

Towards Model-based Definition of Digital Product Passports Supporting Sustainable Smart Product Lifecycles

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Abstract: Sustainability has emerged as a key priority across industries, requiring robust mechanisms to enhance transparency and accountability throughout the lifecycle of smart products. The Digital Product Passport (DPP) presents a solution for achieving these goals by aggregating critical product-related data. However, practical implementation encounters significant obstacles, including fragmented data sources and disparate system integrations. This paper presents an approach that uses the Systems Modelling Language (SysML) to overcome these challenges. First, the DPP's essential components are defined and derived from data generated during product development. Implications from the development of the DPP are summarized and contrasted with the potential of a Model-based Systems Engineering (MBSE) approach. The proposed approach establishes traceable relationships between model elements and DPP attributes, enabling seamless data flow. To validate the feasibility and effectiveness, as an example a 3D printer was developed to create an instantiation.

Keywords: Digital Product Passport; Model-based Systems Engineering; Product Development; Product Lifecycle Management; Sustainability

1 INTRODUCTION AND SETTING

The development of smart products has changed significantly in recent decades due to various complexity drivers. On the one hand, products have become more sophisticated and increasingly complex because of the evolution towards smart and networked products. On the other hand, value chains are more complex and more stakeholders have a direct or indirect influence on product creation. Smart products are cyber-physical systems with the ability to connect via the internet that provide various technologies and internet-based services [1, 2]. These properties enable smart products to offer a wide range of possibilities for adding value to the user. Smart products are, therefore, more complex and more challenging to develop. The generation of data and information in the context of development, production and use poses new challenges for data processing and management systems. In addition, new regulations, initiatives and laws require the collection of additional information during the creation and usage of products, for example, to ensure circularity and sustainability. This information must be collected centrally, which can be done using the Digital Product Passport (DPP). At a regulatory level, the European Union (EU) added product creation and evaluation regulations with policy instruments like the Green Deal in 2019. More political initiatives, such as the Clean Industrial Deal, are in preparation. Approaches such as Systems Engineering (SE) can help to solve the problems described in developing smart products. SE is an integrated approach to help develop complex products and support it by processes, methods, information, tools or assemblies to achieve a specific engineering goal [3]. The entire systems lifecycle is in the foreground, which underlines the influence on the circular economy and especially the DPP. Since traditional document-based approaches to systems engineering are often difficult to maintain or evaluate, these challenges can be overcome by using Model-based Systems Engineering

(MBSE) in addition to general SE approaches [3]. MBSE serve as an approach with focus on central, digital product representation created systematically and across domains [4, 5]. In this way, the models provide an integrated view of the system, from requirements to the initial concepts in development to detailed planning and production in manufacturing. The models are essential in later use because they can be used as a single source of truth regarding the product, since they are unambiguous, up-to-date and consistent. With MBSE, cycle-oriented product development can be supported [6]. The DPP is currently still in the early phase of its practical introduction. Although some guidelines exist, such as the Digital Battery Passport, large parts of the specific implementation are still unclear [7-11]. In principle, the DPP will apply to a wide range of products in the future and will combine a framework that integrates material information, instructions, and sustainability factors.

The paper presents an approach that collects exemplary system models from the development, production and usage phases and transfers them to a digital product platform which is used as a DPP. To gain an understanding of the DPP, potential data and components of the DPP are collected and clustered. As a set of information, these form a potential framework for a complete DPP. The following models are created and structured in a standardized language to establish traceability. Finally, an industrial implementation is presented that schematically describes the development of a 3D printer as a smart product. The complexity in the development is handled by using an MBSE approach. By linking system-relevant requirements in the development at an early stage, the course is set for further use and intensification. Therefore, the following research questions are answered:

- Which possible data sets can be mapped in the DPP and lead to implications for applied approaches?
- How can an MBSE approach address and resolve these implications at an early stage?

2 EXPLORING DIGITAL PRODUCT PASSPORT

2.1 Defining Digital Product Passport

In a systematic search, thirteen sources were found and examined that provide a basis for DPP, including the EU-funded CIRPASS projects, which developed roadmaps for DPP prototypes in the fields of electronics, batteries and textiles (see Fig. 1). The DPP is defined as a dataset containing product components, materials, chemical substances, reparability details, spare parts availability and disposal information [12, 13]. The DPP evaluates product design performance regarding reusability and tracks product lifecycle, including origin and event history. It records environmental impacts, identifies materials and resources, and provides operational data. Initially based on the Digital Battery Passport, DPP categories include value and supply chain, sustainability and circular economy, diagnostics, maintenance, and performance, and product information [11, 14]. There may be an overlap between categories [15]. The DPP mainly but not only focuses on resource-intensive and complex products [16], providing detailed sustainability information throughout all lifecycle phases from development to disposal or reuse and identifying areas for resource conservation [12, 17, 18]. The introduction of passports that provide detailed information on materials and components is intended to make sustainability opportunities visible throughout the entire lifecycle [19]. This increased transparency ensures consumer awareness of sustainability and thus influences consumer behavior. In this way, sustainable consumption decisions can be increasingly made [10]. At the same time, the DPP acts as an indicator of environmental protection, showing which steps or interventions can be carried out in the product lifecycle to protect resources [19]. Integrating sustainability aspects and taking a comprehensive view of all lifecycle phases is consequently considered a climate-friendly instrument that contributes to achieving an efficient and resource-saving economy [20].

To make informed decisions within a circular value chain, access to all relevant data must be as comprehensive as possible [14]. Therefore, manufacturers, users, and all other parties involved throughout the product lifecycle are included [21]. The DPP promotes the exchange between these different actors, who can be summarized under the term stakeholders. Stakeholders can be divided into two groups: those directly associated with the product (manufacturer, maintenance and/or service provider, end user, etc.) and stakeholders in product regulation (governments or authorities) [13]. Circular value creation is therefore based on the principle of providing all relevant stakeholders with the necessary information in a timely and transparent manner. When implementing the circular economy through the DPP, the concepts of the 9R strategies are of central importance. In particular, the strategies of reconfiguration, repair, reuse, refurbishment, remanufacturing, and recycling [22-24] are paramount. The DPP should support all these processes by providing targeted information on possible repair measures, reuse options or recycling procedures.

Table 1 Suggested information and categories for digital product passport

Category/Subcategory/Information	Sources
General product information	[11, 13, 15, 25-31]
Product-specific information	[11, 13, 25, 28, 29, 31, 32]
Product services	[11, 13, 14, 25, 30, 31]
Regulation laws and standards	[11, 13, 25, 26, 28-31]
Storage procedure (operation)	[28, 32]
Product data	[13, 25, 30]
Operating and safety instructions	[11, 13, 15, 25, 28, 31, 32]
User Feedback	[13, 25, 30, 32]
Components, materials and hazardous goods	[11, 13, 15, 25-32]
Manufacturing and production information	[11, 14, 15, 25, 27-29, 32]
Storage procedure	[11, 15]
Transportation procedure	[11, 15]
Information on the supply chain	[11, 13, 14, 25, 28, 29, 31, 33]
Other data of the value chain	[14, 15, 29-31]
Customer data	[11]
General information on environmental protection, footprint, CO ₂ emissions	[11, 13-15, 25, 28, 29, 31-33]
Detailed data on environmental characteristics and CO ₂ emissions	[15]
Working conditions and social conditions	[11, 28, 29]
Energy efficiency/consumption during operation	[11, 14, 25, 28, 29, 33]
Recycling options	[13, 15, 25, 28-30, 32]
Disassembly options and instructions	[11, 14, 15, 25, 26]
Disposal options	[11, 13, 15, 25, 27-29, 31, 32]
Repair options and instructions	[14, 28, 32]
Usage history and condition information (also durability)	[11, 14, 15, 25, 30, 31]
Change History	[11, 13, 15, 25, 27, 28, 32]
Warranty information	[28]
Maintenance information	[11, 14, 15, 25, 28, 31]
Information on spare parts	[11, 31]

In this way, a product's lifecycle can be extended, and material waste can be reduced, leading to a more economical use of natural resources. The individual objectives are closely linked and can each be analyzed at different levels of detail. Sub-strategies can be categorized into three levels to align the DPP with circular strategies such as the 9Rs (see Fig. 1). The lowest level, the energetic level, includes strategies that utilize product components for energy or thermal purposes at the end of their lifecycle. The next level divides product components into materialities for use and recovery in other cycles during or after use. The highest strategy level is the functional level. This examines product components according to their function of reusing and recycling product components in the same, similar, or modified functionality. With each higher level, complexity increases, and so do the potential benefits for the circular economy and the reduction of environmental impacts. The DPP thus forms a data hub that various stakeholders can access to increase resource efficiency and transparency along the product lifecycle in the sense of closed loops [34]. Therefore, the objective and integral part of the DPP should include, standardize, and evaluate detailed information on the functional level.

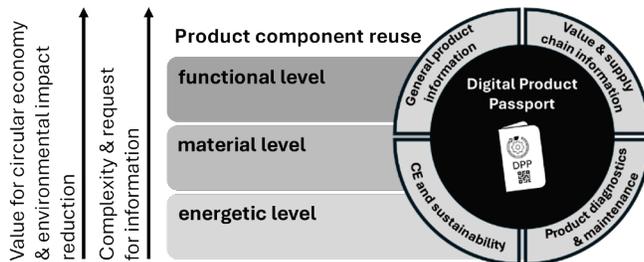


Figure 1 Schematic depiction of the digital product passport with different levels of implementation of sustainability strategies

A detailed DPP can benefit sustainability strategies (and companies that buy parts and components). However, for the respective manufacturers, a detailed product passport represents an increase in effort and, particularly, a risk to trade secrets. It can be expected that each category of company and industry will disclose data on this. However, the question that needs to be clarified is how detailed this information needs to be. Smart products may have unique DPP information requirements. These are currently not being given much consideration, which is why the information requirements for smart products have not been explicitly included in the various tables of content-related components. About legal requirements, for example, the terms of use are considered here as a product parameter, which are needed for the use of software, among other things [35]. This point often affects smart products without being explicitly mentioned here.

2.2 Demands for the DPP

A permanent guarantee of availability, extending beyond the manufacturer's lifespan, must be ensured [8]. Technical and organizational compatibility and interoperability are equally critical, especially where large data volumes are involved [36]. Autonomous data exchange is helpful [36], and legal frameworks can support automated information sharing [8]. With limited resources, companies can opt for DPP-as-a-Service, accompanied by potential financial support measures [37].

The information integrated into the DPP should be selected to minimize administrative overhead [8] while protecting trade secrets. A thorough analysis of information requirements is imperative [38], as these can differ by industry [27], product complexity, or potential for damage [32]. Even under restricted access, sensitive or confidential product information may be required [39]. Therefore, data authenticity, reliability, and integrity must be guaranteed [8]. It is recommended that DPP data be verifiable using internationally recognized standards [39], and new standards may be introduced to bolster data verification [17]. However, the complexity of the DPP can make uniform standardization more challenging [17]. Data collection may rely on the Internet of Things, cryptographic authentication, artificial intelligence (AI), machine learning, or digital twin technologies [40]. The collected data undergo curation processes, such as de-noising, cleansing, imputation, and linking databases via digital threads, alongside big data

analysis [40]. Furthermore, the data transmission interval must be clearly defined [27], and all product information must remain current throughout its lifecycle [40]. The DPP should address existing legislation such as the right to repair, extended producer responsibility, and the General Data Protection Regulation [27]. In addition, creating shared standards for data requirements and data protection is advisable [37], but the DPP's inherent complexity can complicate establishing universal norms [17].

2.3 Implications for a MBSE Approach

Based on the established requirements, implications for an approach from the product development perspective will be transferred. By clustering into potentials (P1-P5), relationships can be established:

P1 Data management, traceability and modeling: Due to the increased complexity caused by smart products and large and complex value chains, an MBSE approach contributes to reducing this complexity by systematically describing systems. A uniform and standardized language meets the distinct call for standardization across all value-added partners and administration in an MBSE environment. For example, SysML ensures uniformity as a system modeling language with components for requirements up to product structures. The transfer into other data formats, such as XML or JSON, and the correlation of this data between languages, enables independent and standardized exchange. A model-based approach ensures uniform modeling languages and the intuitive networking of models, even across different lifecycle phases. The necessity for standardized, unambiguous and versioned identifiers of the models and metadata can be met and even further developed and promoted in an MBSE environment. Interfaces and configuration points are also already part of model-based approaches.

P2 Lifecycle and sustainability: The necessity for central collection, storage and tracking of sustainability-related information distributed over the lifecycle, such as requirements, must already be created and thought through in the development of the products. MBSE offers the possibility of laying the foundation for the requirements of the DPP. By consciously creating requirements for this, products can be compared with established requirements in later phases. Generalized creation for product requirements, which result from the 9R strategies, can also be integrated in the early stages of development via model-based integration. The feedback of usage data (actual data) to the sustainability-related information created in the requirements model is not only possible via the model-based approach but is expressly desired.

P3 Variation and integration: DPP requirements such as the embedding of product variants and their compatibility in a central system model, the development of a digital twin that can interact with the DPP, the consideration of supplier and stakeholder data in the system models and the standardized exchange of information using ontologies and reference models are not only possible via MBSE, but are an integral part of it. The early stages of development are

crucial, as they set the course for later seamless integration and the definition of interfaces to the digital twin, for example.

P4 Compliance & Security: Compliance with legal, normative and internal company regulations, which are an integral part of the DPP, can be ensured in MBSE methods, for example, by formally recording them in requirements. Role and data access management can also be represented officially using MBSE.

P5 Automation & Forecasting: The generation of context-related information for later lifecycle phases or sustainability strategies should be part of the DPP. Automated forecasting models or strategy recommendations can be used to achieve this. However, this requires machine-readable and machine-interpretable data. The consistent, versioned and standardized language in MBSE models and the possibility to compare this real-time data in use enable potential for AI applications. The forecast models correlated on the MBSE models with usage data are only possible through the consistent use of the model-based application.

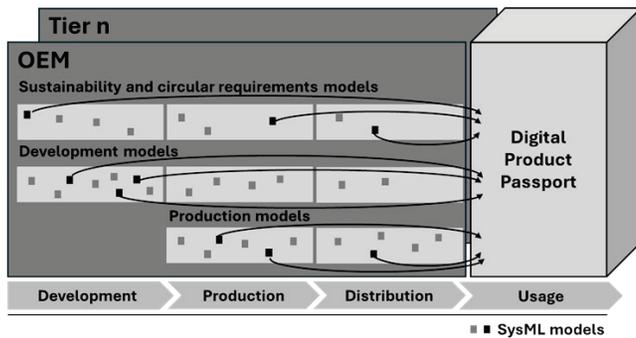


Figure 2 Model-based digital passport creation

Fig. 2 schematically shows how various system(sub-) models from different phases, domains and development stages are extracted into the DPP. The selection of models is adapted to the importance of the objectives already described.

3 DEVELOPING A MODEL-BASED 3D PRINTER DPP

A commercial, consumer-grade and beginner-oriented 3D printer is designed and validated using a model-based development approach to fully handle DPP requirements. Several system models in different product creation phases are created and connected (see Fig. 3).

A general requirements model in which the 9R sustainability strategies, including enhanced strategies like reconfiguration, are defined as overarching goals. Various system models have been developed to handle individual development goals. These include a specific requirements model for the 3D printer with functional, performance and safety requirements, a functional model that divides the printing process into sub-functions such as material supply, heating, print head movement and layer deposition, a product structure in which the individual components (e.g. frames, extruders, sensors) and their interrelationships, a material model that describes the materials used (e.g. plastics, metals)

and their properties in terms of durability and recyclability, and a usage data model that collects information about maintenance, usage cycles, wear and tear, and operating environments (e.g. temperature, humidity). These models are linked using unified, standardized language (in this case SysML and JSON). This creates a consistent digital image of the 3D printer, ranging from the initial sustainability requirements (based on the 9R strategies) to the physical components and the actual operating and maintenance data. Implementing a DPP for a complex product such as a 3D printer requires a holistic view of several factors. As early as the development stage, ecological and sustainability-related requirements (e.g., resource conservation, reusability of components) must be incorporated into the general requirements model and later specified in the material and product structure model. Merging the functional model (description of the processes) with the physical model (components) and the material model (material properties) is challenging. Consistent modeling allows for a seamless data flow from the requirements to actual operation.

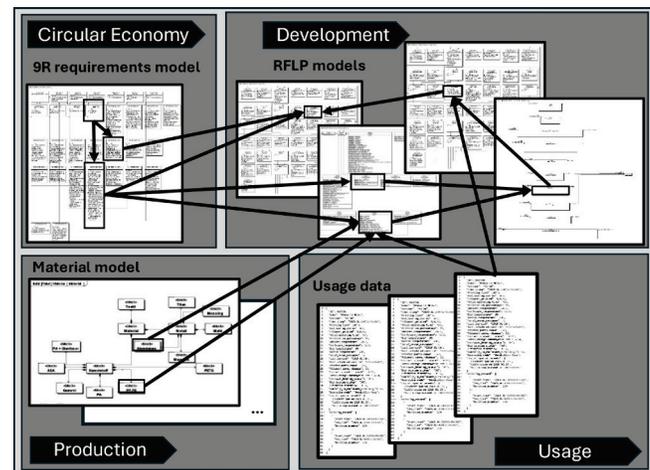


Figure 3 Model-based digital product passport data models of a 3D printer

A 3D printer can be developed or produced in different configurations (e.g. different print volumes, nozzle types). All variants must be mapped in the model and traced later in the DPP. At the same time, data from external partners (suppliers, stakeholders) must be integrated into the system model. Legal provisions and internal guidelines (e.g. regarding data protection or occupational safety) must be formally stored in the requirements. Due to the large number of specifications and standards, this can quickly become confusing. The possibility of using real-time data from the usage data model for AI-supported predictions or maintenance strategies requires that all data is machine-readable and available in standardized formats. MBSE offers a structured approach to overcome the abovementioned challenges. By using SysML or JSON, requirements, function models, product structures, and usage data are recorded in a standardized form. This ensures a clean interface definition and facilitates data exchange between different tools. Each sub-model is linked to the relevant building blocks of other models (e.g., requirement links in SysML). For example, sustainability requirements (9R

strategies) can be traced back to the material model and later validated by accurate usage data. MBSE methods make it possible to capture different versions of the 3D printer in a central model. This facilitates the management of product variants and simplifies integration into the DPP. Legal and normative requirements are formally stored in the requirements model. Safety-related aspects (e.g., access to specific assemblies or materials) can be controlled via role and rights concepts. Since all data is available in standardized, versioned formats, automated analysis during the operation of the 3D printer (e.g., for predictive maintenance) is easily possible. The usage data model can provide real-time information, which is evaluated for forecasts and optimization strategies.

4 CONCLUSION

The model-based approach ensures comprehensive traceability and integration of all relevant data throughout the product lifecycle. The potentials P1 to P5 can be met as follows:

- P1: A uniform modeling language and standardized interfaces enable consistent data management with explicit, versioned identifiers.
- P2: The early anchoring of the 9R sustainability strategies in the requirements model and their implementation in the material and usage data model ensure that sustainability aspects can be considered and verified over the entire lifecycle.
- P3: The mapping of different 3D printer variants and the integration of supplier data are facilitated by MBSE. In addition, the model-based system description lays the foundation for a possible connection to a digital twin.
- P4: Formal and versioned requirements allow legal and normative specifications to be mapped, while role concepts can be stored in the model.
- P5: The consistent, standardized database allows the use of AI algorithms for prediction (e.g. maintenance requirements, material consumption) and contributes to automated decision-making.

In summary, the approach presented systematic management and organization of complex multi-domain data over the lifecycle with seamless, standardized and traceable data integration into the DPP. The possible correlation between the development models and the data requirements of the DPP is shown.

Although MBSE already meets many of the requirements of the DPP, the complementary use of a product lifecycle management system (PLM) can contribute to further optimization. Above all, a PLM system enables efficient change and version management across all phases and seamlessly integrates additional processes (e.g. release and supplier workflows) into the overall digital picture. In this way, model-based development can be further professionalized and extended beyond the boundaries of individual departments and companies. However, the details of integrating machine-readable information from modeling into a PLM environment need to be further investigated and

refined. The automated extraction of product information relevant to the DPP is also part of future research.

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