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Engineering Genetics: Towards The Double Helix Model for Integrative Product and Production Design

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Abstract: The transition to intelligent systems has increased the complexity of development processes, creating a gap due to the underutilization of systems engineering in production. In addition, companies must be able to respond to crises at short notice and meet the demand for short development times. To achieve this, integrative product and production system development is required. The lack of a common understanding of the system hinders integration. This paper presents an integrative product and production design methodology that addresses barriers to application and defines key elements.

Keywords: Systems Engineering (SE), Systematic Approach, Integrated Product Development

1 Introduction

The transition from purely mechanical machines to intelligent technical systems is increasing the complexity of the development process. In product design, development methods have been continuously refined so that today methods such as Systems Engineering address this problem and offer a solution to the complexity of multi-disciplinary product design (Gausemeier et al. 2019).

During product design, the production is being developed in parallel as part of production system design. In production system design, common development methods from factory planning are mainly used to develop these systems (Grundig 2021). Especially in the context of autonomous production or logistics systems, production system design is also highly complex and appropriate methods to manage this complexity are needed (Wilke et al. 2023). In contrast to product design, Systems Engineering or comparable methods are rarely used in production system design, so there is a need to bridge the gap to master the complexity (Dumitrescu et al. 2021).

Complexity is further increased by collaboration with machine and equipment manufacturers in the context of production system design in a value creation network (Seidenberg et al. 2022). Production systems (e.g., machines) represent so-called System-of-Systems, as shown by this example: Company A is the manufacturer of a *consumer good*, and buys a *production cell* from company B. For company B, the *production cell* represents a complete product and self-contained system, which is sold to company A. Company A then integrates the *production cell* as a System-of-Systems in its existing production equipment to manufacture the *consumer good*. The resulting complexity needs to be addressed by a suitable approach that enables an exchange between product design and production system design (Anacker et al. 2022; Maier 1996).

Mastering complexity in the development of intelligent technical systems is currently an unsolved problem in product and production system design. The problem is intensified by many external factors, such as global crises, which highlight the vulnerability of supply chains and the need for rapid responsiveness to product and production changes (Wang et al. 2022). To meet this need for rapid responsiveness, product design and production system design must be brought together (Stoffels et al. 2021). Central visualisation is required to create a cross-enterprise understanding of an integrated product and production system design process. This is the basis for successful collaboration not only across disciplines, but also across cultural and physical boundaries.

The gap in the existing literature is that while product design methods have consistently evolved towards model-based collaboration, this step has not yet been taken in production system design. A close interdisciplinary exchange between product design and production system design is essential to master the complexity between the development areas and to realise further benefits such as shorter development times or reduced costs. Existing methods are currently inadequate because they do not consider important barriers like interfaces between product and production system design and a mainly generic focussing on high level phases making it hard to adapt the approaches in companies.

Therefore, this paper focuses on the development of a new approach to integrative engineering to model the complex network of product and production system design. The novelty of this approach lies in the fact that processes and interfaces of integrative cooperation are defined based on existing methods. The analogy of a DNA double helix is used to illustrate this, as it is useful for representing complex issues and for visualising key elements in the context of integrative development, such as interfaces, milestones, or phases. The research design of this thesis is presented first (Chapter 2). The analogy between complex systems and the double helix and the challenges of integrative engineering are then discussed as part of the problem analysis (Chapter 3). Existing methods are then presented (Chapter 3.2). The developed method is then presented (Chapter 4) and discussed (Chapter 5).

2 Research design

The research framework of this study consists of two elements: a **broad research approach** and a **specific research methodology**. The **broad approach** is guided by the Design Research Methodology (DRM) proposed by Blessing and Chakrabarti (Blessing und Chakrabarti 2009), which comprises four distinct phases: research clarification, descriptive study I, prescriptive study, and descriptive study II. The first phase were completed through a systematic literature review (SLR) to identify the various challenges in integrative planning (Disselkamp et al. 2023). The descriptive study I identified several barriers in the existing literature, which led to the research question (Disselkamp et al. 2024):

What is the ideal reference process between designing a product and designing a production system?

In this paper, we enter the third phase, the prescriptive study, to further explore the identified issues. This involves a more detailed description of the problem, followed by the introduction of a novel method to address the identified challenges.

The **first specific research methodology** used for the review of the literature was the methodology of Webster and Watson (Webster und Watson 2002). The structured literature review focused on the topics of product design, production system design and integrative product creation. Within this review, 25 sources were carefully analysed (some of which are presented in Chapter 3.2). The aim of the analysis was to extract the beneficial aspects of existing integrative approaches to product and production system design, with the intention of constructing a method that efficiently addresses the current challenges.

The **second specific research method** used was the Action Design Research (ADR) method of Sein et al. (Sein et al. 2011) ADR consists of four stages. In the first stage, the problem is formulated based on practical problems and a literature review. A new model is then designed and evaluated. In the third stage, the findings are reflected upon and used for learning. The first three stages are iterated until the desired result is achieved, and this knowledge is finally formalised in the fourth stage (Sein et al. 2011).

3 Problem analysis and state of the art

This chapter begins with a general definition of terms relevant to the paper. Several existing methods are discussed and current challenges in integrative product and production system design are presented.

3.1 Definition of terms

The literature offers different perspectives on the beginning and end of the **product creation** process. While some sources start with the product idea (Abele und Reinhart 2011; Ehrlenspiel und Meerkamm 2017; Gausemeier et al. 2012), others consider product planning as the first step (Bender und Gericke 2016; VDI-Richtlinie VDI2221-1). However, there is a consensus that both product design and production system design are integral parts of product creation. Therefore, in this paper, the product creation process includes the combination of product design and production system design.

Product design (also referred to as product development) is the iterative development of a marketable product based on specific requirements (VDI-Richtlinie VDI2221-1) and includes activities such as component design, system assembly and service development, with predefined development goals such as cost minimisation or function fulfilment (Gericke et al. 2021a; VDI-Richtlinie VDI2221-1).

Production system design (also referred to as production system development) involves the design or planning of production systems, including the planning of workflows, workplaces, equipment, production logistics and material flow (Cochran et al. 2001; Gausemeier und Plass 2014). It is part of factory planning, which also includes building and site planning (Sinnwell 2020; VDI-Richtlinie VDI5200-1).

The complexity of product and production system design processes is well recognised (Gericke et al. 2021b; Helbing et al. 2018). To address this, **integrative product and production system design** is used, where product design and production system design take place simultaneously and in a coordinated manner. This approach aims to optimise both through early consideration of all product lifecycle phases and production requirements, ensuring better alignment across the value chain (Bullinger et al. 1995; Eigner und Stelzer 2009).

3.2 Existing methods of integrative engineering

This chapter presents various integrative methods for product design and production system design.

3.2.1 Method for production system design based on early product information

Sinnwell (Sinnwell 2020) presents a model-based approach to production system planning that extends and builds on the integrated development concepts for cyber-physical products and production systems established in the mecPro² research project (Eigner et al. 2017). This approach uses model-based systems engineering (MBSE) with the primary aim of integrating engineering processes at an early stage to promote a common understanding through a 'common language'. The framework comprises three main elements: an integrated process model for concurrent development and planning from the start of the product creation process, a systematic methodology for early production system design with a maturity model for evaluating preliminary product information, and an object-oriented modelling technique (Sinnwell 2020).

The process model follows the V-model structure proposed in VDI 2206 (VDI-Richtlinie VDI2206b; VDI-Richtlinie VDI2206a) and consists of a micro-cycle for detailed collaboration and a macro-cycle for strategic coordination (Figure 1). While the traditional phases of product and production system planning are retained, they are now linked by the micro-cycle. Each phase begins with at least one iteration of the micro-cycle, represented by cubes in the model, and concludes with a milestone where the interim states of the product and production system designs are reviewed and approved (Sinnwell 2020).

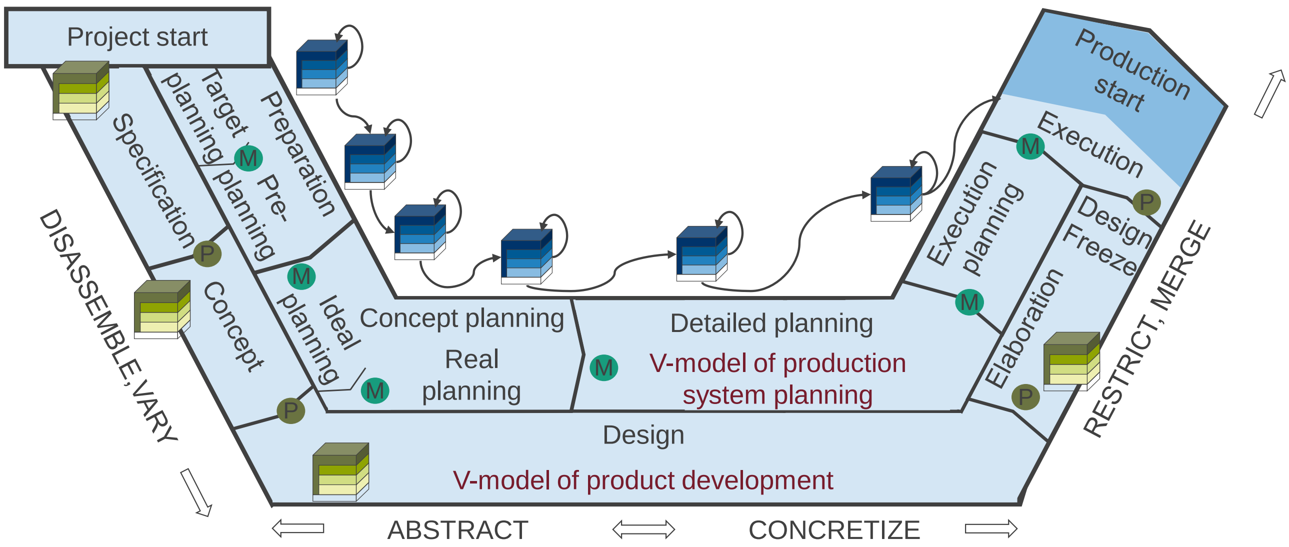

Figure 1. Integrative engineering process model according to Sinnwell (Sinnwell 2020)

The core of the systematic method for production system design based on early product information is the continuous collaborative definition and revision of tasks and requirements for both systems, with particular emphasis on assumptions as a critical component. These assumptions replace missing or immature information within the integrated production system design. A maturity model with five indicators has been developed to determine the maturity of the information (Sinnwell 2020).

Complementing this is the object-oriented modelling approach, which integrates with existing tools by using a model-based language that facilitates the use of model-based systems engineering. For example, UML is used as a common language for requirements definition (Sinnwell 2020).

3.2.2 Product-Production-CoDesign (Generation Engineering)

Albers et al (Albers et al. 2022) propose the concept of product-production co-design (PPCD), which argues that product creation necessarily relies on pre-existing subsystems. This approach emphasises a highly collaborative and parallel process involving the iterative planning, development, and realisation of products together with their associated production systems, extending through to the recycling stage over multiple product generations. The PPCD model is structured around six facets (Figure 2) (Albers et al. 2022).

The first facet involves analysing the product, production system and market over successive product generations to identify recurring needs (I). To facilitate the systematic reuse of knowledge and its interaction, the second facet emphasises the need for appropriate methods and tools (II). These tools are then used within the development process to formally document and explicitly share knowledge among developers (III). The fourth facet focuses on developing business models that are aligned with market needs (IV). The fifth facet involves recognising changing requirements across product generations through specialised processes, methods, and tools (V). Finally, the model states that potential future trends must be anticipated and integrated into upcoming development strategies (VI) (Albers et al. 2022; May et al. 2023).

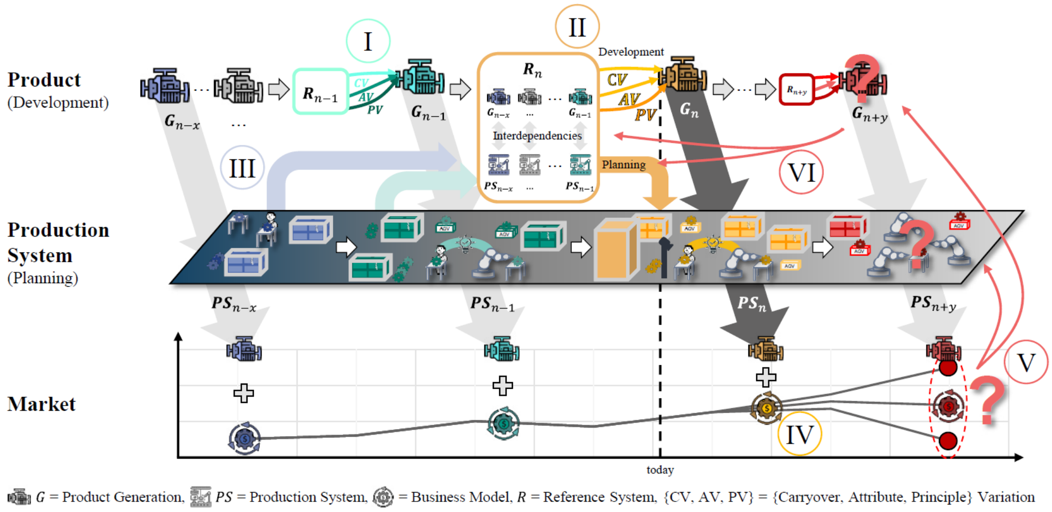

Figure 2. Visualization of six aspects of Product-Production-CoDesign according to Albers et al. (Albers et al. 2022)

3.2.3 VDI Guideline 2206

VDI Guideline 2206 provides a structured process model for the development of mechatronic systems, commonly referred to as the V-model. This model advocates a systematic deconstruction of the product concept into discrete system components, their subsequent elaboration and eventual integration into a cohesive system. Validation and verification are integral, iterative parts of this development process, ensuring that the results at each stage meet the defined requirements. Starting with product planning and requirements specification, the process progresses through detailed design in individual disciplines, followed by system validation and verification, culminating in the development of the production system. The VDI guideline recommends the consistent capture of development results in a product model, for example using model-based systems engineering (VDI-Richtlinie VDI2206a).

The original 2004 version of the VDI guideline emphasises the importance of information exchange between different disciplines (VDI-Richtlinie VDI2206b). However, this iteration lacks explicit guidance on collaboration between product design and production system design, leading to several publications criticising it as insufficient to fully address the nuances of integrative product and production system development (Albers et al. 2019; Jürgenhake 2017). In particular, the 2021 update of VDI Guideline 2206 aims to address some of these criticisms by providing clearer guidance on the interplay between product development and production system design, and by emphasising the importance of an integrative approach throughout the product lifecycle.

3.2.4 Reference model for strategic planning and integrative development of market services (4-cycle model)

Gausemeier and Plass suggest that the product creation process should be conceptualised as a dynamic interplay of tasks rather than a linear series of phases and milestones. Within this framework, they introduce the 4-cycle model, which divides the product creation process into three primary tasks, which are further divided into four interdependent cycles, with a particular focus on the cycles related to product design and production system design (Gausemeier und Plass 2014; Gausemeier et al. 2019) (Figure 3):

1. Strategic product planning is the first cycle in which the overarching business and product concepts are shaped.

2. Product design is the subsequent cycle that aims to transform the product concept into a marketable product. This involves several subtasks, including product conceptualisation, detailed design, and integration into a complete system.

3. Production System Design is the cycle dedicated to creating a production system that is finely tuned to the product and meets various requirements. It mirrors product design in its breakdown into subtasks such as detailed design of the production system, work planning and overall system integration. Work planning itself includes workflow, workstation, material flow and work equipment planning.

4. Service development is the final cycle that brings a service concept to market readiness, recognising the need to view service development as a coordination of multiple tasks.

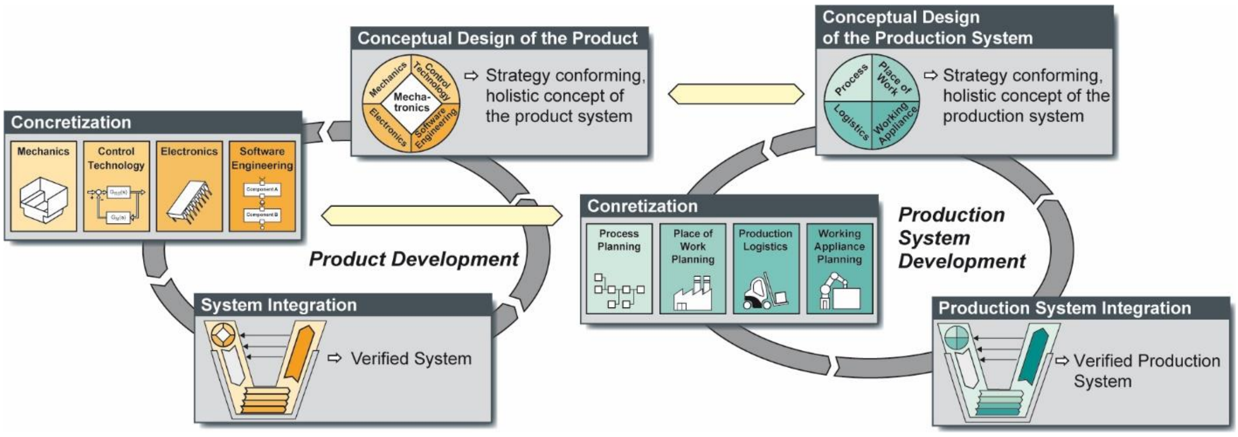

Figure 3. Extract from 4-cycle model of product and production development (Gausemeier et al. 2019)

3.3 Challenges in integrative product and production design

Integrative methods of product and production system development offer significant benefits in terms of efficiency and cost reduction by minimising rework. They improve product quality through early consideration of production issues and accelerate time to market. These approaches support sustainable development, increase flexibility, and promote adaptability to market changes. They also improve communication and collaboration between departments, reduce risks and potential errors, and promote innovation through interdisciplinary collaboration (Bullinger et al. 1995; Eigner und Stelzer 2009)

Despite the existence of numerous integrative methods with clear advantages over the traditional sequential approach, as noted by Sinnwell (Sinnwell 2020), it appears that these have not been widely adopted in industrial practice. This is evidenced by a number of publications pointing out that they have not been adopted (Ehrlenspiel und Meerkamm 2017; Steimer und Aurich 2016; Schäfer et al. 2023). Rather, according to Graner, industry tends to favour the sequential approach or opt for partial parallelization within the framework of simultaneous engineering (Graner 2015).

Numerous challenges prevent the use of existing integrative methods. The challenge of **unclear interfaces** refers to the unclear links between product design and production system design. This lack of clarity leads to uncertainties in process models, making it difficult to effectively integrate product design and production design processes due to undefined interactions and information exchanges (Stoffels und Vielhaber 2015). The **information and organisational management** challenge highlights that existing methodologies only partially address the management of information and organisational structures. This is a critical issue for the holistic management of integrative product creation processes and can lead to an inability to identify and address interdisciplinary issues early in the development process (Eversheim et al. 2005; Francalanza et al. 2018). **Inadequate information exchange** between product design and production system design is a major challenge. This gap requires research into effective information transfer mechanisms between departments, given the large volume of information and the need to synchronise different IT tools (Disselkamp et al. 2023; Albers et al. 2022; Francalanza et al. 2018). A model-based approach to the exchange of information could be promising (Wilke et al. 2024). The challenge of **technical feasibility** focuses on the aspect of implementing integrative methods in practice. Without considering the ease of implementation, these methods may be dismissed by companies that require adaptable and low-effort solutions. **Lack of traceability** is a challenge that arises from the unclear impact of product design changes on the production system. This can lead to undetected problems and subsequent rework, causing significant delays and inefficiencies in the development process. The tendency of existing integrative methods to simply parallelize development processes, rather than fostering continuous interdisciplinary collaboration, presents a challenge in **focusing on process parallelization**. This can result in missed opportunities for integration throughout the development phases (Stoffels und Vielhaber 2015). **Inadequate consideration of legacy** knowledge is a challenge that affects the integration of valuable insights from previous projects. Current integrative approaches fail to effectively use knowledge from previous generations of products or production systems in new development or future planning, which can stifle innovation and continuous improvement (Albers et al. 2022). Integrative methods currently used in engineering often **fail to simplify and visualize complex processes for novices** and therefore lead to resistance in changing and adapting new methods. A key to solving this problem is to improve the visual representation of these methods to make them more accessible and understandable.

4 Suggested procedure

This chapter presents a methodology for integrative engineering between product design and production system design. The process model considers the current challenges for integrative methods (Chapter 3.3). The *Double Helix Model for Integrative Product and Production Design* is inspired by the double helix structure of DNA to enable integrative engineering of product design and production system design. The double helix structure is used for its ability to simplify complex issues and visualise them in a universally understandable way. Instead of the elements of DNA, the model uses engineering concepts, with the double helix serving as a metaphor for the interlocking of the two strands of development. The model has three elements: Engineering Processes, Interfaces and Milestones. These elements are grouped into engineering phases (Figure 4).

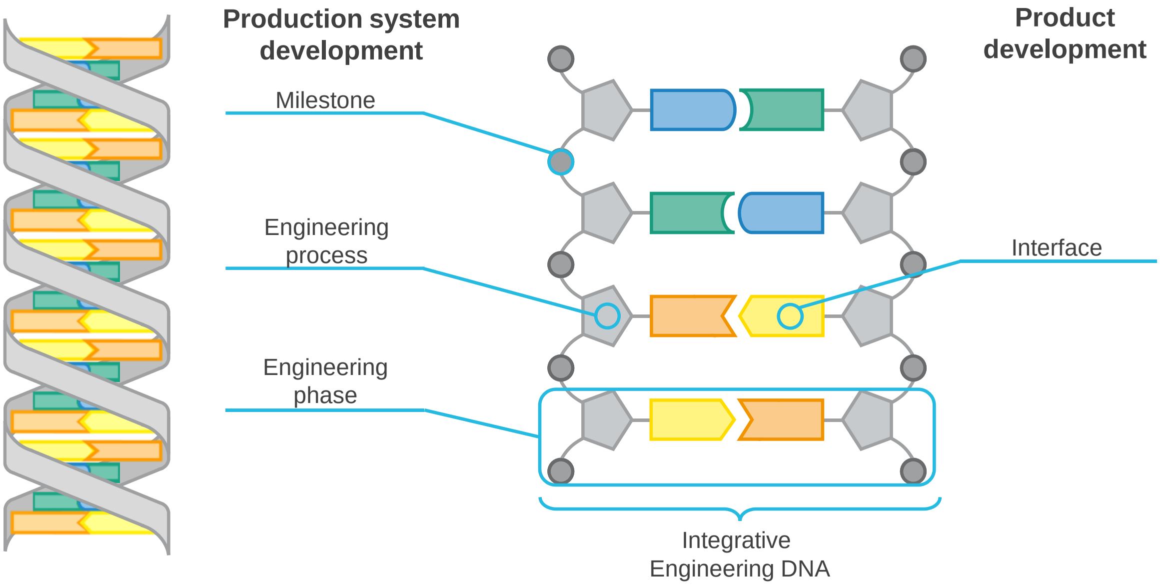

Figure 4. Schematic representation of the Double Helix Model for Integrative Product and Production Design

1. **Engineering processes** are key elements in product and production design that involve engineering activities and are essential for the transition from idea to finished product. These processes include concept development, design decision making and component adaptation. In integrative development, these processes are not isolated from each other, but are closely interlinked and influence each other. The processes are connected via interfaces. The description of the engineering processes is complemented by method and tool recommendations that provide companies with concrete instructions and tools to make the complex processes of product and production system design manageable and efficient. They facilitate the implementation of the individual steps within the engineering processes and raise awareness of the interfaces with other areas. An example of an engineering process is the creation of a production layout, in which the arrangement of machines and systems is optimised to meet both the requirements of the product and the operational processes.

2. The **interfaces** in this model are the connection points where product design and production system design converge. They are essential for the exchange of requirements and information and ensure coordination between the two strands of development. As institutionalised meeting points, they promote communication, coordination, and integration between the teams.

3. **Milestones** are structural markers in the development process that signal the achievement of key goals and the transition between phases. They serve as checkpoints to verify the quality and completeness of the work and to ensure that project goals are met. Through regular evaluation, milestones help to keep the project on track and make progress transparent.

4. The **engineering phases** in the "Double Helix Model for Integrative Product and Production Design" represent the different stages of the development process. They cover all steps from requirements definition and concept development to prototyping and validation. These phases are not rigid, but flexible and iterative to allow feedback and adaptation so that the product and production system design can converge.

Figure 5 shows and describes the proposed reference process for integrative development. As part of the reference model, an example of rough production planning is described below. The following example of the **engineering phase** of rough production planning as part of production system design illustrates the three elements (engineering processes, interfaces, milestones) of the integrative approach presented. In rough production planning, these elements provide the framework within which the engineering phase develops. They provide the flexibility to adjust based on feedback and ensure that the production layout meets both technical and economic requirements. The iterative nature of the phases allows continuous refinement of the production concept.

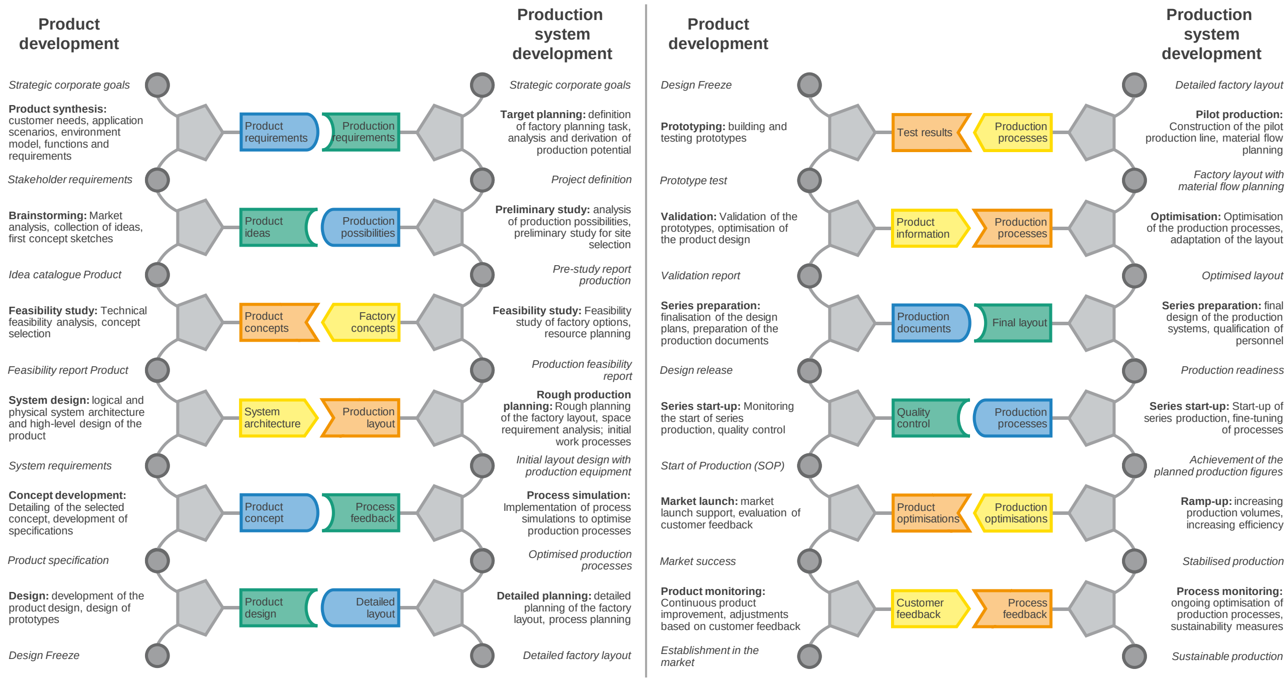

Figure 5. Reference process for integrative Product and Production Design based on Double Helix Model

Rough production planning involves **engineering processes** such as developing initial factory layouts, selecting machinery and equipment, and designing initial work processes. Concepts are developed, design decisions are made, and components are adapted to give a preliminary picture of the future production facility (Grundig 2021). These processes do not take place in isolation, but are in constant interaction with other areas, such as logistics or quality control, to consider the requirements of the product and the efficiency of the production processes. A good example of a rough planning method is the Sankey diagram. It is used to visualise energy, material, or cost flows within production systems. This allows inefficiencies or bottlenecks to be quickly identified and appropriate adjustments to be made. By using the Sankey diagram, companies can identify and exploit optimisation potential in production planning at an early stage, leading to improved resource efficiency and cost savings. Sankey diagrams can be displayed using tools such as SankeyMATIC or visTable.

The **interfaces** act as a link between product design and rough production planning. At this stage, the exchange of requirements and information between disciplines is crucial. For example, product designers and factory planners need to consider together how the production layout can best support the assembly of the product while ensuring the efficiency of the production process.

As part of the pre-design process, **milestones** mark important stages, such as the completion of the initial layout design or the selection of production equipment. They are used for quality assurance, to check that requirements have been met and that planning is in line with project objectives. Milestones are also the point at which interdisciplinary reviews take place to ensure that all aspects of the production facility have been adequately considered.

In summary, rough production planning shows how engineering processes, interfaces, milestones, and engineering phases interact to create an integrated product and production system. Close coordination between product design and production system design is critical to creating an efficient and effective production environment that meets both product requirements and business objectives.

In integrative product and production system design, the interaction of the four core components is supported by a common system model from systems engineering. This model acts as a central source of information, capturing and linking all relevant product and production system data. It promotes a holistic view of the entire project and ensures consistency across all development phases and processes.

The *engineering processes* are supported by the system model, which provides a standardised database for integrating product and production system requirements. The *interfaces* are facilitated by the system model, which serves as a common platform for the exchange of information between all parties involved. *Milestones* are documented in the system model, enabling transparent tracking of project progress and verifiable documentation of results. The system model also supports the iterative nature of the *engineering phases* by allowing changes to be documented and design decisions to be simulated.

5 Discussion

In this chapter the presented methodology is evaluated based on the challenges described in chapter 3.3. The model emphasises the importance of **clear interfaces** between product design and production system design. It promotes communication and coordination between the two development areas and provides institutionalised meeting points for the exchange of requirements and information. The model includes the use of a common system model to capture and link relevant product and production system data. This promotes a holistic approach and supports the **management of information and organisational structures**. The model emphasises the importance of **information exchange** between product design and production system design. It provides a common platform for information exchange and enables the synchronisation of different IT tools by using an integrative system model. The model recognises the importance of **traceability** of product design changes to the production system. It emphasises milestones and quality control to ensure that requirements are met, and problems identified in a timely manner. The model emphasises the interconnectedness and interdependence of engineering processes. It aims to promote **continuous interdisciplinary collaboration** rather than simply parallelizing development processes. The systems engineering approach emphasises the importance of knowledge management to **support the integration of legacy** from previous projects into new development or planning processes. This can be achieved through knowledge databases and lessons learned systems that promote innovation and continuous improvement. The consideration of **technical feasibility** is not presented in this paper and is the subject of further research.

In summary, the "Double Helix Model for Integrative Product and Production Design" addresses most of the challenges mentioned and offers an integrative approach to product and production system design. However, it can be further improved by examining and considering technical feasibility.

6 Conclusion

The transition to intelligent technical systems has increased the complexity of development processes, creating a gap where systems engineering is underutilised in production design, while it is widely used in product development. In addition, companies must be able to respond to crises at short notice and meet the demand for short development times. This requires integrative product and production system design based on a common understanding of the system. In industrial practice, integrative approaches are not yet being implemented due to various challenges, such as unclear interfaces to the development areas.

This article therefore presents the "Double Helix Model for Integrative Product and Production Design" approach, which addresses the existing challenges. To this end, four core elements (engineering processes, interfaces, milestones, and engineering phases) are defined. Engineering processes in the method involve closely interlinked and influencing activities such as concept development, design decision making, and component adaptation, connected via interfaces, and supported by method and tool recommendations for efficient product and production system design. Interfaces in the model serve as essential connection points between product design and production system design, facilitating the exchange of requirements and information, promoting communication, coordination, and integration between teams. Milestones in the development process act as structural markers that signify the achievement of key goals and the transition between phases, ensuring quality, completeness, and progress transparency through regular evaluation. The engineering phases in the "Double Helix Model for Integrative Product and Production Design" encompass all stages of the development process, allowing for flexible and iterative feedback and adaptation to converge product and production system design from requirements definition to prototyping and validation. In integrative product and production system design, the interaction of the four core components is supported by a common system model from systems engineering. The integrative Double Helix Model provides a structured framework for the deep integration of product design and production system design. It enables the coordination and synchronisation of both areas, promoting the parallelisation of activities where possible and the sequential processing of tasks where necessary to support optimal integrative product and production system design.

There is a need for further research in relation to the "Double Helix Model for Integrative Product and Production Design", for example in validation and evaluation, as the model needs to be validated and evaluated in further real use cases to verify its effectiveness and efficiency. In addition, partial aspects of the model need to be published, such as the interface matrix between the processes or the detailing of the engineering phases. The model could be further developed to take greater account of sustainability aspects. This could include, for example, assessing the sustainability performance of product and production system designs or developing methods for identifying and implementing sustainable solutions. In addition, the technical feasibility of the solution should be assessed using an appropriate tool landscape. To further strengthen the integrative model, additional aspects such as digital twins for realistic and up-to-date virtual mapping or agile methods for flexibility and rapid adaptability along the entire product life cycle should be integrated.

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