Design of an ISO 23247 Compliant Digital Twin for an Automotive Assembly Line

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2024 IEEE 7th International Conference on Industrial Cyber-Physical Systems (ICPS) | 979-8-3503-6301-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICPS59941.2024.10640052

***Abstract*—The integration of Industry 4.0 (I4.0) technologies is transforming various society sectors, and particularly the manufacturing sector, promoting a digital transformation that fosters smart and interconnected systems. The Digital Twin (DT) acts as a key component in the digital transformation landscape and its integration with I4.0 technologies paves the way for the implementation of Zero Defect Manufacturing strategies. A spotlight on the automotive industry underscores the power of DT applications for real-time defect detection and improvement of product quality and process efficiency. However, the proper DT implementation, contributing to their integration and interoperability, requires the compliance with standards and reference architectures. Having this in mind, this paper describes the design of a DT architecture compliant with the ISO 23247 standard and aligned with the RAMI 4.0 to cover the dimensional measurement process comprising inspection stations placed in the body shop area of an automotive assembly line. This implementation enables the real-time and early identification of defects along the assembly process, allowing to prevent their occurrence at a single stage and their propagation to downstream processes.**

***Index Terms*—Digital Twin, ISO 23247, Zero Defect Manufacturing, RAMI 4.0.**

I. INTRODUCTION

The advent of Industry 4.0 (I4.0) has caused significant transformations in various sectors through the use and integration of advanced technologies such as cyber-physical systems (CPS), Internet of Things (IoT), cloud computing, Big data analytics and Artificial Intelligence (AI). Considering the manufacturing sector, I4.0 offers a framework for the digital transformation based on smart and interconnected systems, enabling companies to use data and emergent digital technologies to maintain a competitive advantage over the market [1], through the optimization of production processes and an increased operational efficiency.

The Digital Twin (DT) is a key concept for achieving smart manufacturing acting as a major component of the digital transformation [2]. The Digital Twin Consortium defines the DT as *"a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity"* [3]. In a more general sense, this concept can be defined as *"the digital copy of a physical object or system, that is connected and shares functional and/or operational data"* [4], enabling the use of historical and real-time data collected to evaluate the physical assets' condition and enable their improvement through the execution of simulation and data analysis [4], [5]. In this sense, the use of DT allows connecting physical and real world through the creation of virtual representations of physical assets or processes, enabling companies to detect earlier the occurrence of problems, attaining better accuracy in predicting outcomes, improving product design and production, and providing improved customer service [6].

The DT concept, coupled with advanced digital technologies in line with I4.0, enables the realisation of Zero Defect Manufacturing (ZDM) strategies by, e.g., promptly identifying defects and issues, and optimizing processes to enhance overall defect-free performance. This synergy has the potential to enhance the quality and efficiency of manufacturing processes [7] by means of e.g., monitoring, real-time insights, predictive abilities, or process optimization. From this perspective, simulation and modeling technologies, widely used to perform the virtualization of products or processes in DTs, can be seen as part of I4.0 technologies and are considered key enabling technologies for implementing ZDM strategies [8].

In this context of technological innovation, and looking at the automotive industry, a large amount of data is generated in the different phases of an automotive assembly line, which could be effectively used for product and process quality improvement, particularly addressing the ZDM objectives. The implementation of DT applications strongly contributes for this purpose by properly analysing the collected data and enabling the simulation in a virtual context to enhance the process of decision-making [9].

As the DT concept is widespread, some standards are emerging to harmonise its development and application. As example, the ISO 23247 [10] presents a DT Framework for Manufacturing, focusing on the architecture for its development. Many other standards, as presented in [11], e.g. ISO/TR 24464 [12], ISO/IEC AWI 30173 [13] and ISO/IEC AWI 30172 [14], focus on individual components that are part of the DT and can be used in a complementary manner to the ISO 23247 standard. Additionally, some reference architectures were established to implement I4.0 compliant solutions, namely the Reference Architectural Model Industrie 4.0 (RAMI 4.0) [15] that specifies the use of several standards and guidelines, including the Asset Administration Shell (AAS) that is pointed out as a way to implement the DT concept.

Having this in mind, the main objective of this paper is to describe the design of a DT architecture compliant with the ISO 23247 standard and aligned with the RAMI 4.0 to cover the dimensional measurement process of an automotive assembly line case study, particularly addressing the Body Shop area comprising three inspection stations. The aim of applying a DT in this case study is to enable the real-time and early identification of defects related to dimensional parameters along the assembly process, allowing to prevent their occurrence at a single stage and their propagation to downstream processes.

The rest of the paper is organized as follows: Section II describes the ISO 23247 standard and Section III introduces the automotive assembly line case study. Section IV presents the design of the DT architecture based on the ISO 23247 standard for the case study and Section V discusses its alignment with RAMI 4.0. Finally, Section VI rounds up the paper with the conclusions and points out the future work.

II. ISO 23247 STANDARD

The different interpretations on how to approach the DT concept make interoperability and interconnection of DTs difficult [11], requiring the aligning their development with established standards and reference architectures to make more efficient their implementation and integration [16]. The ISO 23247 standard establishes a framework to facilitate the generation of DTs for manufacturing objects, providing guidelines on its composition for manufacturing solutions.

The ISO 23247 series [10] is divided into four parts. The first part provides guidelines related to principles and requirements to develop DTs in manufacturing, also presenting the boundaries of the framework, as illustrated in Fig. 1. These boundaries limit the physical world, presented as observable manufacturing elements (OMEs) and including product, process, personnel, equipment, environment, or even a support document, and the DT framework for manufacturing, being both connected through the device communication domain to ensure their synchronization so that the DTs receive the performance information of the physical system in real-time.

The second part of the standard provides a reference architecture, covering a reference model with a domain and entity perspective, and a functional view specifying functional entities supported by the entity-based reference model. From the domain perspective, several layers are considered, namely the user domain, the DT domain, the device communication domain and the observable manufacturing elements, the last one being outside of the DT framework. The tasks in each domain are performed by entities that divide the domain into sub-systems to provide the functionalities needed by them.

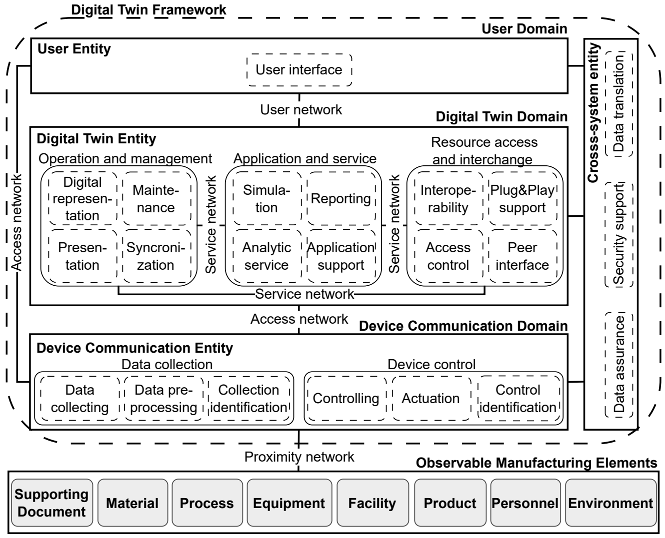

Fig. 1: Functional view of the ISO 23247 (adapted from [10]).

The device communication domain synchronises the OMEs and the DT domain through the data collection and device control, being the first associated to the identification of the required data from the OMEs, its collection and pre-processing, and the second one related to the control that can be carried out in the OMEs, including the actions control commands that can be sent to the OMEs devices. The DT domain contains the digital representation of the OMEs, the definition of the data model and all the information needed to ensure synchronisation between the physical and virtual models and the maintenance of DT operations. This domain also includes DT functionalities, provided in the form of applications and services, including simulations and data analysis that allow, e.g., monitoring, prediction, optimisation, and diagnosis. The resource access and interchange are also addressed considering the interaction between the DT functionalities with the other entities or even other DTs. The user domain interfaces the users (human, device, supervisory system or other DTs) to the DT entity to enable their interaction [2]. The cross-system entity is linked to the three domains within the framework, providing functionalities that are common to them, including data translation, security support and data assurance [10].

The third part is related to the digital representation of manufacturing elements, providing a list of basic information attributes for the OMEs that can be static or dynamic information, depending on if it changes or not during the manufacturing process. Finally, the last part specifies the technical specifications needed for entities in the reference architecture to exchange information. For this purpose, four networks are defined. The *user network* connects user and DT entities as the first uses the DT instances to enable services and applications e.g., visualization, process monitoring, statistical analysis and simulation. The *service network* connects the sub-entities belonging to the DT entity and the *Access network* connects the device communication to the DT and user entities, transmitting the data collected from the OMEs to the DT entity, and commands from the user or DT entities to control OMEs. Finally, the *proximity network* connects the device communication entity and OMEs, enabling the first to receive data from OMEs and to transmit commands to OMEs.

III. AUTOMOTIVE ASSEMBLY LINE CASE STUDY

In a automotive assembly line, one of the main quality factors is the correct geometric positioning of the assembled parts. In this manufacturing process, it is crucial that the dimensions measured at critical points of the assembled car are within pre-established limits, ensuring that the final product fulfills the project specifications Any deviations observed in these values may indicate potential fitting issues in subsequent assembly phases, being required to carry out inspections of the surface alignment at various stages along the assembly line. The case study considered for this work focuses on a sequential set of 3 inspection stations along the Body Shop area through which the cars being produced are moving and the dimensional measurements are taken automatically, as illustrated in Fig. 2.

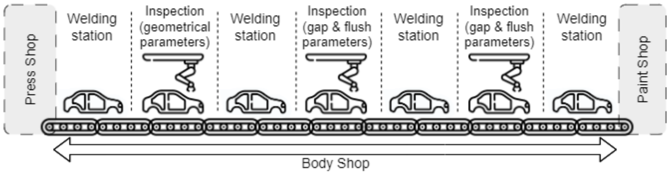

Fig. 2: Layout of the sequence of the inspection workstations in the Body Shop area case study.

In the Body Shop area, located between the Press and Paint shops, the car is in its phase known as "body-in-white", in which only the car's body structure is assembled. The cars are monitored at each measurement inspection station with the goal of detecting deviations related to the expected dimensional parameters as early as possible. The inspection system consists of robots in which Laser Line Triangulation Sensors are attached to measure geometrical parameters of adjacent parts, e.g. Cartesian measures, gap and flush parameters, checking the fitting and alignment between the two surfaces. The first measurement inspection station is located in the initial stage of the assembly of the parts of the car, responsible for checking the X, Y and Z features of the car's frame. The cars moving by the second measurement inspection station have already the doors assembled, being necessary to measure the gap (related to the distance between the parts) and flush (related to the height difference between the two parts). At the last measurement inspection station, the cars are completely assembled and the gap and flush parameters of a higher number of points are verified, including the rear end, front end and sides of the cars.

Currently, the collected raw data is available for the operators through dashboards that allow the visualization and the identification of parts that are outside the pre-established limits, making possible to make some minor adjustments to the assembled parts still in this phase of the process, minimizing the impact of small incorrections in the next phases of the assembly process. This data is also stored and accessible for analysis by sector supervisors. However, the analysis of the huge amount of available data is time-consuming and focused on finding specific information that is not able to embrace the process as a whole. Moreover, the vast amount of data to be analyzed and comprehended introduce some risk of errors. As a result, a significant quantity of data in this area remains untapped and lacks proper correlation.

The introduction of the DT in this context contributes to overcoming these challenges and open issues. A DT can be designed to integrate the collected data from the inspection stations to feed the digital model representing the physical Body Shop process and to encapsulate a set of functionalities that contribute to improve the efficiency of the assembly process. These functionalities, supported by different AI data-driven analytic tools allows to monitor in real-time the assembly process, to predict problems caused by the incorrect sizing or alignment at different stages of the assembly process, to identify the possible causes of defects and get some recommendations to adapt the process to keep the production efficiency and quality, and to enable simulations to find the best operating parameters. The expected benefits of introducing this DT approach are related to preventing the propagation of early detected defects to downstream processes, adapting the assembly stations based on the data collected in the previous stations, and reducing the rework with realignment operations.

IV. DT ARCHITECTURE FOR THE BODY SHOP AUTOMOTIVE ASSEMBLY LINE

The DT architecture for this case study is specified following the ISO 23247 standard, as illustrated in Fig. 3. In the proposed architecture, the four domains established by the standard are being portrayed, as well as the iteration between them, allowing to establish the DT for the dimensional measurement process during the car assembly process.

A. Observable Manufacturing Elements

In this work, the OMEs comprise the three measurement inspection stations, which are the assets from which the information of the physical world comes. The data collected from the measurement equipment includes the station identifier, car identifier number, timestamp, the measures of the dimensional parameters that need to be checked at different points of the car according to the inspection station, i.e. gap, flush or Cartesian measures, and the limits pre-established for the respective measure in each point, as represented in Fig. 4.

As a prerequisite for this work, the data exchanged between the physical and digital worlds is carried out by using AAS, which makes information accessible in a standardized format through their sub-models. In this case, considering the integration of the OMEs and the Device Communication Entity of the designed architecture, the defined data models of the measurement inspection systems will be available on a server,

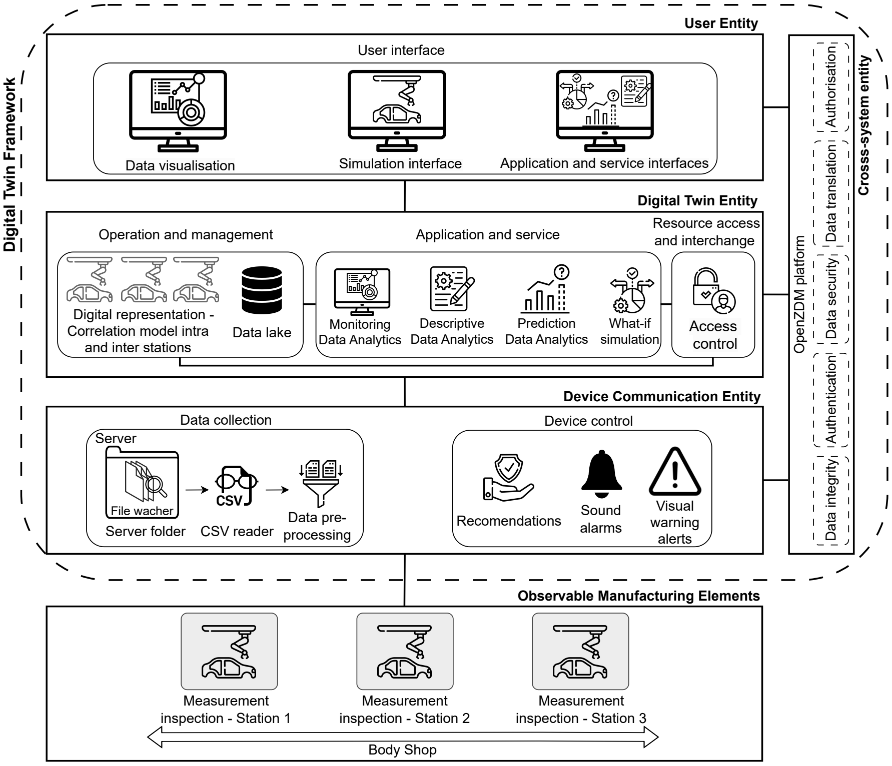

Fig. 3: DT architecture based on the ISO 23247 standard for the measurement process carried out in the Body Shop area of an automotive assembly line.

```
{
  "JSN": "number",
  "timestamp": "datetime",
  "Model": "string",
  "Qual": "number",
  "Data_type": "string",
  "Fixture": "string",
  "Measurement_data":{
    "Meaurement_point":{
      "Name": "string",
      "D":{
        "Gap": "float",
        "Flush": "float"
      },
      "US":{
        "Gap": "float",
        "Flush": "float"
      },
      "LS":{
        "Gap": "float",
        "Flush": "float"
      },
      "UR":{
        "Gap": "float",
        "Flush": "float"
      },
      "LR":{
        "Gap": "float",
        "Flush": "float"
      },
      "UT":{
        "Gap": "float",
        "Flush": "float"
      },
      "LT":{
        "Gap": "float",
        "Flush": "float"
      }
    }
  }
}
```

Fig. 4: Data model for the measurement inspection station.

e.g., AASX server, and externally accessible by a REST API or Message Queuing Telemetry Transport (MQTT) broker.

B. Device Communication Entity

In the device communication entity, the data collected from the system is available in the data collection sub-entity, being stored and made accessible to the other levels of the framework, enabling the synchronization between the OMEs and the DT. In this case, the measurement process data is available in a CSV file on the factory server containing the information of the measurements of each car in each measurement station. To obtain this data, a file watcher monitors the folder in which these CSV files are received and, when a new document arrives, it is detected and parsed in a JSON format to be available for the DT functionalities. The collected data passes by a pre-processing stage where the data cleaning process is carried out, removing incorrect or empty values that do not contribute to the data analysis, being ready to be used in the next level of the framework.

The device control sub-entity allows the action to be performed on the asset. In this case study, it is not possible to act directly in the measurement process and therefore the actions are limited to alerts for the supervision and maintenance team, including visual or audible alerts to indicate, e.g., anomalies or trend detection, need for maintenance or calibration of the inspection system, and possible actions' recommendations.

C. DT Entity

The DT entity is the virtual representation of the OMEs. The *operation and management sub-entity* includes the digital representation of the physical system, through a digital model that represents the functionalities of the physical system, ensuring the maintenance and synchronization of information between the OMEs and its digital representation. This digital model can be a mathematical or numerical model, a Petri net model, or even a visual simulation model. Considering that the main functionalities expected for the target case study are related to analyzing the influence of dimensional parameter variations between points and the propagation of fitting defects during the assembly process, the digital model is related to the correlation among intra- and inter stations of the car's measured points. The data lake enables the storage of the cleaned data collected at the previous domain, contributing to maintaining the information about the OMEs and enabling the use of historical data by other applications.

The *application and service sub-entity* contains the components capable of delivering the expected functionalities, including the services and applications designed to manage and analyze the data coming from the OMEs. In this sense, a set of data analytic tools are defined to provide some algorithms, methods, or techniques for the analysis of the shop floor data, which enable, e.g., the data correlation, statistical analysis, pattern recognition, anomaly detection and data prediction.

In the monitoring data analytic tool, the data coming from the measurement stations is monitored in real-time aiming to verify if the measures are in line with the pre-established limits and to detect outliers or tendencies that might indicate abnormal values related to the dimensional parameters that can result in fitting problems between the pieces during the car assembly. For the prediction data analytic tool, some algorithms can be implemented to estimate the gap and flush values, allowing the early detection of defects in a particular body shop station for the next upcoming cars or in the upcoming body shop stations based on the influence of the data from one measurement station over the next stations. The descriptive data analytic tool can provide the identification of the measuring points that are affecting the assembly fitting and the diagnosis of possible factors causing the detected defects.

Another exploited feature is the what-if simulation that addresses the testing of alternative configuration scenarios where the dimensional parameters can be changed, i.e. the established limits and the values measured at the points, allowing to analyze the impact of these changes on the measurement points at the current and subsequent phases of the assembly process. Examples of simulation modeling software tools that can be used include FlexSim, Arena and Simio.

The structure of these applications and services can be deployed using microservices and docker technologies to ensure the modularity of the implemented solution.

D. User Entity

The user interface aggregates the user interfaces developed based on the functionalities provided by the DT entity. The *data visualization* interface provides the real-time visualization of the collected data along the inspection stations, showing the measured gap and flush parameters. This front-end interface can be implemented through dashboards that display graphs, tables, or texts, retrieving the data stored in the data lake, and technologically developed using e.g., Grafana or React.

The *application and service interface* generalizes the interfaces that can be derived from this functionality in the DT entity, displaying the results gathered from the data analytic tools, which can be presented by means of graphs or alerts. The *simulation interface* is another kind of interface that provides the graphical 2D or 3D animation of the simulation, displayed on computer screens or in virtual reality and augmented reality simulators. Additionally, this interface supports the interaction of the user with the what-if simulation to create alternative scenarios, e.g., by modifying the limits of the points measured at the stations in order to test different configurations and find the most appropriate one for the assembly process.

E. Cross-system Entity

This entity involves the three domains within the framework, aggregating the necessary functionalities to them, i.e. in terms of translation, integrity, security, authentication, authorization, and confidentiality of the exchanged data. In the scope of this work, these features will be integrated into the "openZDM platform" [17], responsible for interconnecting the different components within the DT framework.

V. DISCUSSION

RAMI 4.0 [15] is a reference architecture to implement I4.0 solutions, combining all the components in a structured way in order to promote interoperability for these solutions. RAMI 4.0 is presented as a three-dimensional architecture, composed by Layers, Hierarchy Levels, and Life Cycle Value Stream dimensions. Briefly, the Layers dimension represents the IT perspectives on the digitization of industrial assets, and the Hierarchy Level defines the roles, functionalities, and responsibilities of both hardware and software assets within the factories or plants. Lastly, based on the IEC 62890 standard, the Life Cycle Value Stream dimension depicts the life cycle of plants and products.

In this context, the designed DT following the ISO 23247 is aligned with RAMI 4.0 through the Layers dimension, which is also related to the assets' digitization, as presented in Fig. 5. Analyzing this dimension from the bottom - up, the *asset* layer includes the assets that can be digitized, corresponding to the *OMEs* from the ISO 23247 that in this case study encompass the three measurement inspection stations. The *integration* layer allows the higher levels to access the data collected from the first layer, and the *communication* layer uses standard communication protocols to guarantee that data is exchanged properly, corresponding to the *device communication domain*, which allows both the collection of data from the physical processes and the return of actions to them derived from the implemented DT functionalities. The *information* and *functional* layers outline, respectively, the proper structuring of information communicated between services and components, and the functionalities that the asset is capable to provide, e.g. data analytic tools and what-if simulation, corresponding to the *digital twin domain* in ISO 23247. The *business* layer perceives the services offered by the digital asset from a business perspective, being linked to the *user domain*, in which the data extracted from the functionalities and services offered by the DT are presented or new data can be input into the DT for simulations, with a perspective of being used in the manufacturing decision-making process.

Another concept that can be linked to this analysis is the AAS, defined as a digital representation of the asset [18],

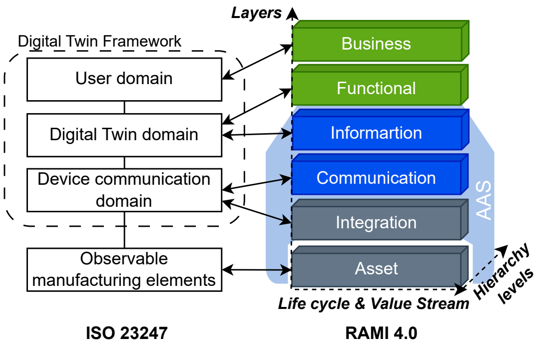

Fig. 5: Alignment of RAMI 4.0, AAS and the ISO 23247.

transforming it into an I4.0 component and enabling interoperability and flexibility for the I4.0 solutions [19] by providing a standard communication interface for connecting physical assets to the I4.0 environment. In spite of some authors, e.g., [19], pointing out that the AAS and DT concepts are moving in the same direction, the AAS is seen as a facilitator for the development of DTs for industrial applications by offering the sub-models with the necessary data structure based on the information gathered from the asset [20]. Considering the layers proposed by the RAMI 4.0 model, the AAS would encompass the *integration, communication and information* aspects, as presented in Fig. 5, while the DT would incorporate also the functional and business layers.

VI. CONCLUSIONS AND FUTURE WORK

The DT concept is a key factor in the development of smart manufacturing solutions. Standards and reference architectures play a crucial role in simplifying the implementation of DTs through the provided guidelines and the standardization of the terms used and the information shared.

This work contributes to understand how the ISO 23247 standard can be applied to develop DTs in manufacturing domain, through the design of a DT architecture for monitoring and improving the operation of the body shop area of an automotive assembly process according to the ZDM strategy. The components and elements belonging to each domain of the DT framework were specified, including the data collection of the measurement processes, the digital model to represent the physical process and the AI data-driven analytics and simulation functionalities. The proposed architecture is aligned with the RAMI 4.0 model, particularly evident with the correspondence of the ISO 23247 compliant DT domains with the layers dimension of the RAMI 4.0.

Future work includes the implementation of the proposed DT architecture for the Body Shop case study, the extension of the DT to cover also the final assembly area and the study of design principles to specify DTs architectures to this multi-stage process, considering the trade-off of a centralized approach (one DT for all process) or a distributed one (one or more DTs for each asset).

ACKNOWLEDGMENTS

This work was partially supported by the HORIZON-CL4-2021-TWIN-TRANSITION-01 openZDM project, under Grant Agreement No. 101058673. The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support through national funds FCT/MCTES (PIDDAC) to CeDRI (UIDB/05757/2020 and UIDP/05757/2020) and SusTEC (LA/P/0007/2021). The author Victória Melo thanks FCT Portugal for the PhD Grant 2022.13868.BD.

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