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Enabling collaborative lifecycle engineering of smart products and services by an adaptive innovation infrastructure

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Abstract. Due to the continuously rising digitalization of traditional products towards smart product-service systems, there is a considerable need for new methods, processes and IT tools in future product development. As well as for collaboration and integration of various stakeholders in engineering in particular. This contribution aims at analyzing and addressing the challenges in collaborative lifecycle engineering of smart products and services considering the entire product lifecycle. With a focus on cross-discipline collaboration an adaptive innovation infrastructure for lifecycle engineering a innovative research transfer infrastructure in Kaiserslautern has been developed in order to support a variety of heterogeneous target groups in industry and education. Focusing on hybrid prototypes along the engineering 4.0 lifecycles, the scenario of racing car within the engineering 4.0 lab infrastructure serves as an example for a cross-discipline engineering scenario.

Keywords: smart product engineering, collaborative smart product and service engineering, engineering 4.0 lab.

1 Challenges in collaborative smart product and service engineering

In the age of digitalization and information technical integration of products, processes and services the engineering complexity is rising dramatically while the corresponding potential for support by virtual engineering methods and technologies is increasing disruptively too. This means fundamentally new opportunities for product development and engineering, but also a strong need for integrated information and model management including all engineering disciplines involved. This is true not only for traditional product development phases but for the entire lifecycle of Smart Product-Service Systems (SPSS), beginning in early cross-discipline innovation phases, including the product use and reconfiguration and the end of life of SPSS components. In parallel companies have to integrate new value network partners as well as additional stakeholders in their engineering processes and to shorten innovation cycles in order to be able to meet current customer needs in line with the market [1].

Besides a multitude on converging software and hardware innovations (e.g. in the field of artificial intelligence, cloud computing, embedded chips, mobile devices and 5G) the Internet of Everything (IoE) serves as a core enabler for SPSS. SPSS are defined as intelligent multidisciplinary products capable to communicate and interact with their environment and other smart products by using product-related, internet-based services offered in data driven business models [2,3]

The transition from traditional mono-disciplinary and mechatronic products towards connected SPSS can be observed in almost all industrial sectors. Examples in the consumer industry (e.g. smart phones using app stores), in the machinery and plant industry (e.g. predictive maintenance and remote assistance services) and in the automotive industry (e.g. mobility and assistance services and platforms) show the disruptive potential of this transition impressively.

Considering the more and more dominating share of SPSS in the revenue of industrial companies, there is a strong need to enable collaborative engineering processes, methods and IT tools to meet the challenges determined by SPSS.

Beginning in early innovation phases the requirement engineering of SPSS has to integrate existing and potential use cases from customers and value network partners covering the whole SPSS lifecycle with a special focus on the use and reconfiguration. This also includes requirement development facilities gained by the analysis of product and service use data gathered in Internet of Things (IoT) platforms using industrial data analytics methods [4, 5].

According to enhanced V-model approaches like [6,7,8,9,10] cross-disciplinary functional and logical SPSS models integrating SPSS shares of the engineering disciplines mechanical, electric/electronic, software, service and business model engineering as well as the co-creation by customers and partners build the core of early product development phases. Here overall SPSS architecture models including all initial components of a well-defined system of interests have to be considered. This includes also the connectivity, communication capabilities and product and service related platforms and ecosystem components. By a partitioning process of these cross-discipline SPSS models consistent discipline specific engineering shares as well as technical interfaces have to be defined. Here agile collaboration of SPSS system architects and discipline-specific knowledge provided by business model architects, methodical and virtual mechanical engineers, electrical engineers, software engineers, service engineers and user experience experts are essential prerequisite. The methodical approach and the result can vary fundamentally depending on the concrete SPSS focus, the customer and market priorities and the company specific constraints.

The partial models of a SPSS developed in the respective engineering disciplines using a specific set of engineering methods and IT tools have to be validated within the corresponding discipline context and in an integrated context comprising a set of interdisciplinary SPSS components and environment components. As a basis for the validation the concept of the digital product twin provides a set of digital SPSS models which is specified according to specific use cases (e.g. validation use cases) and according to a concrete SPSS lifecycle phase [7, 11, 12].

The concept of the SPSS instance specific product twins serves as a core for the production planning in the context of the digital factory approach and as a basis for the

tracking, preventive maintenance and reconfiguration of SPSS during its use phase. Thus, the current state and configuration structure of each SPSS instance is permanently known by the SPSS provider and linked with the sensor data captured by the SPSS over the operating time.

The relevance of the digital twins for this purposes in industrial companies is also analyzed in studies like [13]. Here 92 percent of the respondents for instance stated that they were concerned with the concept of the digital twin because they see the influence and opportunities of the concept on digitization projects. Of those surveyed, 36 percent had already launched initiatives and 50 percent said they would launch initial pilot projects in the next twelve months. However, more than 50 percent of respondents still indicated that a transfer to ongoing operations is not expected until the next three years. There is significant relevance of the concept of the digital twin in a cross-company ecosystem solution. Just under 80 per-cent of respondents still indicated that use is internal to the company. According to respondents, internal use will change to cross-enterprise use in the next five years (77 percent of respondents) [13].

2 Collaborative engineering infrastructure concept for smart Product-Service Systems

The main vision to meet the mentioned challenges is to establish a highly adaptive infrastructure for the engineering of future SPSS in order to systematically support the knowledge transfer in the field of digitalization and the associated transformation of business processes and to create their own innovative engineering ecosystem. Enabling companies to serve customer requirements in the future with new business models as well as smart products and services in a most innovative way. As outlined in chapter 1, products in the future will have significantly more complexity (e.g. high amount of partial models) than traditional products, for example. And the many different partial models in particular will have to be considered holistically in terms of information technology using an integrative approach in order to keep the complexity in the engineering phases manageable. Due to the increasing servitization within the SPSS and their individual functionalities, however, there are also considerably more interfaces, for example to other surrounding ecosystems and industries (e.g. system of systems) and this throughout all life phases of a SPSS, not only in the classic usage phases as past products were usually classified.

The engineering 4.0 lifecycle, as shown in figure 1, describes a multi-stage process from requirements development, interdisciplinary product design, discipline-specific design, product integration and validation, production and product logistics to the operation and reconfiguration of SPSS. The process is also bidirectional, which means that all partial models are linked with each other in terms of information technology and feedback from the various phases along the life cycle is available in an integrated form. On the basis of this guiding process, cross-disciplinary requirements such as those to the infrastructure were derived on the basis of well-founded analyses in order to provide adequate support for the engineering of SPSS. One of the main focuses here

was on the consistent integration of all partial models within the engineering 4.0 lifecycle. Furthermore a conceptual framework for a future collaborative engineering infrastructure was developed (as shown in figure 2) based on the identified challenges as described in chapter 1 and the expertise of the participating professors from various disciplines. In addition to the information technology coverage of the partial models along the engineering 4.0 lifecycle, for example, the aspects of the corresponding lifecycle phases regarding a comprehensive knowledge transfer from and to the industry were also included in the conception of the framework.

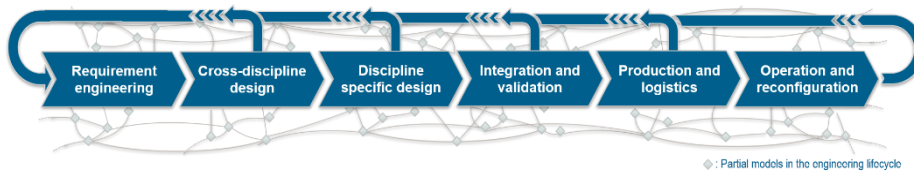


Figure 1: Engineering 4.0 lifecycle for SPSS

On the one hand, this includes direct exchange with industry for example, through use-cases and best practices from specific industry applications. On the other hand also the transfer of knowledge to industry from the research activities of the various partners and stakeholders along the engineering 4.0 lifecycle. Furthermore, a distinction is made between different levels of knowledge transfer (demand-oriented transfer): Beginner, enthusiast, expert. In addition, the depth of content can be scaled again depending on the industrial purpose or educational purpose. E.g. trainees (e.g. pupils, students) will be enabled to get to know and be able to use appropriate engineering methods and processes already during their training. The focus here is not only on the direct acquisition of knowledge, but also on the development of further competencies in the engineering field, such as the development of associated soft skills. In order to be able to build up and transfer this knowledge, the infrastructure concept is thus combined with a corresponding heterogeneity of different experts and partners (e.g. chairs, institutes, key software partners, etc.) as also corresponding laboratories (e.g. a design thinking tank laboratory and a mobile engineering lab) are integrated into a virtual collaboration concept in order to achieve the highest possible coverage of all relevant disciplines for the engineering of future innovative SPSS. However, it is not always possible to develop the innovation potential of the disciplines and experts involved in a collaborative manner and to leverage it in the most comprehensive manner possible. To address this in the context of the engineering 4.0 lifecycle and the corresponding conceptual framework for a collaborative and adaptive engineering infrastructure, a highly dynamic interior concept was designed on the basis of studies on innovative working methods and future office space concepts. A so-called engineering 4.0 lab (e4lab) [14] was set up for this purpose based on the derived requirements from the analysis described above.

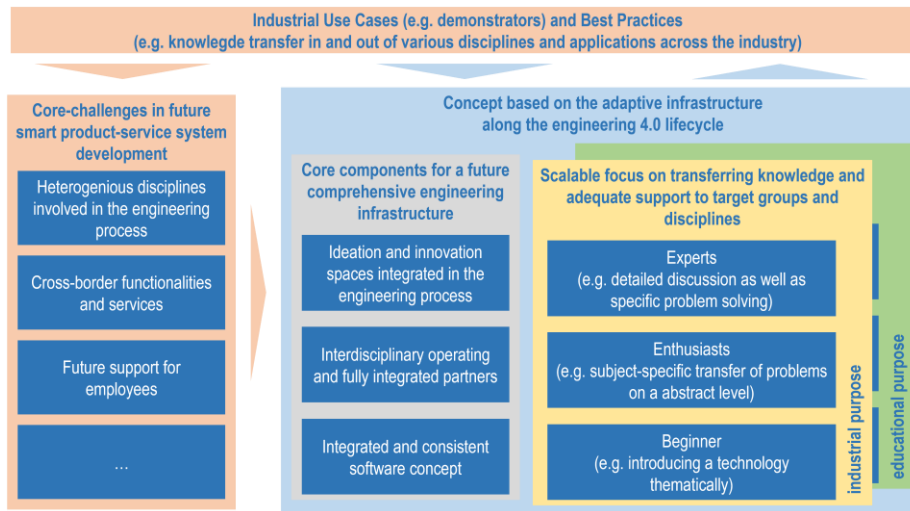


Figure 2: Conceptual framework for a collaborative engineering infrastructure

The engineering 4.0 lab is operated by 9 professors with 20 scientists and covers the engineering 4.0 lifecycle holistically in terms of information-technology as well as specialized departmental with the participating professors, as shown in the figure 3 on the upper half. This concept divides the engineering 4.0 lab area into three consecutive areas: Innovation and Ideation Area (as shown in figure 3); Educational and Software-based training Area; Elaboration and Reconfiguration Area.

The innovation and ideation area is the central hub in the infrastructure of the e4lab. this is where the exchange of content between the various stakeholders mainly takes place. The setup and the fully flexible structure allows for a complete redesign of the space within a few minutes. In this way it is possible to react adequately to the needs of the respective partners in order to maximize the quality of the according knowledge transfer. Another special feature is the integrated design thinking area, which can also be virtually connected to a specialized design thinking tank laboratory for expert workshops and used collaboratively. In order to facilitate companies' entry into the transfer process, various physical and virtual demonstrators and use cases have been set up and mapped in the innovation area along the engineering 4.0 lifecycle (various partial models) and linked with each other. The e4lab software concept also plays a key role here. Together with the strategic partner Siemens Industry Software GmbH [15], a holistic software concept was designed and set up along the engineering 4.0 lifecycle in order to achieve consistency across all partial models and partners within the entire e4lab infrastructure and areas. In the Educational and Software-based training Area, there is also the possibility to work in detail on focused problems referring to the software ecosystem and partial models used and to evaluate various solution areas. Here, the main focus is on scalable transfer at the content level in order to be able to work out the required solutions in a target-group-oriented manner. This includes, for example, general training on various individual software components in use as well as specific software concepts for concrete applications from industrial use cases.



Figure 3: Innovation and Ideation Area of the engineering 4.0 lab Kaiserslautern

The third area, the Elaboration and Reconfiguration area, is primarily used for building and testing the physical demonstrator scenarios. Here, it is possible in particular to build up and test the challenges of future SPSS, specifically for the scenario intended and thus to validate it before it finds its way into the corresponding innovation area. This means that a scenario can be updated promptly as soon as new aspects arise from research or from the industry itself. As also ensuring all demonstrators and partial models along the engineering 4.0 lifecycle are always up to date and conducive to innovation, in order to be able to ensure the highest possible innovative potential in the transfer of knowledge as well as in collaborative work within SPSS engineering in the future. In addition, in pandemic times like these, where aspects such as travel restrictions and social distancing are in the foreground making it difficult for some companies to access

transfer offerings, the e4lab has been successively expanded to include specific aspects such as virtual collaboration workshops, virtualization of physical demonstrator scenarios, virtual tours, etc., in order to cover not only the stationary infrastructure of the engineering 4.0 lab, but also to make it easily accessible and thus available to various target groups on a virtual and on-demand basis. The engineering 4.0 lab now also has a virtual innovation and collaboration ecosystem in the form of a digital twin of the engineering 4.0 lab that complements the stationary offerings.

3 Smart product-service system based hybrid prototypes as an exemplary engineering lifecycle use case

One area of application from engineering, which creates a constructive, agile and at the same time cooperative framework distributed over the complete engineering 4.0 lifecycle, is the combination of initially SPSS-dependent but equally discipline-dependent combined know-how for the creation of prototypes. Through this, the complex SPSS and especially their integrated sub systems can be virtually tested to be developed and enhanced in a most efficiently and data-driven manner in terms of information technology.

The comprehensive SPSS prototyping considers the holistic integrated engineering lifecycle management of heterogeneous systems (e.g. further described in [8, 9, 10, 11]) and promotes, among other things, the parallelization of the interdisciplinary development steps by applying agile engineering methods for example. Cross-disciplinary relevant partial development processes can be considered together with downstream process steps at an early stage as a result innovation cycles can be shortened. Thus the functional SPSS prototypes can be designed in a collaborative way by incorporating all relevant product information from e.g. mechanics, electric/electronics, software as well as product-relevant and product-specific external dependencies as covered by the involved professors and scientists along the engineering 4.0 lifecycle supported by the adaptive innovation infrastructure of the e4lab. Depending on the existing physical, virtual and/or simulated sub systems, these can be applied throughout the entire product lifecycle according to the needs and requirements. In terms of the SPSS lifecycle, prototypes continue to develop in line with the maturity of the SPSS. Thus, in the early phases of SPSS development, mostly purely virtual or simulated models are initially designed. For example, to be visualized initially by using virtual reality (VR) methods and techniques. In the Phase initial design reviews can be carried out and first functions of the later physical, smart product or service can be simulated and further tested in different use case specific scenarios. Be able to be expanded in the further development, when the first physical prototypes have already been produced. The amount of virtual components is increasingly being replaced by physical components and developed in an iterative way into a hybrid prototype. The so-called hybrid prototype is in this case a prototype consisting both, virtual and physical systems and components which can be realized via augmented reality (AR) and mixed reality (MR) methods and techniques. Even before the complete physical implementation, hybrid models of the SPSS can be

created and multimodally simulated and validated in their actual functionality and interaction with the intended context or environment. Joint interaction with these prototypes creates intuitive and immersive working environments in which specialists experience a comprehensive understanding of complex interrelationships of the SPSS in close cooperation with each other. These methods and tools promote the merging and combining of the knowledge required for product understanding across the entire value chain.

Using exemplary partial models of the KaRaT e.V. [16] racing car, the cross-lifecycle design of processes, methods and IT tool chains for the engineering of SPSS is to be further described and thus the continuous information technology networking in the engineering 4.0 lifecycle is to be demonstrated as shown in figure 4. The phase of requirements engineering at the beginning of the engineering 4.0 lifecycle must already be designed cooperatively and iteratively along the involved stakeholders and partners in order to be able to determine, analyze and define the systems requirements. In this context, an essential step is to provide the results in downstream processes or partial models and their validation to be fed back in order to adapt the feedback in the corresponding requirements models. Based on the requirements models, the interdisciplinary product design can be implemented in the first purely virtual prototypes in one of the subsequent partial models. The racing vehicle is now initially created based on abstract parameters (e.g. geometric information, safety restrictions etc.) and is available virtually, for example in virtual reality applications, for design reviews or construction space estimations. So the system model is used to validate design requirements or initial system behavior or functionalities in the early phase of the SPSS development. Likewise, variants of the racing car can be compared with each other and serve as the basis for further decisions.

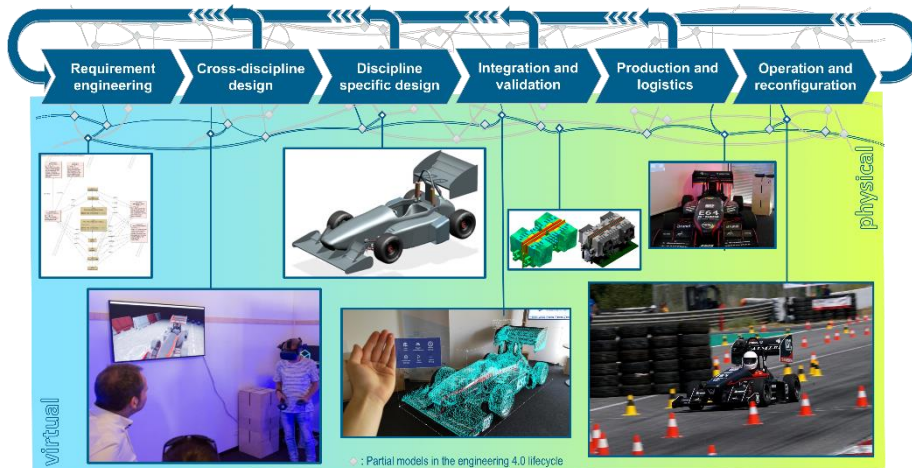


Figure 4: Exemplary prototypes across the engineering 4.0 lifecycle based on the design Use-Case of the KaRaT e.V. racing car

This first early prototype of individual systems (e.g. components) and also the entire vehicle can lead to adjustments in the previously created requirement models in an iterative way. For example, different iterative loops optimizing the further requirement models, which can be tested again as a revised model of a prototype in a collaborative way with all involved cross-discipline experts and partners. This procedure links many individual partial models of the vehicle with each other in a holistic way and creates a highly innovative information transfer that is not exclusively forward-driven, but also includes equally backward-driven feedback processes. In the further phases in the engineering 4.0 lifecycle, the first physical components such as the chassis and many other components of the racing vehicle are also created in addition to the purely virtual prototypes. Together with prototypes of other product models, some of which are already virtual or simulated, these can grow into a more appropriate, fully integrated hybrid prototype. With the merging of all information technology data-driven systems, supported by AR, physical components can be combined with virtual aspects and systems and/or validated. As a basis for the new AR scenario, data from the earlier models can be integrated and processed according to the development status and needs at the specific maturity level of the system. This enables a very powerful network of all data and specific SPSS sub systems, models and information at an early stage in the engineering 4.0 lifecycle, which compresses detailed knowledge and leads to a deep SPSS understanding for discipline-dependent experts, beyond their actual competencies. The vehicle can be flexibly developed further in application-specific ways, for example in VR, AR, MR and/or other systems combined. Information from collaborative decision-making processes is also structured on a higher level through networking and can thus also be used for other systems and partial models. This creates a very powerful SPSS at an early stage in terms of its lifecycle.

In the vehicle's usage phase, prototyping is used for further validation (e.g. of new services and functionalities) and dynamic reconfiguration of the actual SPSS instance. The special feature here is the combination and variety of available data and possibilities. Among other things, technical analyses of usage, new software developments, but also the practical experience of the driver as an end user can be included and directly linked to the physical, fully operating SPSS in the field (like in this example the racing car). Hybrid scenarios can be built on its physical as well as information technology foundations and tested directly in real use cases. The new findings thus count as valuable fully validated further developments that can be used directly for new SPSS development.

For example, a further developed rear spoiler can be linked to the real vehicle as well as the existing models and the first steps for a new SPSS instance can be initiated. In small, functional prototypical implementations, possible changes can thus be tested quickly and iteratively directly on the vehicle.

The engineering 4.0 lifecycle is not completed at the end but enables a permanent connection back to the earlier phases in order to start the next development cycle or reconfigure the existing SPSS instance in the field. Particularly at this late stage in the engineering 4.0 lifecycle, the continuous, lifecycle-accompanying consistency of the cross-disciplinary SPSS models, process-related and at the data level, supported by a strongly integrated IT infrastructure, is benefited from.

4 Outlook & Summary

The contribution shows how an adaptive innovation infrastructure is supporting a collaborative smart product and service lifecycle engineering. For this purpose, a conceptual framework for a collaborative engineering infrastructure was developed and presented on the basis of the discussed future challenges for the development of smart product service systems (as shown in figure 2), which includes the core components for a future comprehensive engineering infrastructure along the engineering 4.0 lifecycle (as shown in figure 1). Another focus is the integration of the various disciplines and partial models involved supported by an adaptive innovation infrastructure.

In order to be able to promote an adequate transfer of knowledge in future SPSS engineering, a further point of the framework is the transfer of knowledge, in particular to and from industry. Especially on knowledge transfer in and out of industry at different scales (e.g., industrial purpose, educational purpose) and levels of granularity (e.g., beginner, enthusiast, expert). Finally, the conceptual framework was translated into reality with the engineering 4.0 lab in Kaiserslautern, creating an adaptive innovation infrastructure. This includes the know-how of 9 professors and 20 scientists along the engineering 4.0 lifecycle (as shown in figure 3) as well as the integration of further experts (e.g. key software partners) and partner labs (e.g. design thinking tank laboratory). The possibility of integrating additional experts, for example, is a future-oriented approach in case further experts are needed along the engineering 4.0 lifecycle. This prevents knowledge gaps and enables seamless integration into the existing infrastructure of other fields of expertise and experts in the future.

Based on the topic of hybrid prototypes along the engineering 4.0 lifecycles, the scenario of the race car within the engineering 4.0 lab infrastructure was then used as a cross-disciplinary example scenario to demonstrate collaborative work within the adaptive innovation infrastructure in the operation of the engineering 4.0 lab. This includes various partial models from requirements development to the usage phases of the SPSS as well as its reconfiguration in the field (as shown in figure 4).

Further research is needed especially in the area of virtual collaboration in the context of the digital twin of the engineering 4.0 lab as one potential new normal, as well as in the further integration of additional disciplines such as economics and didactics on the one hand, and the integration of socio-political aspects in the area of sustainability on the other hand. As they are not covered completely by the participating experts and professors involved in the engineering 4.0 lab at the moment. In order to consolidate the lessons learned from the operation of the engineering 4.0 lab, there are already initiatives started such as the internationally ERASMUS+ project Connect4PLM to ensure the feedback in the area of transfer activities from research to future education and industry.

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