Ingenieure e.V., 2019)

4.2. VDI Guideline 2206

The VDI Guideline 2206 provides a process model for the development of mechatronic products. The model - also known as the V-model - basically involves breaking down the product idea into individual system elements, working them out and then integrating them into an overall system. During this process, the development results are continuously validated and verified. The procedure is based on the phases of the product development process. The process begins with product planning and requirements definition. The system is then detailed in the individual disciplines and then verified and validated. Finally, the production system is developed. Development results should be continuously stored in a product model, e.g. using model-based systems engineering, according to the VDI guideline. (Verein Deutscher Ingenieure e.V., 2021)

The original version of the VDI guideline from 2004 also emphasises the exchange of information between the specialist areas. (Verein Deutscher Ingenieure e.V., 2004) However, no details for the cooperation between product and production system development are mentioned, which is why the version of VDI Guideline 2206 is described as insufficient in several publications. (Albers *et al.*, 2019; Gräßler *et al.*, 2017; Jürgenhake, 2017)

4.3. 4-cycle model

According to Gausemeier and Plass, the product development process should not be divided into a series of phases and milestones. Rather, it should be viewed as the interaction of different tasks. To this end, the authors group the product development process into three main tasks and divide these into three interdependent cycles. This categorisation is referred to as the 4-cycle model (Figure 1 focuses on the two cycles of product development and production system development.) (Gausemeier and Plass, 2014) (Gausemeier *et al.*, 2019):

Strategic product planning: This phase serves to determine the business and product idea.

Product development: The aim of product development is to develop a marketable product based on the product idea developed in the first cycle. Product development is divided into the tasks of product conceptualisation, design, and elaboration as well as integration into an overall system.

Production system development: The aim of production system development is to develop a production system that is optimally tailored to the product and other requirements. Similar to product development, production system development is divided into the tasks of production system design, work planning and integration into an overall system. Work planning is also subdivided into workflow, workstation, material flow and work equipment planning.

Service development: This phase transforms a service idea into a market service, considering different aspects and understanding service development as an interplay of tasks.

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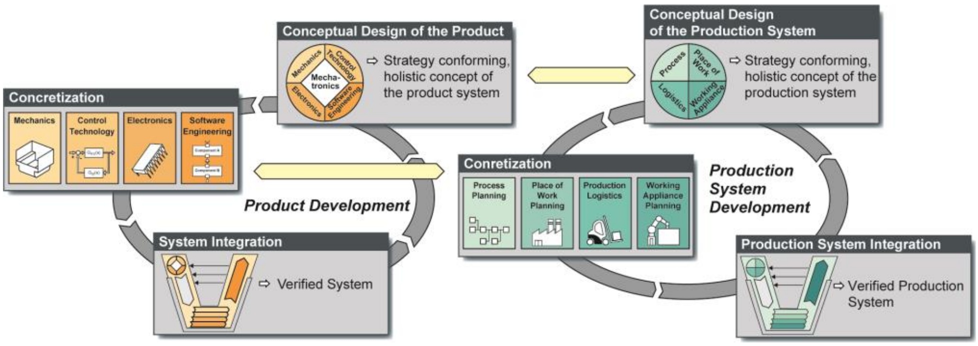

Figure 1. Extract from 4-cycle model of product and production development (Gausemeier *et al.*, 2019)

4.4. Method for production system design based on early product information

Sinnwell presents a model-based approach for the planning of production systems. (Sinnwell, 2020) It adapts and extends the model developed in the research project mecPro² which adapts and extends the concept of integrated development of cyber-physical products and production systems using Model-Based Systems Engineering (MBSE). (Eigner *et al.*, 2017) The main objective of Sinnwell's method is to integrate engineering processes at an early stage to improve mutual understanding based on a "common language". The concept comprises three main elements: a holistic process model for the development and design of products, a systematic methodology for the early design of manufacturing systems using a maturity model to evaluate early information about the product and an object-oriented modelling method. (Sinnwell, 2020)
The integrated process model follows the structure of the procedure described in VDI 2206 V-model (Figure 2). (Verein Deutscher Ingenieure e.V., 2004, 2021) It consists of a micro cycle and a macro cycle. The macro cycle is used for coordination. Cooperation and collaboration take place in the micro cycle. The phases of classical product and production system planning are retained but are part of the micro cycle. Each phase starts with at least one iteration of the micro cycle, as shown in the model cubes. The end of each phase is a milestone at which the intermediate stages of product and production system development must be validated.

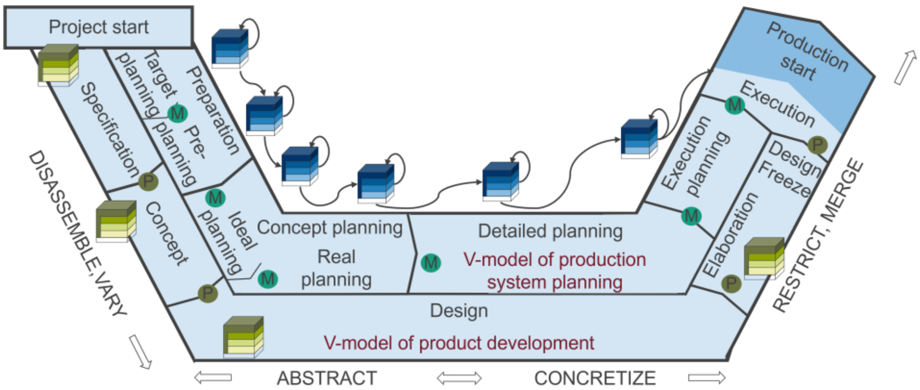

Figure 2. Integrative engineering process model (Sinnwell, 2020)

5. Findings

This chapter presents the results of the analysis of the papers reviewed (Table 1). The focus is on the barriers that limit the use of integrative product development approaches in companies.
Nine obstacles were identified based on an expert discussion with research and industry representatives, which are described in more detail below:

1. Insufficient consideration of integrative approaches in norms and standards.
2. Interfaces between product development and production system development unclear.

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3. Information management and organisational management only partially considered.
4. Lack of information provision from product development to production system development and vice versa.
5. Lack of consideration of the technical feasibility of integrative methods.
6. Lack of traceability: unclear effects of product changes on the production system.
7. Focus of existing methods especially on parallelizing processes with an exchange at the end of a development phase instead of interdisciplinary integrative cooperation.
8. Insufficient consideration of legacy from existing projects.
9. Cross-departmental values not considered.

Table 1. Reviewed integrative methods

Method	Identified barrier	Method	Identified barrier
(Albers *et al.*, 2022)	2, 5, 9	(Olsson, 1985)	3-6
(Albers *et al.*, 2019)	2, 6, 7, 9	(Schäfer *et al.*, 2023)	2, 8, 9
(Bender and Gericke, 2021)	2, 5-9	(Sinnwell, 2020)	2, 5, 8, 9
(Boothroyd *et al.*, 2010)	3, 6, 9	(Stoffels *et al.*, 2017)	2, 5, 7-9
(Brandis, 2014)	5-9	(Stoffels *et al.*, 2021)	5, 6, 8, 9
(Ehrlenspiel and Meerkamm, 2017)	6, 8	(Stoffels and Vielhaber, 2015)	2, 3, 5, 7-9
(Francalanza *et al.*, 2018)	3, 4, 7-9	(Stoffels and Vielhaber, 2016)	4-9
(Gausemeier *et al.*, 2011)	2, 6-9	(Stoffels, 2017)	6, 8, 9
(Gausemeier *et al.*, 2012)	2, 6-9	(Thompson *et al.*, 2018)	2, 7-9
(Gräßler *et al.*, 2017)	5, 9	(Verein Deutscher Ingenieure e.V., 2004)	1-3, 5-9
(Gräßler *et al.*, 2021)	2, 3, 7, 9	(Verein Deutscher Ingenieure e.V., 2021)	1, 2, 4-9
(Jacob *et al.*, 2018)	9	(Vielhaber and Stoffels, 2014)	3-9
(Kampker *et al.*, 2012)	4, 5, 8, 9		

The **insufficient consideration of integrative approaches in norms and standards** is particularly evident in the example of VDI 2206. The V-model according to VDI 2206 offers a rough guideline for the development process. (Verein Deutscher Ingenieure e.V., 2021, 2004) This initially includes very few links to production system development. Only the last checkpoint contains control questions on the transfer of information to production system development. (Verein Deutscher Ingenieure e.V., 2021) This research gap has been recognised and an extension of VDI Guideline 2206 to include further links between product and production system development has been proposed as having great potential for increased application of the method. (Gräßler *et al.*, 2021) At an international level, ISO 15288, for example, also shows that integrative development is not taken into account. (International Organization for Standardization, 2015)

Despite the large number of existing approaches, the **interfaces between product development and production system development are unclear** in many process models. Traditionally, the links between the areas are based on the requirements of the stakeholders and the assessment of manufacturability. In both cases, the designs of the product and the production system must be analysed and compared. (Stoffels and Vielhaber, 2015) One criticism is that some integrative methods only provide links in one direction, i.e. from product to production system development, but not vice versa. (Stoffels and Vielhaber, 2015) Furthermore, it is criticised that some approaches only contain trivial connections between product and production system development, but do not offer a fully integrative approach. (Stoffels and Vielhaber, 2015)

Information and organisational management are **only partially considered** in existing methodologies. This is particularly important because holistic information and organisational management of the processes involved is the basis for integrative product creation. (Eversheim *et al.*, 2005) This allows potential interdisciplinary problems and challenges, such as those arising from

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product development decisions in production system development, to be identified and addressed at an early stage. (Francalanza *et al.*, 2018)
Another barrier is the **lack of information provided by product development for production system development** and vice versa. There is a need for research into the transfer of information between the departments involved. The challenges are the sheer volume of information and the need to synchronise the IT tools of different departments. (Disselkamp *et al.*, 2023) Current advances in the area of collecting, processing and analysing data offer the potential to use larger amounts of knowledge. (Albers *et al.*, 2022) Added to this are the technologies summarised under the terms digital factory or Industry 4.0, which can counteract the lack of knowledge provision. (Francalanza *et al.*, 2018)
The **lack of consideration given to the technical feasibility of integrative methods is** another reason why they are not used in practice. It is therefore difficult to apply them in practice with a minimum of effort, as many companies require a high degree of customisation to establish the methodologies.
The lack of traceability in integrative product development also poses a challenge. It is unclear how **product changes** affect **the production system.** As a result, there is a risk that cross-connections will go undetected, resulting in a high level of rework.
The **focus of the existing integrative methods** is **on the parallelisation of product and production system development**. The work results are exchanged between the areas after the completion of defined development phases. This is particularly evident in simultaneous and concurrent engineering. (Stoffels and Vielhaber, 2015) In these methods, the integrative approach is achieved by overlapping the processes of product and production system development. (Gräßler *et al.*, 2017) Model-based approaches, which use overarching models for interdisciplinary collaboration rather than simply parallelizing processes, also exchange information after specified phases or leave the exchange of information open. As a result, both in product development methods and in industrial practice, the development of production systems is regarded as a process that follows product development and is carried out by a separate department. It is only in the final stages of the product development process that objectives or requirements for the production system are specified and, in some cases, the production process is defined in the form of work plans. (Gräßler *et al.*, 2017) (Gräßler and Yang, 2016)
In addition, the current integrative approaches **do not take sufficient account of** the **legacy from existing projects**. Knowledge from old product or production system generations is neither integrated into the product development process nor is it planned for future generations. (Albers *et al.*, 2022) In addition, many methodologies do not differentiate between brown-field and green-field production system planning. This leads to difficulties for companies with a brown field planning approach.
The **lack of inclusion of cross-departmental values** leads to a lack of acceptance of the methods, particularly among management. For example, the lack of a clear process for integrating flexibility into the overall development process in existing methods has made flexibility difficult to integrate. (Beibl *et al.*, 2023)

6. Conclusion

Shorter product lifecycles and a shift from mechatronic to cyber-physical systems are leading to greater product complexity. This complexity can be addressed by more intensive cooperation between product and production system development. Due to the complexity, integrative product development methods are used for this purpose. Despite intensive development in recent years, these process models have not been able to establish themselves in corporate practice.
For this reason, this paper analyses the existing methodological approaches to identify the reasons for their lack of use in practice. Nine barriers to the use of integrative methods were identified in the analysis. The analysis has shown that methodological approaches need to consider the technological realities of companies and industries. For example, the interfaces between departments are unclear and information cannot be made available at the right time in the development process. In addition, traceability is often lacking, making it difficult to analyse change processes. Another obstacle to applying the methods is that many companies rely on existing systems and machines, especially when developing production systems, and there is no provision for taking old data or old systems into account. For example, the interfaces between product and production system development are often unclear and legacy objects from previous product generations are insufficiently considered.

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Based on the findings of this paper, there is a need for future research in three areas: Identification of further barriers to the adoption of integrative methodologies, methodological support and awareness raising for integrative methodologies. Further barriers need to be analysed, e.g. to identify industry or country specific limitations. This study has a strong European focus, so further research in international academia and industry is needed to identify further barriers or solutions. There is also a need for methodological research, e.g. to develop an adaptive methodology tailored to the specific technologies and processes of different industries. This can be supported by tools such as a matrix that clearly defines the interfaces between product and production system development. In addition, there is a need to explore how flexibility and other inter-organisational values can be systematically integrated into product development. The third area for future research is to raise awareness for integrative methods, e.g. by developing best practices for integrating legacy systems and data into new development processes. In addition, the development of frameworks for better traceability and analysis of change processes in complex product development can help to enable other technologies for which integrative development acts as an enabler. In addition, the establishment of integrative approaches should be focused on the level of norms and standards.

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