Theodor Borangiu · Damien Trentesaux ·
Paulo Leitão · Christoph Legat
Editors

Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future

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Editors
Theodor Borangiu
Faculty of Automatic Control
and Computer Science (Automatica)
National University of Science
and Technology POLITEHNICA Bucharest
Bucharest, Romania

Paulo Leitão
Polytechnic Institute of Bragança
Bragança, Portugal

Damien Trentesaux
LAMIH UMR CNRS 8201
Université Polytechnique Hauts de France
UPHF
Valenciennes, France

Christoph Legat
Technical University of Applied Sciences
Augsburg, Germany

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Preface

This volume gathers the peer-reviewed papers presented at the 14th edition of the International Workshop on Service-oriented, Holonic and Multi-agent Manufacturing Systems for the Industry of the Future SOHOMA'24, organized on September 26–27, 2024 by the Technical University of Applied Sciences Augsburg in collaboration with University Politehnica of Bucharest (the CIMR Research Centre in Computer Integrated Manufacturing and Robotics), Polytechnic University Hauts-de-France (the LAMIH Laboratory of Industrial and Human Automation Control, Mechanical Engineering and Computer Science) and Polytechnic Institute of Bragança (the CeDRI Research Centre in Digitalization and Intelligent Robotics).

The main objective of SOHOMA workshops is to foster innovation in smart and sustainable manufacturing and logistics systems and in this context to promote concepts, methods and solutions for the digital transformation of manufacturing through virtualization, service orientation and agent-based control with distributed intelligence

The theme of the SOHOMA'24 Workshop is "**Industrial Artificial Intelligence in the Data-Driven Industry of the Future: Models, Architectures, and Applications**".

In this edition, the workshop focused on exploring the intricacies of cross-enterprise data sharing and the strategic use of artificial intelligence (AI) within manufacturing and service systems. Thus, the workshop focused on methods, tools and architectures for data sharing in an automated and secure way, and the value-adding application and integration of AI in industrial production and logistics for the transformation to a data-driven industry of the future.

SOHOMA'24 has organized a technical session with the scope to assess the current research perspective on **data spaces**, derive characteristic properties and evaluate current initiatives in practice, highlighting shared properties and requirements. Data spaces are introduced as an abstract data management concept, addressing drawbacks of traditional data management systems concerning data heterogeneity and variability, as well as complex relationships between participants such as large industrial companies and service providers.

In the presented research, the infrastructure of a data space is partitioned on three levels: the *technology level* providing the communication infrastructure built on a unique vocabulary for key roles and properties of data sources and a cross-domain vocabulary for user data to ensure interoperability, including keyword searches and queries; the *governance level* that administrates relationships between participants and controls the communication within a data space; mechanisms for cooperative data administration must ensure data visibility, transparency and sovereignty within data spaces; the *business level* grants fundamental economic properties of the data space.

The ability of heterogeneous data sources to exchange data, thus enabling communication between a variety of members, is addressed by standardising the communication protocols for syntactical interoperability by assuming domain-specific and cross-domain ontologies and by using special means to ensure semantic interoperability.

Several papers related the research on industrial data space to the Industry 4.0 context. A first paper presents a concept of data operating platform for a technology research environment while focusing on storage as a first step towards a universal platform for research data management. The platform is able to store and query time-series data, files (images, text documents, spreadsheets, CAD/CAM files) and metadata describing experiments; it also provides descriptive statistics and visualizations for time-series data. This is realized by storing Parquet files in MinIO buckets, and using the Asset Administration Shell (AAS) standardized interface to exchange information and describe I4.0 assets when adding new data sources, e.g., from machines or sensors to one shop floor ecosystem.

Another paper is devoted to the integration of the AAS in engineering data management systems. The research reports where the AAS may find its use cases in the context of the prevailing IT infrastructure of SME companies, how it can be integrated into the existing and running systems, and finally how companies can gain added value from the application of the AAS as an enabler of digitization, using the example of a medium-sized company from the mechanical engineering domain. Driven by the Industrial Digital Twin Association, the AAS is an implementation concept for Industry 4.0, representing a standardized digital framework that captures information about an asset (e.g., characteristics and behaviours), thus facilitating secure and reliable data exchange among stakeholders within the value chain. The research identifies three essential steps for the integration of the AAS into Data Management Systems (DMSs) by which value is added to a company's value network: (1) the ability to generate and manage AASs in data management systems and apply them in the context of the leading data objects; (2) the provision of AASs in one of the common formats (Type1 AASX file, Type2 REST, Type3 Peer-to-Peer) [9] to exchange information as an AAS between DMSs of a value creation network (import/export); (3) making AAS information available and integrating it into the users' daily work of a DMS and thus into their business applications.

In the same area of industrial data space for Industry 4.0, the relationship between the Digital Product Passport (DPP) and the Digital Twin (DT) concepts is analysed, highlighting their alignment and exploring their similarities and differences, and how they complement each other. Thus, the typology of assets, data model and functionalities were analysed, as well as an architectural and component alignment based on the elements provided by ISO 23247. Passports provide data about the origin and characteristics of products throughout their life cycle, being a digital representation of a physical product that includes information about properties, materials, manufacturer data, production processes, maintenance records, usage duration and directives of its reusability, recycling or discarding. The analysis performed concludes that the DPP stands out as a data repository, consisting of a digital statistical representation of the information collected throughout the life cycle of a product; on the other hand, the DT is a digital model that represents the dynamic behaviour of a physical asset, enabling data analytics to support monitoring and decision-support on the asset's performance. A modular conveyor transfer system was considered to illustrate the implementation of a DPP and DT. These concepts can be used in a complementary manner, with the data needed for the digital model of the DT coming from the DPP digital model and the results of the analysis performed by the DT being updated to the DPP to complement its information.

A final presentation within this technical session is a review of methods that are used to synchronize Digital Twins in an industrial context, among which five mechanisms are described: multi-system data synchronization, multi-fidelity model synchronization, multi-resource state synchronization, multi-level state synchronization and multi-stage operation synchronization; each of them is detailed.

A technical session of the SOHOMA'24 workshop was devoted to **industrial applications of Artificial Intelligence**, which are defined as software program systems that use AI techniques to perform specific tasks ranging from simple, repetitive tasks to complex, cognitive tasks that require human-like intelligence.

In this context, human-autonomy teams in Industry 4.0 involve the collaboration between human workers and autonomous systems including robots and AI to enhance efficiency, productivity and competitiveness in industrial environments. These hybrid teams operate in a vertical cooperation structure, where a higher-level hierarchical agent oversees and holds authority, while the lower-level agent offers advice; AI can analyse situations and events and suggest a course of action to the human operator. Reported research investigates the trust in human-autonomy teams (HAT) within Industry 4.0 situations; it presents the different concepts on trust in autonomy in terms of behavioural performance (compliance with AI) and trust layers (dispositional trust, situational trust, and trust in signal). Two case studies in the paper provide insights on how each trust layer can play upon compliance and how these layers are interrelated; it is demonstrated how trust and compliance can be modified and manipulated by varying agent transparency.

In the same domain of applied AI, a research paper approaches the communication gap in the degree of abstraction between human operators and robots and proposes a task-based interaction (TBI) architecture that allows human operators to assign complex tasks to machines through the use of triplets in task specification. This approach uses a task breakdown and a reasoning mechanism based on the Soar cognitive architecture.

Ethical issues in the use of Generative Artificial Intelligence (GAI) in performance management are analysed in this session by the help of two industrial case studies. In line with previous conceptual works on handling ethics in the performance management of industrial systems of the future, a paper explores the potential impact of the use of GAI in performance by adopting an ethical point of view. The ethical risks associated with the use of GAIs in industrial systems and their short, medium- and long-term impact on performance are identified; they concern generally: the replacement of humans; the power taken over by AI and the damage to the company's image. In terms of performance, this clearly shows the threat to long-term performance. Accordingly, recommendations are formulated for: Human replacement—GAI should remain at the service of humans, not the opposite (humans must keep up their skills); AI empowerment—GAI should be seen as an aid, not as a means of making decisions (GAI can be seen at best as a trainee or at worst as a competitor, requiring thus to be under supervision); Company image—data used and provided by GAI should be checked; Performance—GAI must be used to enhance performance. The industry case studies as well as the proposals developed in this paper support the idea that taking into account the ethical risks associated with the use of GAI is a way to ensure performance while protecting human well-being.

An important analysis is offered to reveal the interconnections between research, regulation and standardization of Artificial Intelligence and Digital Twins in Industry 4.0 from an European perspective. It is recommended that Digital Twins should be capable of actively contributing to decision-making processes by leveraging AI-based learning capabilities across a variety of assets and domains. Simulation could include predictive and prescriptive analytics that interact continuously with physical assets to optimize operations in real time. This concept allows AI to enhance decision-making, predictive maintenance and autonomous operation by leveraging the standardized data models established within the AAS framework. In an industrial context, the incorporation of AI also entails ensuring compliance with regulatory guidelines. The introduction of AI into production automation systems introduces a cognitive layer, thereby boosting intelligent operations across distributed manufacturing processes. This stresses the importance of establishing a unified regulatory framework to meet the growing demands of industrial automation.

The research reported in the technical session on **digital twins and simulation models** is applied in different industries: manufacturing, healthcare, smart buildings and public transport. A first paper analyses the energy consumption patterns of manufacturing resources—vertical articulated industrial robots; it defines energy requirements for various types of linear movement tasks performed by a six—d.o.f. robot. By employing a detailed trajectory generation model experimentally validated, the paper analyses how energy consumption (EC) is influenced by the motion pattern and speed profile. The model-based EC analysis is embedded in a hybrid data- and model-driven digital twin aggregate (DTA) architecture for optimal layout design, planning and operating of energy-efficient robots in the Industry 4.0 framework.

The ethical implications of digital twins and simulation models are analysed in the healthcare domain. To mitigate the risks caused by the integration of AI in medicine and to uphold patient rights, several key principles are defined. A generic architecture for Digital Twin in the clinical field of ophthalmology is proposed. The DT instances represent digital models used for the simulation and optimization of surgical procedures. They include: personalized simulation of cataract surgery for patients; simulation of the surgical intervention for optimization; surgical training and preparation; monitoring the patient's postoperative recovery and updating the treatment plan. Specific ethical risks such as violation of patient privacy, absence of consent and transparency due to misuse of surgical data for administrative purpose, and potential loss of initiative among medical staff are also addressed.

Simulation models in healthcare, in particular their type (i.e., abstraction level) and twinning process are reviewed, with a special focus on the emergency departments. (e.g., Abstraction level) and the twinning process. The results of the review lead to three main conclusions. Firstly, most of the simulation models are at the specific level, which limits their reusability. Secondly, existing generalizable models are not used to build specific models. Thirdly, most of the models lack a connection between the cyber and the physical world. Also, the main type of connection used by the models is unidirectional (i.e., digital shadow, a single connection from the physical to the cyber world). In healthcare, the digital model can provide certain recommendations, but no action is automatically executed. The human operator in charge (the doctor) needs to review the simulations and the recommendations and make the final decision.

The concept of digital shadow is further proposed for the healthcare domain to manage all the information about the current state and history of an emergency department (ED, the physical object) in a virtual object (data storage). Based on this data storage, process mining enables discovering historical treatments, calculating new measures (KPI), and providing new insights about the ED process. The extracted knowledge enables ad-hoc evaluations and building of models by help of data-driven simulation. A digital shadow provides raw data, process mining enables the extraction of relevant simulation data, and data-driven simulation enables patient virtualization. The presented research work proposes and evaluates a concept for patient and resource virtualization in EDs and discusses strategies and requirements for its implementation. Two challenges are addressed: (1) to provide a concept for patient and re-source virtualization, enabling the prediction of patient journeys and resource waiting lines in real time; (2) to evaluate the required time and performance for real-time prediction, based on patient and resource virtualization. The implementation and validation of the concept is given in an illustrative case study.

Appropriate data models for building management systems are investigated to create a data-driven digital twin from historical and real-time data, which will be embedded in decision-making and process automation. The research defines a workflow addressing DT standardization for smart buildings in three stages: (i) Data collection (using a Building Operating System that aggregates the metadata associated with each IoT point, which includes the device type, control command, and building topology with properties); (ii) The ETL algorithm that extracts and transforms metadata and time-series data into structured data following the REC (real estate core) semantic model and format; (iii) visualization (loading the exported REC graph schema into a graph database management system for visualization and manual verification of the extracted LPG (labelled property graph)). Linking the time-series data to the standard semantics of the sensors and equipment, the resulting model facilitates the exploration of the data structure by applying graph algorithms for fault detection and diagnosis and decision-making tool within the digital twin framework.

The application of digital twins and artificial intelligence in public transportation is further described, with an implementation model based on multi-agent system (MAS). The DT model for the transport system integrates MAS to simulate the interactions between buses, stations, and passengers; by incorporating advanced AI models such as ARIMA, SARIMA, and LSTM, the DT can predict passenger flow in real-time. In this architecture, there are three types of decisional entities (virtual twins, agents): *Global Decisional Entities* (GDE)—the coordinator program that monitors the data flow, tracks the execution of operations and supervises the interactions with the prediction model; *Local Decisional Entities* (LDE)—represent passengers that must be transported; *Resource Decisional Entities* (RDE)—represent technology and infrastructure (buses, stations that move the LDE in the physical environment). The performance achieved by the layered DT is a 14% reduction in passenger waiting times.

In the context of digital manufacturing orchestrating, optimizing and monitoring, **operations and performance** are facilitated by the advent and rapid development of the new information, control and communication technologies (IC^{2}T); this theme is examined in one SOHOMA'24 technical sessions. *Zero Defect Manufacturing* (ZDM) has emerged as a key IC^{2}T paradigm, which requires an innovative architectural monitoring tool where real-time data are continuously gathered and analysed to predict defects and assess their potential impacts. It also necessitates the seamless integration of diverse data sources, advanced processing algorithms and Digital Twins to align with industrial requirements. Research on ZDM is reported; it describes the design, implementation and testing of a real-time, rule-based monitoring tool aligned with the Reference Architectural Model Industry 4.0 (RAMI4.0), integrated in a real-world car manufacturing use case. A server based on AAS was implemented for real-time data collection and serialization with the rule-based monitoring tool through a microservice architecture to ensure data interoperability between systems part of an assembly line. The tool successfully generated early alerts for quality deviations, enabling production engineers to shift from a reactive to a proactive approach by detecting potential quality issues early in the manufacturing process.

The development of *performance dashboards* as a means for continuous performance management of manufacturing systems (MSs) is further discussed. A methodology for performance management of small and medium-sized enterprises (SMEs) is defined by a quadruple <*principles (paradigms), process (activities), notations (languages), tools (for automation)*>. In a structured approach, the authors propose a three-step process based on DMAIC (Define, Measure/Analyse, Improve/Control) method from six sigma and related tools (SIPOC, VOC) coupled with a KPI meta-model that stands from objectives to measures. It supports the definition of a KPI tree that serves as a repository for storing simulation or real running data feeding a performance dashboard for a given MS configuration. This KPI meta-model has been instantiated on the Lampex learning factory from the Strasbourg University.

This SOHOMA'24 edition maintained the traditional focus on **multi-agent and holonic** manufacturing control architectures, addressing Industry 4.0 research lines:

- Holonic architectures and multi-agent systems for smart industrial systems
- Product-driven automation and product intelligence in manufacturing and services
- Service orientation of control and management in the manufacturing value chain
- Application of information- and operational technologies: IT—edge, fog, and cloud computing, MAS, AAS, …; OT—holarchy, SOA, digital twin; AI technologies—machine learning, prediction, big data analytics in intelligent manufacturing
- Cyber-Physical Production Systems and Industrial IoT implementations for I4.0

One such research paper describes an agent-based control solution for mobile multi-robot order picking in dynamic logistics environments. The study introduces enhancements of the Agent Oriented Software Engineering (AOSE) methodology to develop a *Greif and Drive*-type system (GaD) utilizing mobile robot-to-robot transfer of goods. A decentralized, agent-based control solution is adopted for the two multi-robot teams: (1) AMRs—autonomous mobile robots, retrieve goods from storages, and (2) MMRs—mobile manipulator robots, perform pick and place tasks directly from the retrieval robot. The multi-agent system plans, configures and tracks the AMRs-MMRs meetings in terms of robot selection, location computing and meeting scheduling aligned with logistics objectives, monitoring the interaction and reconfiguring meetings at the occurrence of unexpected events. The Designing Agent-based Control Systems (DACS) methodology has been enhanced by the creation of a flow chart that describing in detail the control and material flow of the multiple-resource, multi-task robot GaD system. The proposed agent-based adaptations to DACS provide a more granular control over autonomous interactions and improve system responsiveness to real-time changes.

Models and methods of *ontology*-customizable multi-agent planning for managing mobile resources are analysed in the same research line. The adopted solution uses a *multi-agent network* of software agents representing *demands* and *resources* (DRN) which cooperate and compete on the virtual last-mile delivery market (the global service system). An ontology-customizable multi-agent low-code platform has been developed, allowing for the rapid prototyping of smart systems for managing various mobile resources such as trucks, taxis, couriers, mobile teams of technicians, gas and electricity workers, merchandisers, nurses, etc.

In the holonic research line, an ARTI-based holonic architecture is presented for an operation support system to coordinate and manage resources in a fruit treatment facility. The proposed process supervision and resource coordination system uses the Activity-Resource-Instance-Type (ARTI) reference architecture. The paper discusses how the architecture design complies with four holonic system design principles: *Specialization Versus Generalization*; *Mirror the World of Interest*; *Self-Similarity*; and *Complexity of Interaction.* The paper contributes to a novel application class of the ARTI architecture, illustrating its use beyond manufacturing.

Papers in this technical session show how holonic design principles can be applied to distributed control of manufacturing and other types of processes, such as food industry (e.g., fruit treatment) or underground mining. The holarchy developed for mining supervision is used as framework to build a Human Cyber-Physical System that improves worker safety by coordinating task execution, monitoring their health and safety, and granting support to decision.

Digital solutions for **reconfigurable production systems** are presented in a dedicated session; they aim at improving decision-making processes and adapting to fast-changing markets with mass customization. Such a solution is introduced as a framework for a decision-support system designed for managing the complexity of multi-level and multi-scale settings. Three levels of decision-making are established in this research: the strategic, tactical, and operational levels which intersect with three physical scales: macroscopic, mesoscopic, and microscopic. The framework also emphasizes a human-centric approach, considering the cognitive workload and situation awareness for humans within cross-sectional analysis.

Another reported research describes the development of a dynamic, distributed on-the-fly reconfiguration control system based on the IEC-61499 standard, which is applied to a modular conveyor transfer system, automatically adapting its operation to changes in the number and position of the conveyor modules. The developed solution uses the Dynamic Intelligent Architecture for Software and Modular Reconfiguration (DINASORE) platform in which function block structures are developed with Python.

Following the SOHOMA'24 technical program, this book is structured in six parts that gather chapters reporting results of the research presented in the workshop: the first part: *Industrial Applications of Artificial Intelligence*; the second part: *Digital Twins and Simulation Models*; the third part: *Industrial Data Spaces in Industry 4.0 Context*; the fourth part: *Operations and Performance in Digital Manufacturing*; the fifth part: *Reconfigurable Production Systems*; the sixth part: *Agent and Holonic Architectures.*

All these themes are presented in the SOHOMA'24 book, which we hope you will find of great value for the study of holonic, agent- and service-oriented manufacturing control in the Industry 4.0 vision.

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Valenciennes, France
Bragança, Portugal
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Theodor Borangiu
Damien Trentesaux
Paulo Leitão
Christoph Legat

Industrial Data Spaces in Industry 4.0 Context

Operations and Performance in Digital Manufacturing

Relationship of Digital Product Passport and Digital Twin in Industry 4.0 Context

Victória Melo, Fernando de la Prieta and Paulo Leitao

Abstract The advances brought by Industry 4.0 contribute to the digital transformation and green transition, accelerating advances toward a circular economy. In this context, some interconnected concepts share similarities and complementarities, that can be analyzed to understand the potential benefits of their associated use. This paper discusses the relationship between the Digital Product Passport (DPP) and the Digital Twin concepts, highlighting their alignment and exploring their similarities and differences, aiming to understand how they complement each other. Therefore, the typology of assets, data model, and functionalities were analyzed, as well as an architectural and component alignment based on the elements provided by ISO 23247 while considering that the DPP concept is still in development. A case study is also presented to illustrate the implementation of both concepts.

Key words: Digital Product Passport, Digital Twin, Industry 4.0.

1 Introduction

Industry 4.0 (I4.0) is contributing to accelerating the digital transformation and green transition, driving advances toward a circular economy [11]. Along with its evolution, I4.0 introduces new interrelated concepts that share similarities and complementarities, e.g, Cyber-Physical System (CPS), Digital Twin (DT), Digital Thread, Asset Administration Shell (AAS), and Digital Product Passport (DPP).

Victória Melo and Paulo Leitao
Research Centre in Digitalization and Intelligent Robotics (CeDRI), Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal, e-mail: {victoria, pleitao}@ipb.pt

Fernando de la Prieta
BISITE Digital Innovation Hub, University of Salamanca, Edificio Multiusos I+D+i, 37007, Salamanca, Spain, e-mail: fer@usal.es

The DPP concept has been standing out as a proposal by the European Commission towards a transition to more sustainable products and the circular economy [9]. Within the European Green Deal scope, the Ecodesign for Sustainable Products Regulation (ESPR) encourages circularity through resource and energy efficiency, the development of more sustainable products, i.e. in terms of durability, repairability, reusability, and recyclability, and the availability of the product information via the DPP [10]. The purpose of creating a DPP includes the recording, processing, and sharing of product-related data between supply chain companies, consumers, and authorities, aiming for the regulation and monitoring of the products available on the market under a sustainable standpoint [9]. Passports provide data regarding the origin and characteristics of each product throughout its life cycle [17], being a digital representation of a physical product that includes information about properties, materials, manufacturer data, production processes, maintenance records, usage duration, and directives of its reusability, recycling or discarding. In this scenario and driven by the advances brought by the digital transformation boosted by I4.0, digitalization is a key factor as the idea of making the product's information available digitally through its digital representation is a requirement for traceability and transparency [13], allowing the different players along the product's life cycle to access and update its relevant information.

Alongside the DPP, the DT is another well-known concept that explores the assets' digital representation [16]. According to the Digital Twin Consortium, entities and processes from the real world can be represented virtually by a DT, respecting the needed synchronization and fidelity between them [6], and offering capabilities in terms of modeling, monitoring, optimization, analysis, and simulation [4]. Along with the growing interest in this topic, its definition varied according to the research field or application area, but they are linked by the consensus that, in addition to being the virtual representation of the asset, there is a need to have a bidirectional transfer of data between the two parties [14, 20]. Although several implementations of DTs are available in the literature, the ISO 23247 standard [12] establishes a framework to guide its development in the manufacturing context in terms of its composition and requirements, supporting the analysis of this concept in this work.

Having this in mind, the main objective of this work is positioning the DPP within the context of I4.0, more specifically establishing relationships with DT, highlighting their alignment, exploring their similarities and differences, and contributing to understanding how they complement each other by considering the potential benefits of their associated use. A case study of a modular conveyor transfer system was considered to illustrate the implementation of both concepts.

The rest of the paper is organized as follows: Section 2 overviews the DPP for a deeper understanding of this concept. Section 3 analyzes the alignment of the DPP and DT concepts in terms of typology of assets, data model, and functionalities, as well as bringing an alignment from the point of view of architecture and components required for their development based on the guidelines provided by ISO 23247. Section 4 illustrates the implementation of both concepts through a case study. Finally, Section 5 rounds up the paper with the conclusions and points out future works.

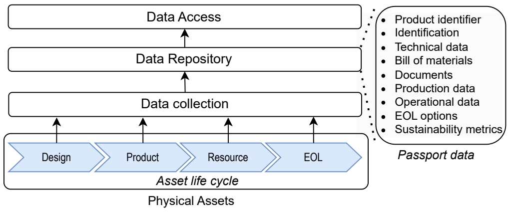


Fig. 1 Digitization process of products aiming the implementation of the Digital Product Passport.

2 Digital Product Passport Overview

The European Commission defines the DPP as a set of pre-defined product-related data associated with a unique product identifier and accessible electronically via a data carrier [9]. This concept emerged in 2020, under the Circular Economy Action Plan (CEAP) adopted by the European Commission [7], as part of the sustainable principles for product regulatory activities through the digitalization of product information, being pointed out by [11] as a key regulatory element by enabling the traceability of products and their related components. In 2022, the DPP was included as a norm to regulate products in accordance with the proposed ESPR [8, 9], bringing the idea of identifying products and linking to them relevant data related to sustainability and circularity, facilitating access to this information by all the players involved in the product value chain and the traceability of products and materials throughout the life cycle [8]. It is expected for 2024 to have the initial guidelines and definitions of the passport contents, as well as the beginning of its implementation starting with the batteries, electronics, and textiles sectors, and expanding in the following years to the other sectors foreseen by the ESPR [7–9].

Despite the fact that there is still no consensus on the architecture of the DPP and the minimum elements that should be part of its composition, as well as about the necessary data for its development and the structure that it should follow, some authors present their perspectives on this topic. In this sense, [11, 18] present some directives related to the key elements that should be represented in a DPP and emphasize the need for a unique product identifier and a physical data carrier, e.g., QR code, RFID tags, or barcodes, to allow access to the information available digitally. Fig. 1 illustrates the digitization process of a product in the development of a DPP.

In this process, the data collection of the products is performed through the different stages of its life cycle, i.e. starting with the design phase, passing through the production, continuing to the phase in which this product becomes a resource, and ending at the product's end of life (EOL). All the acquired information forms the digital representation of the asset, which is stored in the data repository, making the information for the digital passport available. This information must include the product identifier and other information that contributes to understanding the product's journey from the manufacturing process until it becomes a resource to be used by the end consumer. It should also cover instructions for handling the product when it reaches the end of its life and the environmental impact of the product. This repository must store the acquired information to maintain the digital representation and allow the use of historical data in services that contribute to the overall product analysis and its traceability. Other aspects that should be considered at this level include access control, concerning the available information and the level of access required by each user throughout the product's life cycle, and interoperability with other product passports concerning organizational, technical and semantic aspects of communication and data exchange [9], which is crucial, particularly concerning the DPP system [1, 18] and the need for interconnection for the distributed DPP system services [1]. User interfaces allow different users throughout the product's life cycle to access its information, e.g., through web pages or mobile applications.

3 Alignment of Digital Product Passport with Digital Twin

The definition of the DPP is increasingly being explored as the digital representation of the product, including data related to the product at all stages of its life cycle. From this perspective, DPP has been associated with the DT concept since it also explores the digitization of assets and uses digital representations. Therefore, this section presents the alignment of these two concepts, bringing up their similarities and differences, and exploring their alignment considering the architecture and components required for their development based on the elements provided by ISO 23247, aiming to identify how DPP and DT concepts can complement each other.

3.1 Typology of Assets

The first analysis is related to the type of physical object for which a digital representation is created. For the DT concept, the physical object is considered as an asset, specified by [12] as manufacturing resources, including, e.g., a product, process, personnel, material, equipment, environment, and facility, when focusing on the manufacturing sector. For the DPP, this physical object is mainly reported as a product, even due to the designation of the digital passport itself. However, the interpretation of the meaning of this "product" instance can vary according to the stage of its life cycle. For example, during its design phase, a robot is a set of design materials, including a CAD drawing, bill of materials, and process plan, while during its production phase, it is a product. Still, when it enters the operation/service phase it becomes part of the process, being considered a resource in use to carry out the needed tasks. Finally, at EOL, it becomes material for disposal or recycling. For this reason, the passport should store the different information required for the diverse phases of the product life cycle.

This reflection leads to some research questions, as discussed in [15], analyzing the relationships between DTs and assets from the perspectives of how many and which DTs are needed according to the level of granularity to represent the individual components defined within the asset, as well as to deal with the different information of an asset throughout its life cycle, and also the collaboration and composition relationships that can exist between the DTs themselves.

Similarly to the DT that can be designed as “System of systems” [5], “DT of Twins” [19], the DPP can be analyzed in terms of composition considering that products and processes can be made up of multiple products and processes, recalling the holonic principles. In this context, the passport must aggregate the information of each component that is part of this composition aiming for the complete traceability of the product, e.g., a car is a product composed of several sub-products, or an assembly line that is composed of several stations, which in turn are composed of several resources. Therefore, the research questions that can be raised relate to the aggregation of product information that composes a final product, considering how it can be transmitted and represented throughout the product’s life cycle.

3.2 Typology of Data Model

Although the concepts of DT and DPP present similarities related to their digitalization processes, the DPP can be distinguished by its static characteristic, collecting and storing the products’ information but being unable to interact with the physical asset, while the DT stands out by its dynamic capability, allowing the bidirectional real-time data exchange between physical and digital assets. These characteristics substantially influence the type of data needed to feed each digital representation, with the DT being associated with the asset’s behavior and the analysis that can be established to provide feedback related to its performance, turning the functionalities and services offered inherent to its existence since without them there would only be a digital model to represent the object. On the other hand, the DPP is established to provide the product information throughout its life cycle that may be used as input of features and does not have these features as an essential part of its existence. In this sense, the digital model of the DT is dynamic, enabling the representation of the assets’ behavior, while the digital model of the DPP is a static representation aiming to record the product information.

To implement the DT, the information collected from the asset to feed the digital model should be real-time data able to represent or inform its current state at that specific moment of its life cycle so that it can be used by the various services and functionalities it can offer. Some data analytics explores the historical data for a better understanding of its current operating condition, and enabling forecasting, diagnosis, or optimization analysis to be carried out. For DPP, the data collected is static, with the main objective of reporting the entire life cycle of the product, ensuring traceability. In this sense, the types of data vary according to the phase the product is in, but in general, can include, e.g., data on its identification, material composition, technical data, manufacturing details, documents, EOL options, and sustainability metrics. Although operational data can also be represented by the DPP and is continuously updated, this type of data does not yet characterize dynamism since it is not used for analysis enabling decision support regarding its operation.

Another aspect that should be considered is the need to standardize the collected data addressing interoperability. Some reference architectures provide guidelines for the development of I4.0 compliant solutions, e.g., the Reference Architectural Model Industrie 4.0 (RAMI 4.0), and the Industrial Internet Reference Architecture (IIRA). The AAS is defined by RAMI4.0 as the digital representation of an asset, and, therefore, a key enabler of the DT implementation [2] standing out as a potential enabler for DPP implementations [1, 3]. More specifically for the DT in a manufacturing context, ISO 23247 provides a framework to guide its development. For the DPP concept, there is still no reference architecture for its development, although many works in the literature are already discussing this topic.

3.3 Typology of Functionalities

The third analysis is related to the functionalities that can be performed through the life cycle coverage. As highlighted in the previous section, the data collected from the asset for the DT represents its current state and historical operation, and any physical asset can have different DTs throughout its life cycle [4], e.g., design, production, resource and EoL, being also addressed as Digital Thread [3,16]. However, the data repository component of the DPP can store data from multiple life cycle phases simultaneously, even if the product's composition changes throughout these phases, and this data is made available to different users with different needs.

In general, traceability is the most outstanding functionality of the DPP. However, the most relevant functionalities expected for the DT can be detailed. In the *design* phase, the DT can be associated with simulating the asset to evaluate its characteristics and enable initial tests to validate its performance. For the DPP, data regarding the materials' specifications can be stored, contributing to greater rigor in their selection, assuring compliance with regulatory standards, and the use of superior, more ecological products with a higher rate of reuse, as well as the documentation of the design specifications.

For the *production* phase, where this asset is produced, the DT can be used to analyze production data to ensure monitoring, optimization, and fault prediction to guarantee the final quality of the product produced. Simulations can be performed to analyze how changes during production affect the product quality. The DPP should keep data about all the sub-products that compose the final product in production and also store data from the manufacturing process that contributes to the quality control of this product, e.g., the need for rework, and factors that determine its sustainability index, e.g., the amount of energy used during its production.

When the product is available to be used in its *resource* phase, the DT must analyze operational parameters to monitor, optimize, predict, and diagnose faults. Simulations can be carried out to analyze different criteria related to its performance. The DPP records the usage data, e.g., ownership, maintenance, and repair information, as well as provides the necessary documents for the end user, e.g., warranty, repair information, maintenance instructions, and user manual. Finally, in the *EOL* phase, the DPP offers the EOL options, containing information about the recycling, disassembly, and disposal instructions, but the DT can be used to simulate the scenarios for optimizing the recycling process and for its monitoring and optimization.

From this perspective of the different types of data and the different functions performed by the DPP throughout its life cycle, it is important to consider adapting the level of access that each user has to the available information. The DPP still needs to be consolidated from the point of view of having standardized information available covering all stages of the product's development, maintaining data integrity to guarantee that the information can not be altered, and ensuring confidentiality by providing each user with the relevant information. Another consideration for both concepts is the challenge of gathering data while the asset is in its resource phase. For the DPP, users need to update the data related to the asset usage. In terms of the product's operational data, when it is used in a manufacturing environment or as a means of production for a company, for example, it becomes more feasible and financially attractive to implement technologies for data collection to improve process efficiency. However, when used by an end consumer, it is essential to have products capable of collecting operational parameters, e.g., using embedded sensors, to continually update to the digital model and provide data analysis services to support the decision-making process.

3.4 Architectural Alignment Based on ISO 23247

Based on the analyzed similarities and complementarities, it is possible to define the main requirements that form the basis of their digitization processes. As for the DT and any term that involves the digitization process, the digitization of assets in the form of a DPP should be based on the functionalities it can offer [3]. Although some works address the types of data and minimum requirements needed in terms of IT and components that should be part of the passport composition [9, 13, 17, 21], a structured and well-defined architecture is still missing. Fig. 2 illustrates the alignment of the DT and DPP concepts concerning their digitization process following the ISO 23247 standard and highlighting the elements composing the DPP.

The physical assets represent products and resources that should be digitalized. The collected data feed their digital representations, either to be part of the data repository of the passport, tracking the assets' information throughout its life cycle, or to compose the digital model, which contains all the information needed to represent their functionalities or dynamic behavior, allowing some functionalities to be exploited through the DT features. Both cases require synchronization between the information of the physical assets and their digital representation and the storage of historical data to be used later by the data analytics functionalities.

Considering the various product information that can be included in the DPP data repository [18], the features that can be provided based on the information collected depend on the expected analysis to be performed, which can vary in terms of product instructions, traceability of materials, record of operational parameters, or definition

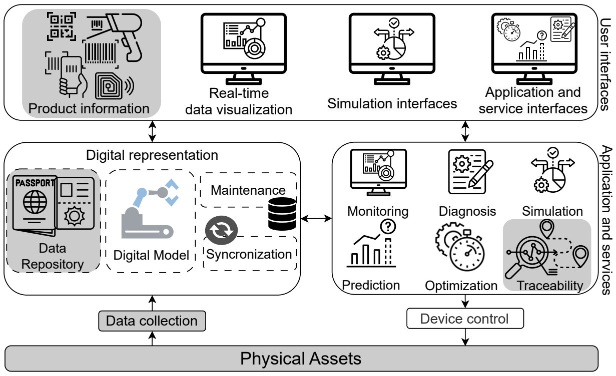


Fig. 2 Alignment of DT and DPP concepts within the I4.0 context following ISO 23247.

of sustainability indexes. For the DT, the data gathered from the physical assets relates to its functioning or operation, aiming the evaluation of its operating condition and the decision support through data analysis and simulation, enabling monitoring, diagnosis, prediction, and optimization. In this sense, the DT is also differentiated by its ability to return information to the physical asset based on the performed analysis, acting directly to control the asset when possible or through recommendations and alerts that enable action to be taken.

User interfaces can be perceived in how the information is presented based on the reason for the asset's digitization, which directly determines the functionalities expected to be provided by both the DPP and the DT and the intended interaction with the user in terms of the type of information needed to be accessed. For the DPP, the passport information can be accessed through the data carrier associated with the asset, presenting the data related to the traceability of the product. From the point of view of the DT, depending on the services offered from its implementation, it is possible to design different interfaces for presenting the generated outputs. For example, the *Real-time data visualization interface* can provide data acquired from the asset instantly or by consulting the database, ensuring that it can be monitored using graphs or text presented on dashboards. The *application and service interfaces* can be used to provide results obtained from DT's data analysis functionalities, which can be presented as graphs or alerts. The *simulation interfaces* can display graphical 2D or 3D animations used to model the asset's behavior or to assist the user's interaction with the what-if simulation to build alternative scenarios.

4 Case Study Implementation

This section illustrates the implementation of DPP and DT concepts using a conveyor transfer system as case study.

4.1 Description of the Case Study

The case study is composed of several Fishertecknicks conveyor modules, as illustrated in Fig. 3. Each module has in its physical part two photoelectric sensors for input and output detection of parts, a conveyor belt and a DC motor operating the belt, and vibration and current sensors enabling the collection of data to monitor the system's operating condition. For the cyber part, an agent is running in a Raspberry Pi to perform the control of the module according to the exchanged data between the agents running in the other modules. Although the system is made up of four modules, the implementations considers each module individually and the current phase of this asset life cycle, i.e. a product in the service stage.

4.2 Implementation of the DPP Concept

The development of a DPP for this case study provides a data repository related to the conveyor module. The passport is developed considering the data collected at this phase of its life cycle, but also some data related to past phases, i.e during the design and production. Fig. 4 illustrates the DPP development and the main components involved.

The data repository of the DPP contains the digital model and the necessary mechanisms to enable the data storage and synchronization. The primary information on the passport is the product identification, which must include, e.g., a unique identifier for each one, the brand and the model. The technical data includes the product description, presenting the components that compose the physical and cyber parts and their respective specifications. The production data inform the location and date of production. The conveyor operation is illustrated through a video. At this stage of the life cycle, it is also possible to gather operational data, including the state of the motor and input and output sensor, the battery level, the motor operating time, the number of pieces transported and the time need to transport them. Therefore, the digital model in this implementation represents the conveyor module digitally, enabling the storage of its needed information and its access by the allowed users. The

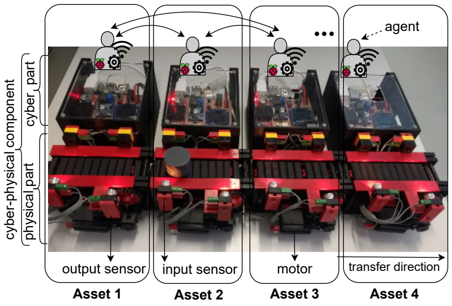
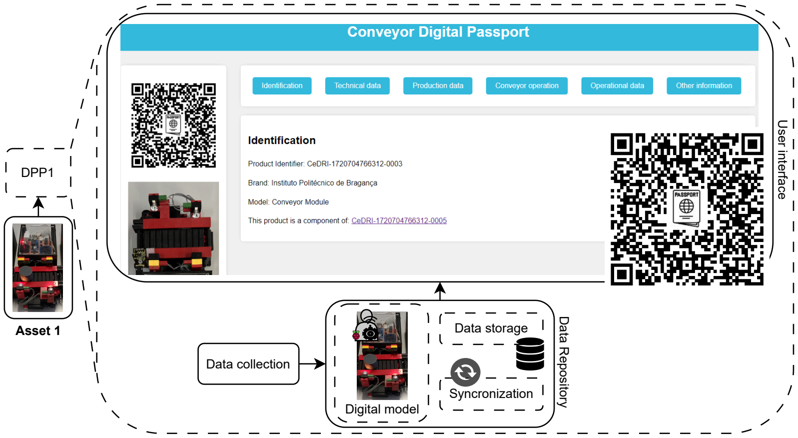


Fig. 3 Modular conveyor transfer system used to support the development of the DPP and DT approaches.



Identification

Product Identifier: CeDRI-1720704766312-0003

Brand: Instituto Politécnico de Bragança

Model: Conveyor Module

This product is a component of: CeDRI-1720704766312-0005

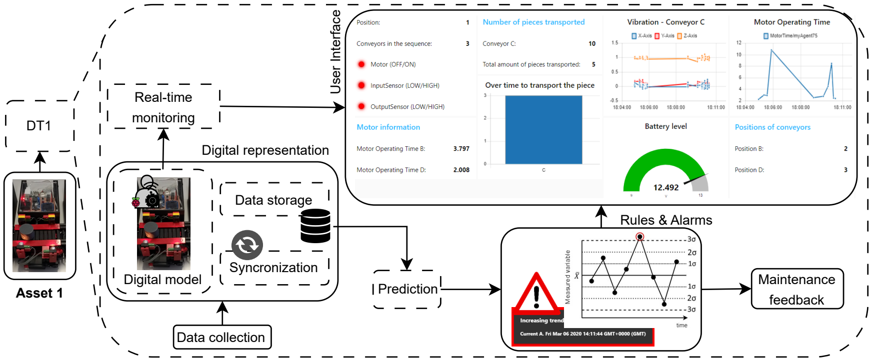
Fig. 4 Digita Product Passport implementation for the conveyor module.

user interface provides access to the passport data via a dashboard, presenting the QR code associated with the specific conveyor, its image, and the collected data. The described DPP development for one conveyor module can be replicated for the other modules since they present similar characteristics.

4.3 Implementation of the DT Concept

The development of the DT enables the monitoring of the health condition of the conveyor module and the prediction of failures. This approach considers the implementation of one DT for each conveyor module, illustrated in Fig. 5, selecting the asset with the same level of granularity as for the DPP implementation, allowing a better understanding of the collected data, digital model, and data visualization. the components of the DT designed for the conveyor module.

The digital model represents the conveyor behavior and is fed exclusively with the operational data previously described in the DPP implementation, contributing to analyzing its operating condition. Mechanisms for data storage, analysis, and visualization are also explored. The functionalities offered in this implementation differ by being able to, in addition to enabling real-time monitoring, detect the occurrence of overtime to transport the piece and continuously analyze the stored data to predict failures and return an alert for maintenance if an outlier or trend is detected, enabling an earlier detection of failures. More details on the digitization of this system can be found in [15].



Position: 1
Conveyors in the sequence: 3
Motor (OFF/ON)
InputSensor (LOW/HIGH)
OutputSensor (LOW/HIGH)
Conveyor C: 10
Total amount of pieces transported: 5
Motor Operating Time B: 3.797
Motor Operating Time D: 2.008
Position B: 2
Position D: 3
Current A. Fri Mar 06 2020 14:11:44 GMT+0000 (GMT)

Fig. 5 Digital Twin for monitoring the operating conditions of the conveyor module.

5 Conclusions and Future Work

The new regulations proposed by the European Commission through the ESPR aim to encourage a transition to a more circular economy supported by digital transformation and new technologies associated with the I4.0 context. These regulations also introduce the DPP concept, aiming to ensure the quality, circularity, and sustainability of products under development through their regulation and traceability.

This work contributes to fostering the discussion of adopting the DPP in the development of I4.0-compliant solutions and also analyzing its relationship with the DT concept, as both are based on the development of digital representations. The alignment of these concepts was explored in terms of their typology of assets, data model, and functionalities, as well as the architectural components needed for their development based on the ISO 23247. The DPP stands out as a data repository, consisting of a digital representation that statically represents the information collected throughout the life cycle of a product. On the other hand, the DT is a digital model that can represent the dynamic behavior of a physical asset, enabling data analytics to support monitoring and decision-support on the asset's performance. A modular conveyor transfer system was considered to illustrate the implementation of a DPP and DT. Another idea that arises from this study is the use of these concepts in a complementary manner, with the data needed for the digital model of the DT coming from the DPP digital model and the results of the analysis performed by the DT being updated to the DPP to complement its information.

Future work includes extending this research to align the DPP with reference architectures and industrial standards, e.g., RAMI 4.0, and the development of an architecture addressing the integration of DT and DPP concepts.

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SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020). Victória Melo thanks FCT Portugal for the PhD Grant 2022.13868.BD.

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