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Validation of the Intelligent and Integrated Product Lifecycle Management ("i^{2}PLM") based on Data from Smart Factories and Smart Products

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Abstract

Product engineering and subsequent phases of product lifecycles are predominantly managed in isolation. Companies therefore do not fully exploit potentials through using data from smart factories and product usage.
The novel intelligent and integrated Product Lifecycle Management (i²PLM) describes an approach that uses these data for product engineering. This paper describes the i²PLM, shows the cause-and-effect relationships in this context and presents in detail the validation of the approach. The i²PLM is applied and validated on a smart product in an industrial research environment. Here, the subsequent generation of a smart lunchbox is developed based on production and sensor data. The results of the validation give indications for further improvements of the i²PLM. This paper describes how to integrate the i²PLM into a learning factory.

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Keywords: product lifecycle management; product engineering process; i²PLM; smart customizable product families; mass customization; lifecycle engineering; CPS; learning factory

1. Introduction

1.1. Initial situation and background of research

Customers demand products that fit their individual needs. Products must have a high degree of customisation and innovations [1]. The development of such products is complex. This is why a company's ability to develop and produce such products in a successful way is a significant factor for gaining and maintaining a competitive advantage [2]. However, the widespread separation of the development of the product and the production system makes this difficult [3]. The production of customized mass products, referred to as mass customization, is a current trend [4]. An important factor that enables mass customization is that components have a variable product architecture. Variable product architecture is a system of components with interfaces from which a variety of products can be assembled [5]. In addition, there is a trend to shorten development times. Although this is necessary from a sales perspective in order to bring customizable products to the market, it does not reflect the increasingly complex products and production systems [6]. In summary, increasing individualization with increasing product diversity and the shortening of development times leads to frequent changes in product generations. In current product lifecycles, product and process engineering are mainly separated from each other [7].

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1.2. Research problem and objectives

There is a research gap in the context of Industry 4.0 on product customizability and product lifecycles [3] [8]. To counter this, a new product lifecycle is necessary, which uses the possibilities of Cyber-Physical Systems (CPS) and their data processing [9]. In existing product lifecycles, the potentials offered by using smart product and smart factory data for smart, customizable product families are not being exploited. Due to the separation of product engineering and subsequent phases data from the smart factory and smart products is not used for the product and process engineering [3]. This means that potentials for product improvement, are not fully exploited [10].

1.3. Research methodology and design

The procedure of this work is based on Österle's Design Science Research [11] [12] with a focus on a practice-oriented research approach [11]. The model starts with the analysis phase, where a mixed literature analysis with a focus on snowballing is used to develop the theoretical foundations. Product lifecycles described in the literature are analyzed and evaluated. With the theoretical foundation a reference process is created. In addition, cause-and-effect relationships (CER) in a product lifecycle and relevant data types are identified. In the draft phase, the novel i²PLM is created based on the reference process, the CERs, the data streams and fundamentals from literature. The focus of this paper is the evaluation phase. In the validation, the i²PLM is applied in an industrial research environment. The research results are incorporated into two scientific papers in the diffusion.

1.4. Limitations

Companies and their processes are usually specific and depend on the company structure, business model, and product or service range. This work is limited to smart products with modular product structures that are part of a product family with multiple generations and build in a smart factory production environment. With this work the applicability to an example product in an example environment is validated.

2. Current state of research

The research work includes the areas of Industry 4.0, smart customizable product families, product lifecycles.

2.1. Industry 4.0 in the context of product lifecycle engineering

[13] describes Industry 4.0 as a range of technologies transforming manufacturing from machine dominant to digital manufacturing [14]. Leading technologies have the core of connecting machines and objects through, for example, CPS or Internet of Things. Also, the technologies big data, simulation, autonomous robots and cloud services are creating new opportunities in a product lifecycle. Data and flexible production systems are provided that offer potential for optimising a product lifecycle [14]. Future trends of Industry 4.0 include artificial intelligence, which can optimise systems in an automated way [15]. Industry 4.0 technologies provide a basis for collecting data about production and the company and with standards data can be used for business processes.

2.2. Smart customisable product families

Mass customization means the automated manufacturing of bespoke products with lot size one on a large scale at the cost of mass products [16] [17]. For mass customization, a combination of technologies from digital manufacturing and smart factories is necessary. Product families provide the product-basis for mass customization. Product families are a range of products derived from a standard product platform to meet different market applications while having a uniform basis [18] [19]. However, interrelationships in a product lifecycle become more complicated due to the interfaces in and between individualized products and the product family. With smart products important data about the interrelationships can be generated [20] [21]. For this, the product must be equipped with sensors and network-compatibility to send sensor data during production and use, enabling the system to react to circumstances and act automatically. To use the data of smart products and smart factories, it requires an advanced data management system that can handle the heterogeneous data and make it usable for all phases of the product lifecycle. It is imperative to use the data and information from the entire lifecycle to improve product properties and the efficiency and effectiveness of processes around the product families [22] [23].

2.3. Product lifecycles

A product's lifecycle ranges from the initial product idea, through conception, development, production and use, till the product becomes unusable and is disposed of [24]. In product lifecycle management, the entire lifecycle of a product is managed [25]. Within product lifecycle management smart products have an increasing influence on processes [26]. *iPeM* is used as the reference process for the i²PLM [27]. The reference process is extended to include the *Product Engineering Process* [28] and the *Product Life Cycle* [29]. In the *Product Engineering*

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Process, the phases of product and process development are focused on, and in the *Product Life Cycle*, the phases till End-of-Life are detailed.

3. The intelligent and integrated product lifecycle management i²PLM

The i²PLM developed in this paper closes the research gap described in section 1.2. by focusing on data streams in the product lifecycle. It is structured as a phase model and consists of six modules, described in the following.

Module 1 – Main phases of the product lifecycle: The first module of i²PLM provides the user with guidance on the main phases of a product lifecycle. The product lifecycle is divided into six phases, namely; (1) Pre-development, (2) Product engineering, (3) Process engineering, (4) Production, (5) Use and (6) End-of-Life.

Module 2 – Portfolio radar: The portfolio radar gives the user an overview of the current status of other product variants, generations or versions.

Module 3 – Organizational processes: The organizational processes are divided into project management, knowledge management, market launch and data management.

Module 4 – Product lifecycle database: As a central database, the product lifecycle database' purpose is storing, analyzing and providing data on the entire product lifecycle. Functions that are defined by the CERs are used to find solutions based on analyzed data. The database covers all product types and is available in each phase.

Module 5 – Business processes: The business processes represent all activities around the product. These include the idea generation and development of the product, the planning of the production environment, validation and verification processes, and the analyzation of the utilization and decommission. After producing the product, the operation, maintenance and the various end-of-life strategies are described as processes.

Module 6 – Multi-layer for product portfolio: Since most products are developed in generations, and these generations have variants and versions, a multi-layer view has been integrated into the i²PLM.

4. Validation of the i²PLM in a learning factory

A learning factory is a research and education environment with innovative industrial digital engineering and physical manufacturing infrastructure. The learning factory Werk150 of ESB Business School at Reutlingen University is chosen as the validation environment. Werk150 is a research environment where the latest production and logistics technologies are developed and represent a state-of-the-art CPS production system. To develop and test technologies a pedal scooter and a modular, intelligent mobility box is manufactured [30].

4.1. Selection of the validation procedure

Validation is the process of checking whether the proposed solution meets the expected requirements. Here, The correctness of the overall result is validated [31]. The focus of the validation is on checking the correctness and applicability of the product lifecycle and if it meets the set requirements. The chosen method for validation is experimentation where a specific assumption or conjecture is validated in a practice-oriented investigation.

4.2. Description of the experiment

The limitations, product, production, procedure, and numbers of the experiment are described in the following.

4.2.1. Limitations

To define the limitations of the experiment the system to be investigated is described according to [32]. In this validation, the system to be examined is a product, which is developed with the i²PLM. The input variables that can be changed are in the engineering phase the construction of the product depending on use phase data. In the production phase, the 3D printing parameters can be adjusted based on the product quality data. The input variables are non-changeable are the material of the product and the production process, with its work steps. Furthermore, the end-of-life of the product is not taken into account, as the average use phase of the example product is with five years too long to be covered by this work [33]. As measurable results, the system provides the product data in use phase and the product quality in production quality management.

4.2.2. Product and production

The modular intelligent mobility box (MIMB) of Werk150 is used as a product for validation since it underlies the framework conditions of the i²PLM. This means that it is a smart product of a customizable product family with hard- and software (sensors) for storing, processing and analyzing data. It is connectable to a network to send and receive data. The lunchbox (shown in Figure 1) consists of the 3D-printed top and bottom, a temperature and humidity sensor, a data gateway, and a velcro. The use case states that it is to be leak-proof and keeps chilled food fresh for one's way to work. This means that it keeps temperature below 15 *°C* for one hour after removal from the refrigerator [34]. During the use the sensor of the lunchbox measures the temperature inside.

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Fig. 1. Smart lunchbox.

The production of the smart lunchbox takes place in Werk150. The production includes a Stratasys Objet Connex3 3D printer and assembly workstations. The production starts with 3D printing the parts. Then the parts are reworked. The sensor is attached to the lid and afterwards all parts are assembled in the final assembly.

4.2.3. Experiment procedure

The procedure for the experiment is based on the processes of the i²PLM and is shown in Figure 2. In *Variant 1* the lunchbox is already developed, and the process engineering has already been carried out. This is followed by the production of the lunchbox in Werk150 where data is generated on the quality characteristic. The product is used by experiment participants in the use phase where temperature data is generated while carrying out the use cases. These data are converted into a temperature curve which flows into a CER and triggers product and production changes for the subsequent generation (*Variant 2*).

Variant 2 is a customized lunchbox. The changes in the product engineering of *Variant 2* are mainly incorporated by changing the wall thickness, as this significantly influences the temperature curve on the product side. In process engineering, new requirements result in changes of 3D printing properties. Subsequently, the product is engineered, produced, and used and the same data types are recorded to validate product improvements.

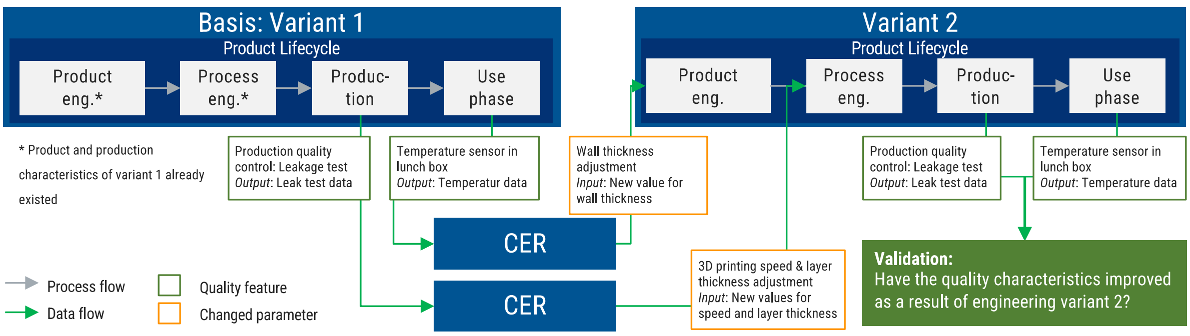

Fig. 2. Schematic diagram of the experiment procedure.

4.2.4. Number of pieces and repetitions

A partial mass is used to represent the total mass [35]. A distinction is made between the number of variants (mass of the production study) and the number of users (mass of the use study). To determine the partial mass of the production variants, the full-factorial experimental design according to [32] is used. The number of factors (n_f) that can be changed are in this experiment the part orientation and material composition of 3D printing. To check the influence of the change in factors, the quality characteristic of the density of the lunchbox is used. During production, a quality control is carried out in which the product is divided into two defect categories. For the factors, the levels (n_l) high (+) and low (-) value are selected. The experimental effort is calculated according to the following formula and results in an experimental effort of four products to be built.

$$n_r = {n_l}^{n_f} = 2^2 = 4 \qquad (1)$$

To find the right quantity of users that are representative, the Cochran formula for calculating sample sizes for smaller populations is used [36] and shown in the following. The representative quantity of users is 36.

$$n_0 = \frac{Z^2 p(1-p)}{e^2} = \frac{1{,}28^2 0{,}5(1-0{,}5)}{0{,}1^2} \approx 40{,}96 \qquad (2)$$

$$n = \frac{n_0}{1+\frac{(n_0-1)}{N}} = \frac{40{,}96}{1+\frac{(40{,}96-1)}{258}} \approx 35{,}47 \qquad (3)$$

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4.3. Results of the validation and conclusion

The results from production quality control are that *Variant 2* is in contrast to *Variant 1* leak-proof, and in addition, the surface is smoother, and the rework effort of the 3D printing is reduced. In the use phase, temperature curves are generated by 36 users and shown in the diagram in Figure 3. The average temperature curve of *Variant 1* is shown with a dotted line and *Variant 2* with a solid line. *Variant 2* meets the required temperature after one hour with 13.2 °C and improved by 6.5 °C compared to *Variant 1*. Improvements occurred in the product properties, as well as in the production time and quality.

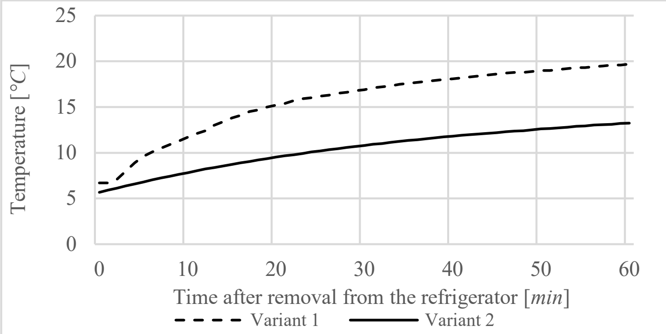

Fig. 3. Temperature curve comparison of smart lunchbox Variant 1 and 2.

5. Integration in a Learning Factory module

The i²PLM awakens the understanding of the importance of data in a product lifecycle. For this reason, it will be taught in a module in Werk150. The module will be divided into two afternoons of four hours each. At the beginning, the theoretical basics of product lifecycles are taught with a classroom method. This is followed by a 15-minute brainstorming session in which the students work out cause-and-effect relationships in a product lifecycle. This is followed by a group task with the aim of developing an improved version of the lunchbox. *Variant 1* and the production are presented. This is followed by the generation and analysis of temperature data. Based on this, the students are to design *Variant 2* in the digital engineering environment of the LF and start 3D printing. *Variant 2* is produced in the factory for the second day, followed by reworking and assembly. Afterwards, data will be recorded and analyzed. The results are presented in group presentations. In the end, an excursus on automated product engineering with the use of generative design follows. The competence requirements for application of the i²PLM approach are shown in the following KODE competence map [37] in Table 1.

Table 1. KODE competence map gained by the i2PLM learning factory module.

Technical-methodical competencies	Social-communicative competencies	Personal competencies	Activity and implementation-oriented competencies	Cognitive skills
▪ Product lifecycle ▪ Industry 4.0 ▪ Data analyzation ▪ 3D printing ▪ Generative design	▪ Presentation skills ▪ Cooperativeness ▪ Communication ▪ Problem-solving ▪ Data description	▪ Willingness to learn ▪ Personal responsibility ▪ Openness to data analyzation	▪ Independent work ▪ Ability to design and optimize complex systems ▪ Decision making	▪ Data understanding ▪ CER understanding ▪ 3-dimensional construction ▪ Monitoring / controlling

6. Summary and recommendations for further research

The i²PLM is validated in this work by building a product with two variants of a customizable smart product family. In *Variant 1*, data are recorded in the production and use phase. These data serve as the basis for improving the product in *Variant 2*. As part of the validation, the CERs for converting data from other phases into product requirements are checked. It is detected that the mechanisms of the i²PLM improved the product, measured by improved quality indicators from production and by improved product characteristics. This proved that correct data is recorded and analyzed. In summary, the results confirm the fulfilment of the research objective and a successful implementation of an integrated and intelligent product lifecycle that uses smart factory and smart product data for efficient development of customizable smart product families. A concept to integrate the i²PLM in a learning factory module is presented. As an outlook, the module is expected to start in the summer semester of 2023 and thus teach the comprehensive understanding of interrelationships and data in a product lifecycle.

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References

[1] R.K. Sikhwal, P.R.N. Childs, Product design for mass individualisation for industrial application, in: 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2017, pp. 674-680.
[2] B. Müller-Stewens, K. Möller, Performance in new product development: a comprehensive framework, current trends, and research directions, Journal of Management Control, 28 (2017) 157-201.
[3] C. Mandel, T. Stürmlinger, C. Yue, M. Behrendt, A. Albers, Model-Based Systems Engineering Approaches for the integrated development of product and production systems in the context of Industry 4.0, in: 2020 IEEE International Systems Conference , 2020, pp. 1-7.
[4] Y. Wang, H.-S. Ma, J.-H. Yang, K.-S. Wang, Industry 4.0: a way from mass customization to mass personalization production, Advances in Manufacturing, 5 (2017).
[5] A. Richter, T. Sadek, M. Steven, Flexibility in industrial product-service systems and use-oriented business models, CIRP Journal of Manufacturing Science and Technology, 3 (2010) 128-134.
[6] E. Douma, A. Belderok, M. Roelofsma, Roland Berger Focus – A modular future, in: R.B. GmbH (Ed.) Roland Berger Focus, Roland Berger GmbH, https://www.rolandberger.com/publications/ publication_pdf/roland_berger_modularization_1.pdf, 2019, pp. 1-20.
[7] R. Günther, S. Beckschulte, M. Wende, R.H. Schmitt, Wertschöpfungskettenübergreifendes Fehlermanagement, Zeitschrift für wirtschaftlichen Fabrikbetrieb, 117 (2022) 187-191.
[8] M. Pessoa, J. Jauregui-Becker, Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development, Research in Engineering Design, 31 (2020) 1-21.
[9] I. Lee, K. Lee, The Internet of Things (IoT): Applications, investments, and challenges for enterprises, Business Horizons, 58 (2015).
[10] M. Nourbakhsh, N. Morris, M. Bergin, F. Iorio, D. Grandi, Embedded Sensors and Feedback Loops for Iterative Improvement in Design Synthesis for Additive Manufacturing, 2016.
[11] M. Benner-Wickner, R. Kneuper, I. Schlömer, Leitfaden für die Nutzung von Design Science Research in Abschlussarbeiten, in, IUBH Discussion Papers-IT & Engineering, 2020.
[12] H. Oesterle, J. Becker, T. Hess, D. Karagiannis, H. Krcmar, P. Loos, P. Mertens, A. Oberweis, E. Sinz, Memorandum zur gestaltungsorientierten Wirtschaftsinformatik, http://www.alexandria.unisg.ch/Publikationen/71074, 62 (2010).
[13] E. Oztemel, S. Gursev, Literature review of Industry 4.0 and related technologies, Journal of Intelligent Manufact., 31 (2020) 127-182.
[14] D. Trotta, P. Garengo, Industry 4.0 key research topics: A bibliometric review, in: 2018 7th International Conference on Industrial Technology and Management (ICITM), 2018, pp. 113-117.
[15] Y. Lu, The Current Status and Developing Trends of Industry 4.0: a Review, Inf. Syst. Front., (2021) 20.
[16] H. Kull, Mass customization: Opportunities, methods, and challenges for manufacturers, 2015.
[17] M.K. Thomassen, E. Alfnes, Mass Customization Challenges of Engineer-to-Order Manufacturing, in, Springer International Publishing, Cham, 2017, pp. 27-39.
[18] L. Gauss, D.P. Lacerda, P.A. Cauchick Miguel, Module-based product family design: systematic literature review and meta-synthesis, Journal of Intelligent Manufacturing, 32 (2021) 265-312.
[19] M.H. Meyer, A.P. Lehnerd, The power of product platforms, Simon and Schuster, 1997.
[20] S. Raff, D. Wentzel, N. Obwegeser, Smart products: conceptual review, synthesis, and research directions, Journal of Product Innovation Management, 37 (2020) 379-404.
[21] C.Y. Wong, D. McFarlane, A. Zaharudin, V. Agarwal, The intelligent product driven supply chain, 2002.
[22] G.Q. Huang, L. Li, T. Lau, X. Chen, A generic and extensible information infrastructure framework for mass-customizing platform products, International Journal of Computer Integrated Manufacturing, 20 (2007) 292-306.
[23] X.-W. Pan, X.-Y. Zhu, Y.-J. Ji, Y. Yang, Y.-M. Wu, An information integration modelling architecture for product family life cycle in mass customisation, International Journal of Computer Integrated Manufacturing, 27 (2014) 869-886.
[24] J. Stark, Product Lifecycle Management (PLM), in: Product Lifecycle Management (Volume 1), Springer, 2022, pp. 1-32.
[25] J. Duda, S. Oleszek, K. Santarek, Product Lifecycle Management (PLM) in the Context of Industry 4.0, in: International Scientific-Technical Conference MANUFACTURING, Springer, 2022, pp. 171-185.
[26] Q. Zhang, X. Lu, Z. Peng, M. Ren, Perspective: a review of lifecycle management research on complex products in smart-connected environments, International Journal of Production Research, 57 (2019) 6758-6779.
[27] A. Albers, N. Reiss, N. Bursac, T. Richter, iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering, Procedia CIRP, 50 (2016) 100-105.
[28] J. Feldhusen, K.-H. Grote, Der Produktentstehungsprozess (PEP), in: Pahl/Beitz Konstruktionslehre, Springer, 2013, pp. 11-24.
[29] J. Niemann, A. Pisla, Life-Cycle Management of Machines and Mechanisms, Springer, 2021.
[30] Reutlingen-University, Werk 150, in: Werk 150, Hochschule Reutlingen, https://www.werk150.de, 2022.
[31] S. Fenz, A. Ekelhart, Verification, validation, and evaluation in information security risk management, IEEE Security & Privacy, 9 (2010) 58-65.
[32] K. Siebertz, T. Hochkirchen, D. van Bebber, Statistische Versuchsplanung, 2. Auflage ed., Springer, 2017.
[33] A. Dallmus, S. Vollmer, Butterbrotpapier oder Brotbox - was ist besser?, in, Bayrischer Rundfunk, Web, 2016.
[34] S. Bundesamt, Zeitaufwand für den Weg zum Arbeitsplatz, in: S. Bundesamt (Ed.), https://www.destatis.de/DE/Themen/Arbeit/Arbeitsmarkt/Qualitaet-Arbeit/Dimension-3/zeitaufwand-weg-arbeit.html, 2016.
[35] L. Berekoven, W. Eckert, P. Ellenrieder, Marktforschung, Springer, 1989.
[36] W.G. Cochran, Some Methods for Strengthening the Common χ 2 Tests, Biometrics, 10 (1954) 417.
[37] V. Heyse, J. Erpenbeck, Kompetenztraining: Informations-und Trainingsprogramme, Schäffer-Poeschel, 2009.

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