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Enabling digitally integrated product design and production through digital continuity and feedback to design

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Abstract

Due to global and political influence, resilient and versatile production systems are unavoidable. Based on existing Product Lifecycle Management (PLM) systems there is a growing need for a consistent communication between machines and product design to enable integrated product and production process design. Core aspects are integrating the product design information directly into the production equipment and their feedback into the product design as well as into other phases of the product creation and usage. Therefore, a generalized production description language as well as an architecture for the digital integrated product design and production need to be developed. This paper presents the first results of a use case in the automotive industry. The approach of developing the functional architecture is shown. Several feedback to X approaches were researched in literature and analyzed regarding functional requirements for integration in the developed architecture. The results are the main basis for further implementation within the automotive production. Moreover, the main challenges and next steps are discussed.

Keywords: product and production system architecture; production description language; design methodology, tools and technologies

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1. Introduction

Modern production systems must be rapidly adopted to cope with fast-changing circumstances, such as global supply chains affected by political influences, increasing product complexity, a greater variety of product configurations and shortened development cycles [1–3]. Therefore, establishing an integrated process and continuous flow of data throughout the entire product lifecycle is essential to create resilient and versatile product ecosystems. The implementation of this so-called digital thread in product creation facilitates the development of dynamic production systems. This enables rapid adaptation to changing requirements through data consistency and accessibility for all stakeholders [1]. By means of automated information processing, self-governing and self-correcting attributes are implemented, thereby minimizing the requirement for human involvement and regulation [2–4].

1.1. Problem statement

Current processes in product creation, including product design, simulation, production planning and production, are assisted by various tools leading to a heterogeneous IT landscape. Due to variations in language and semantic data structure, building interoperability between different applications can be extremely complex and even unattainable [5]. This results in a high demand for a universal framework that guarantees a continuous digital thread across the entire Product Creation Process (PCP), with no limits concerning the chosen tools and methods. The implementation of an integrated process also enables the automated upstream flow of information. Hence, feedback during the later phases aids in making decisions and optimizing product and process parameters during earlier stages [6–8]. In addition, production systems have a substantial environmental impact due to their

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high energy and resource consumption, generation of emissions and waste [9]. To reduce the overall impact, it is essential to assess the contributions of individual life cycle phases and unlock corresponding optimization potentials through feedback to previous decision processes during earlier phases [10].

1.2. Goal

Digital continuity is defined by The National Archives as "[…] the ability to use digital information in the way that you need, for as long as you need" with "usable" being characterized by five criteria [11]:

- find it when you need it,
- open it as you need it,
- work with it in the way you need to,
- understand what it is and what it is about,
- trust that it is what it says it is.

The goal of this research can therefore be described as reaching digital continuity within product creation comprising all phases from product definition to production execution. In this study, there is a special focus on integrating upstream directed feedback data. It aims to answer the following research question RQ: *"Which functionalities are required for the integration of feedback data into a bidirectional DPC?".*

This work addresses the lack of a generic description of fundamental functionalities for the process-wide integration of feedback information in literature. The results serve as the foundation for developing a technological reference implementation that can be applied to a wide range of use cases.

2. Methodical Approach

To address the posed RQ, the current state of integrated feedback to X approaches is analyzed through an exploratory literature review. Subsequently, identified research gaps are defined and the methodical approach is described.

2.1. Current integrated feedback to X approaches

Within the literature review, approaches were considered that address process phases from early design to final production execution matching the given use-case. In this context, the design phase comprises activities regarding the definition of relevant product parameters and information for production. It also includes the selection of appropriate production technologies. During production planning, detailed work plans, and associated resources including machines, tools and auxiliary materials, are specified. Production data are processed during production controlling, where the machine program is generated before being transferred to the production line for execution by production resources. In addition, approaches for integrating sustainability assessment are included. Table. 1 shows an overview of all identified approaches within literature clustered with regard to their main focus as well as source and addressed phase.

Table 1: Clustering of feedback to X approaches.

Nr.	Feedback to	Main focus	Ref.
1	Design	Reuse of design knowledge	[12–14]
		Predictive evaluation	[15–17]
		Feedback from production	[6,7,18–20]
2	Production planning	Feedback from controlling and execution	[8,21–23]
3	Production controlling	Feedback from execution	[6,24,25]
4	All phases	Integrated feedback from sustainability assessment	[10,26–34]

1) Feedback to design

In the following, approaches that include an upstream directed data flow to the design phase are described. The fundamental goal of integrating knowledge from later process phases to support optimal design decisions is also addressed by design for X approaches. However, these approaches do not necessarily imply cross-phase and digitally continuous data integration and are therefore not explicitly listed.

Reuse of design knowledge. The reuse of design knowledge, can be seen as feedback to design from earlier design processes. Fundamental to the realization of integrated knowledge provision is the linking of product-related data (e.g. parameters, simulation results, calculations) with associated process phases and activities. In this way, Brandt et al. [12] describe a so-called process data warehouse where knowledge is structured and linked in a flexibly expandable ontology. The uniform, semantic data representation enables linking of complex relationships between different contents generated during former processes. By comparing the current development status with a predefined process model, relevant data and solution proposals for the current design task can be provided automatically. Further approaches concerning early stages of design are given by Baxter et al. and Costa et al. [13,14].

Predictive evaluations. Integrating information and tools of distinct phases of product creation enables the establishment of predictive approaches, simulating design related impacts during later process phases. Feng et al. [15] describe a knowledge base that enables design parameters to be linked to relevant manufacturing processes and resources. Within a multi-agent system, process schedules and available manufacturing processes are automatically determined and an early time and cost estimation for preliminary design drafts is provided. Other approaches focus on early validation of the manufacturability of design concepts. For example, Cao et al. [16] define a manufacturability analysis system that represents the dependencies of domain-specific design aspects and manufacturing capabilities through a knowledge base. Ko et al. [17] consider a process chain in additive manufacturing. The created manufacturing forecasting models allow for early design verification and decision-making assistance.

Feedback from production. Finally, other approaches focus on integrated feedback from the production into the design. For this purpose Brandmeier et al. [7] describe a concept in which sensor-detected production errors are automatically validated with regard to their dependence on design-specific features. Furthermore, information is provided on how the detected defects can be avoided. A combination of three knowledge bases link the dependencies between defect patterns, production process and product design in uniform ontologies. Other approaches describe the integration of PLM and Manufacturing Execution Systems (MES). Khedher et al. [18] choose a multiple ontologies approach where the MES and PLM ontologies are linked through formalized mapping. Various benefits of PLM and MES integration are illustrated by D'Antonio et al. [6] through a use case in the field of laser welding in the automotive industry. Process-related irregularities in the production process are sensory detected, evaluated automatically and communicated to the design department. Further examples of on-line monitoring and controlling approaches are given in literature [19,20].

2) Feedback to production planning

Production planning requires in-depth knowledge of the available production processes and tools. For automation, it is therefore essential to access updated data and to integrate autonomous decision-making concepts [8,21,22]. Addressing this Shea et al. [8] describe an integrated approach for an autonomous design-to-manufacturing system. Knowledge models for mapping manufacturing processes, tools and materials are combined with autonomous planning methods. Relevant feedback integrations result from the final component validation. Another fully integrated approach comprises the application of knowledge bases for the automated generation of process plans from the evaluation of design data [23]. Real-time production data such as machine availability, tooling and adjustable parameters are retrieved from a Digital Twin (DT) of the production. Based on this data and further simulations, the developed process plans are validated and optimized. To ensure a uniform understanding: This paper refers to a DT as a digital representation of an asset meaning product, process or service [35]. Messner et al. [22] focus their work on providing accurate master data for production planning through real-time analysis of current production processes. The evaluation is based on the cycle times of production steps. Statistically relevant deviations from the planned data are automatically recorded, evaluated and fed back into the Enterprise Resource Planning (ERP) system.

3) Feedback to production controlling

The main feedback source addressing production controlling is the inspection phase [24]. Since this work focuses on the process steps up to and including final production, only feedback approaches with in-process measurements (during machining) are considered below. Zhao et al. [24] describe a cognitive process planning system with an integration of inspection feedback into the process control of manufacturing processes. For this purpose, interoperable data models are created, which enable the automated exchange and comparison of geometry data, tolerances and inspection information. An automated real-time comparison of measurement data and the initiation of process control corrections is implemented. The previously mentioned approach encompasses an online monitoring system for real-time quality evaluation of a laser welding procedure [6]. By assessing optical measurement data, unexpected deviations in the production process are identified and transferred to an adjustment of process parameters. A more conceptual framework for ensuring the resilience of production systems is presented by Eirinakis et al. [25]. An architecture for a DT with cognitive capabilities including detection and handling of process deviations is described and related tools are mapped. The goal is to ensure an adoptable process flow for reducing production downtimes and the associated cost and time losses.

4) Sustainability assessment: Integration and feedback

The Life Cycle Assessment (LCA) methodology has become a widely accepted approach for evaluating the environmental impact of product systems [26]. Realizing sustainability assessment through integrated process models provides time and labor efficient monitoring of sustainable impacts [26,29,31]. Ferrari et al. [27] describe a framework for a dynamic LCA that is integrated into an existing tool environment of MES and ERP systems. In a given use case real-time data on energy and resource consumption during production is automatically collected and processed for continuous assessment. The results are used to redesign the product for minimizing the environmental impact [28]. Another approach focuses on the integration of real-time data for the precisely assignment of the calculated environmental impacts to a certain manufactured product, even with changing product and process parameters [29]. Cerdas et al. [26] combine real-time data with simulation data, such as demand for auxiliary materials or the amount of material removed from downstream processes, as the basis for performing a dynamic LCA in the shop floor environment. A merged visualization present at the workstation informs the worker of actions that can lessen the predicted ecological impact. Further examples for automated LCA of production systems are given by Schneider et al. [30].

Alternative approaches describe the concept of the DT as a central technology for integrating data collection, processing and evaluation in the course of an LCA. Riedelsheimer et al. [10] describe the Digital Lifecycle Twin (DLT) framework for Life Cycle Sustainability Assessment (LCSA). The data base comprises real-time data from production, the information system (MES, ERP) and external data sources. The data is stored in the DLT and linked to the corresponding product or process. As part of the evaluation of the LCSA, deviations from the prototype models can be identified and fed back to the design as decision support in the early stages of development. Another approach is presented in a four-layered framework, in which the DT provides the necessary data representation for the validation of products and processes within the LCA context. The objective is to provide automated support for sustainable decision-making [31]. Additional methods for integrating sustainability assessment through DT and other Industry 4.0 technologies can be found in academic literature [32,33].

2.2. Research gap and methodical approach

The literature review reveals a diverse range of approaches that mainly focus on individual process phases and consider feedback integration primarily as an additional effect of the downstream oriented integration of process phases.

Furthermore, a particular technological implementation is usually described without providing a standardized functional framework that facilitates the adjustment to domain-specific circumstances. Identified research gaps result in (i) the development of a solution-independent architecture that considers functional requirements for bidirectional digital continuity throughout the PCP. Additionally, (ii) a description of functional aspects that must be explicitly considered for the integration of feedback data is absent.

Therefore, the double diamond process is applied for developing an appropriate architecture, as it is well suited for solving complex and systematic problems [36,37]. At the *Discover* stage, the downstream data flow in a representative automotive Original Equipment Manufacturer (OEM) use case is described. Therefore, expert interviews with relevant stakeholders and documented process descriptions are conducted. Subsequently, in the *Define* stage, 29 fundamental requirements for a DPC are developed in dialogue with the project participants. This leads to the definition of a functional architecture that clusters the functionalities in a generic manner. Based on the integrated feedback approaches described previously, fundamental requirements for the integration of feedback are defined and their implementation in the described architecture is discussed. Further stages of *Develop* and *Deliver* will be carried out in future work.

3. Results

3.1. Process description

The process for product creation which has been analyzed at the representative automotive OEM comprises the described phases (section 2.1). The entire process flow includes a large number of manual and partially automated interfaces for exchanging and linking data. For the purpose of this paper, the process steps are simplified (see Fig. 1) as the identified process steps and tools at the OEM align with the literature research. However, unlike the highly automated process chains researched, the use case process involves a sequential, non-automated flow of information. Additionally, feedback information is only exchanged asynchronously through personal communication between departments such as design and production planning. Any required changes to the product or process must be approached in a laborious and time-consuming manner through human participation and interpretation which confirms descriptions in literature [4,5].

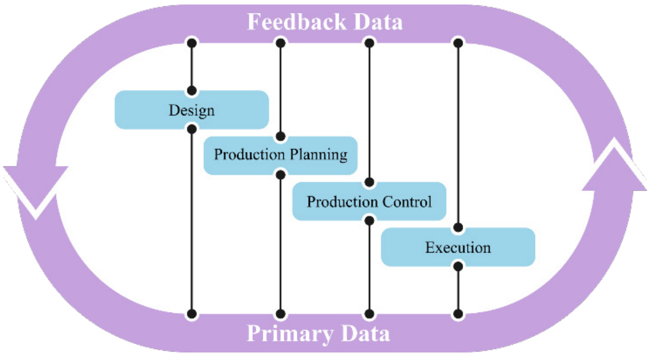

Fig. 1: Simplified process model.

Thus, this study aims to enable digital integration between all process steps, allowing for direct communication between individual phases. It enables minor design alterations, for instance, to be seamlessly transferred to the executing machine. At the same time, the advancement of digital continuity also presents the opportunity to exchange information upstream and downstream. The implementation of feedback loops, which are built on these upstream and downstream connections, enables the unlocking of various potentials with regard to the optimization and adoption of product and process parameters.

3.2. Functional architecture

As a result of the *Discover* phase of the methodology requirements and capabilities have been identified and integrated in an architecture on functional level – meaning solution-independent. The three main functions (F1, F2, F3) emerge from a basic grouping of the 29 fundamental requirements. These are then broken down into sub-functions until all requirements are captured. For instance, the main function *Representation* clusters requirements related to cross-departmental visibility and intuitively visualization of data (*Visualization*), as well as implementing machine- and human-readable data formats (*Data Representation*). The functional architecture is shown in Fig. 2 and further described.

Data needs to be accessed by the various applications and stakeholders across the process. The minimum requirement therefore is the establishment of a *Data Representation* (F1) with a defined and optimally standardized semantic. If tools require the data directly there needs to be a functionality to *Transform Data* automatically in the required format based on defined rules (F2). The data also needs to be transferred between the different stakeholders and applications and if there are changes in the data sets, the relevant stakeholders and applications need to be notified on these. Additionally, the process chain needs to be open for the *Integration* of further applications and stakeholders. As multiple stakeholders access the same master data, it is of utmost importance, to administrate (F3) who can access the data and what conditions apply. To keep the consistency of the data, *Data Checks*, *Protocolling* and *Backup* are also involved.

Lines between the subfunctions briefly show some exemplary interlinks between them (Fig. 2). The *Data*

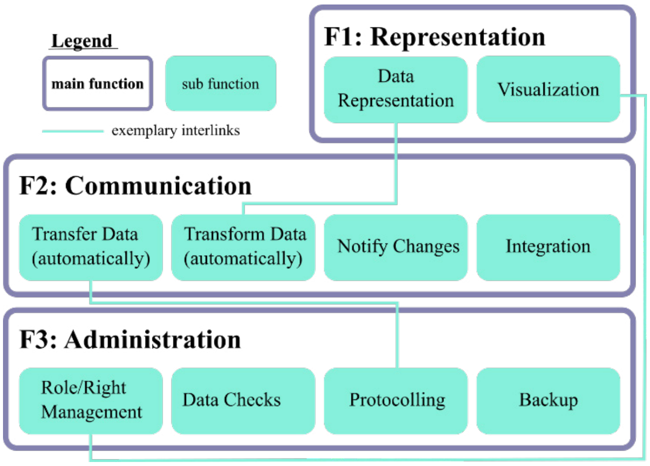

Fig. 2: Functional architecture.

Representation needs to be accessed to transform and then transfer data. The transferred data needs to be protocolled to keep the consistency, and the roles and rights can then be used to define how the data has to be represented visually.

3.3. Requirements for integration of feedback to X

Based on the described approaches, the essential requirements for the integration of feedback to X into the DPC are summarized below. The main objective is to enable seamless integration in terms of generalization and data continuity. Therefore, key requirements are listed in Tab. 2.

Table 2: Requirements for integration of feedback information.

Requirement	Ref.
Machine processable representation of product and process data (e.g. product geometry, machine capabilities, cycle times, energy consumption)	[7,12,13,27]
Seamless transfer of digital continuous data through the entire process chain	[7,8,17,20,23]
Integrated (real-time) data collection and measurement (e.g. sensory, processual)	[6,7,17,20,28]
Integration of mapping and contextualization of data from distinct process phases (e.g. linking product with process parameters)	[12,13,15,16]
Interfaces to cognitive simulation, evaluation and assessment systems (e.g. decision support/LCA tools)	[6,7,15,17,20,23,28]
Feedback communication and visualization (e.g. dashboard at workstation)	[12,15,26]
Continuous updating storage of data and knowledge (e.g. knowledge bases)	[12–14,17]

4. Discussion

The fundamental requirement for the seamless transfer of feedback information along the entire process chain is mapped in the functional framework of *Communication*. Furthermore, the incorporation of evaluation applications is basically considered within the general *Integration* of further interfaces in the communication flow. Related software, encompassing simulated systems, evaluative algorithms or life cycle assessments, are fundamental for the processing of feedback information and serve as decision support or even initiate automated adaptation processes. However, this work concentrates on fundamental functionalities of an architecture and data structure that enable appropriate further processing. The basis is a machine-readable representation of all product and process data, as listed in the main function *Representation*. This allows corresponding feedback information such as production deviations or resource consumption to be automatically recorded, transferred and validated. In order to be able to represent more complex interrelationships and dependencies, the linking of data is necessary. Through a corresponding contextualization of design and process parameters such as design features and resulting manufacturing steps, resource inputs and cycle times, subsequent effects like costs, times and manufacturability can already be validated during the design phase. At the same time, a prediction model is automatically generated against which measured, real process parameters can be compared and unwanted deviations can be detected and fed back for supporting actions. This linking of data is currently not included in the architecture. In the context of the transformation of data described above, the transition from product data (e.g. maximum torque for screwing) to concrete production parameters (e.g. angle of rotation) according to defined dependencies is currently primarily considered. For the mapping of more complex interactions, corresponding linking options must be provided in terms of a general *Representation* and must be taken into consideration in the further procedure. Similarly, the current architecture does not address the integrated real-time collection and measurement of data. This is fundamental to enable the automated comparison of real data with planned data and should be considered in the main function *Communication*. In addition to the collection of data, the continuous storage of data and knowledge is also a fundamental functionality. In this way, newly generated knowledge, such as the integration of new design features, can be made available automatically for future processes. However, the physical storage capability is not within the scope of the given architecture, as it can be seen as an additional type resource accessible through the functionality of *Integration*. The fundamental aspect of a corresponding structure supporting the contextualization of data is considered through the previous mentioned functions of *Data Representation* and linking of data. Finally, possibilities for communication and visualization of feedback information must be provided. This aspect is central to any interface where people interact with applications and machines. Therefore, this functionality is already considered within the sub function of *Visualization* and *Notify Changes.*

In summary, basic capabilities for feedback integration through functionalities regarding data representation and transfer are already included in the current downstream-oriented architecture. Interfaces to further applications for the evaluation and visualization of feedback information are also intended. Additional requirements result from ensuring the linking of data for holistic contextualization. Integrated data collection must be provided for as well. Corresponding capabilities have to be considered in the subsequent development of a technological implementation.

5. Conclusion

A functional architecture for a seamless information flow with respect to data continuity was derived from the analysis of a product development process of a representative use case of an automotive OEM. In addition, the analysis of published approaches was used to identify fundamental requirements for the implementation of an integrated feedback exchange supporting decision making in previous life cycle phases like design. It was then evaluated whether the defined architecture meets these requirements within the main functions of representation, communication and administration. It was found that extensions were required to enable the linking and integrated collection of data. Addressing the identified research gaps, this leads to a solution-independent functional architecture for a DPC with explicit consideration of the integration of feedback data.

The next step is to evaluate existing technologies for implementing the functional blocks using the example of the representative use case of an automotive OEM. From this, a generalized implementation of a digital end-to-end process chain will be derived and validated in further use cases.

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