Realization of a digital twin for welded assemblies in an industrial manufacturing environment using an ISA-95 compliant framework

Citation for the original published paper (version of record):
Hultman, H., Cedergren, S., Vallhagen, J. et al (2026). Realization of a digital twin for welded assemblies in an industrial manufacturing environment
using an ISA-95 compliant framework. International Journal of Advanced Manufacturing Technology, 143(11-12): 6847-6864. http://dx.doi.org/10.1007/s00170-026-17786-3

(article starts on next page)

The International Journal of Advanced Manufacturing Technology (2026) 143:6847–6864
https://doi.org/10.1007/s00170-026-17786-3

ORIGINAL ARTICLE

Realization of a digital twin for welded assemblies in an industrial manufacturing environment using an ISA-95 compliant framework

Hugo Hultman[1] · Stefan Cedergren[1] · Johan Vallhagen[1] · Kristina Wärmefjord[2] · Rikard Söderberg[2]

Received: 12 November 2025 / Accepted: 18 February 2026 / Published online: 21 March 2026

Abstract

In order to reduce fuel consumption, aero engines are increasingly made from complex welded assemblies rather than singular monolithic castings. This increases variability in the manufacturing process, calling for an advanced geometry assurance approach to ensure adequate quality. Digital twins for geometry assurance have previously been suggested as way of increasing the precision of welded assemblies. However, these systems have mostly remained at the conceptual or experimental level, and their potential has not been realized in the industrial environment. No clear and unanimous view exists for industrial implementation of digital twins for manufacturing. This paper proposes a digital twin for welded assemblies, combined with a roadmap for industrial implementation based on established industry standards. The proposed digital twin functionality is based on individual locator adjustment combined with a genetic optimization algorithm and a non-nominal weld simulation method. This functionality is organized into the ISO 23247 framework to facilitate the information flow within the digital twin and support efficient implementation. To ensure compatibility with the industrial environment, an extended activity model based on the widely used ISA-95 standard is introduced based on the activities defined within the ISO 23247 framework implementation. This extended activity model for digital twins has a networked structure, enabling fast and direct information exchange between different activities while maintaining compliance with the ISA-95 information model. This lays the foundation for a digital thread to support the digital twin with relevant data. By combining the digital twin with existing frameworks, a full methodology is formed for the industrial implementation and realization of the proposed digital twin for welded assemblies. Finally, a case study shows how a digital twin implementation in Matlab and RD&T can decrease variation in a welded assembly. This methodology is applicable for implementation of a wide range of digital twin functionalities within industrial environments based on the ISA-95 standard.

Keywords Digital twin · Non-nominal welding simulation · Geometry assurance · Genetic algorithms, ISA-95, ISO 23247

1 Introduction

As the aerospace industry strives towards lower fuel consumption, stricter requirements are placed on the weight and overall efficiency of the aircraft. For aircraft engines, fuel efficiency needs to be increased while keeping weight to a minimum. At the same time, safety and reliability cannot be compromised, and the quality of each component is held to high standards. To meet these requirements, fabrication is seeing increased use within engine manufacturing [1]. In this context, fabrication refers to a production approach where components are made from a welded assembly of smaller parts instead of being made from a single piece of material such as a large casting. An example is shown in Fig. 1. Fabrication allows more freedom when designing the engine compared to working with large castings, since each part of the assembly can be made using different manufacturing methods such as additive manufacturing or sheet metal forming. However, it also adds more sources of variation that need to be managed. Every surface on a part will have some deviation from its intended, nominal geometry. This deviation is kept within an allowed margin

---

✉ Hugo Hultman
Hugohu@chalmers.se

[1] GKN Aerospace Engine Systems, Trollhättan
SE-461 38, Sweden

[2] Department of Industrial and Materials Sciences, Chalmers
University of Technology, Gothenburg SE-412 96, Sweden

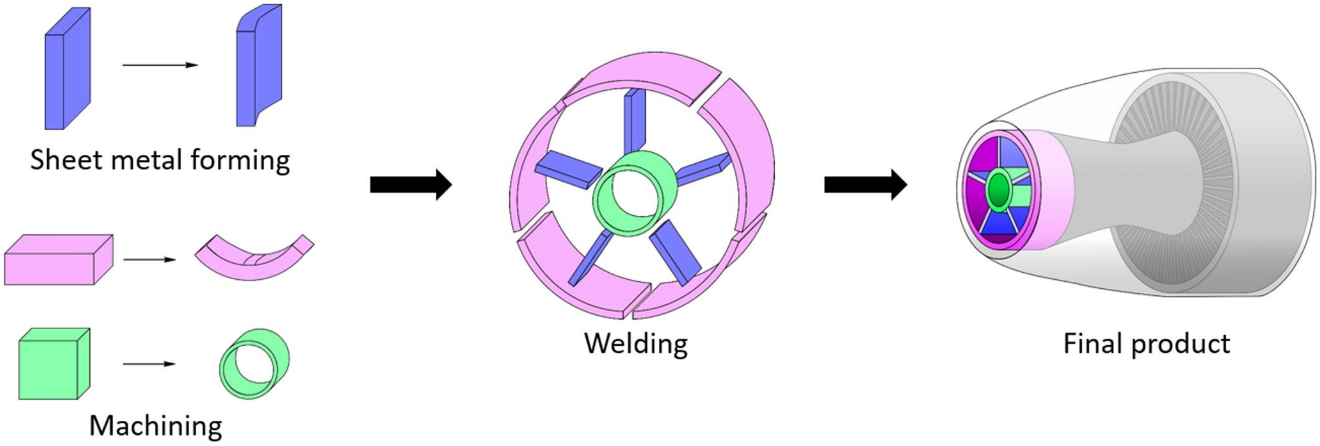

Fig. 1 Overview of a fabrication process for an aero engine exhaust structure

of error using tolerances. A fabricated assembly will have multiple interfaces between different parts, and the variation in these interfaces will never be zero. This makes it difficult to manage the geometrical quality of the welded assembly due to the many individual variation sources. In order to get a good fit in every interface between the assembled parts, careful adjustment of the weld fixture is required. This work is challenging due to the complexity of the assembly and strict quality requirements placed on all engine components. Expensive rework is often required in order to achieve a sufficient fit between parts before welding the assembly [2].

1.1 Geometry assurance

Geometrical variation in manufacturing is usually approached with geometry assurance tools to analyze tolerances and increase robustness. These tools can be applied in the design phase of a product, finding optimized locating schemes [3] and tolerance allocations through variation simulation [4]. A locating scheme for a rigid part consists of a set of six locators, locking the six degrees of freedom of a part. The placement of these locators can be optimized by simulating how geometrical variation affects the positioning of the part for a certain locating scheme. Geometrical variation can be assessed with 3D statistical variation simulation based on the MC (Monte Carlo) method, which simulates various variation behaviors which might occur during production. This simulation can also be used to set tolerances for the acceptable amount of geometrical variation in each dimension of the part. This requires a compromise between precision and cost. Since lower tolerances are generally more expensive, tolerances should never be lower than what is deemed necessary to achieve sufficient quality in the final product.

Variation simulation can be done with either rigid or non-rigid assumptions for part geometries. A rigid assumption can be made when the effects of part deformation during production is assumed to be negligible for the final product quality. If this is not the case, a non-rigid model is needed [5]. This requires a FEM (Finite Element Method) model which approximates the part as a combination of linear elements. For thin parts such as sheet metal components the part can be modeled with flat shell elements [6], while thicker parts require solid elements which are more computationally heavy. Non-rigid models can capture the behavior of over-constrained fixtures with clamps, and it can also be used to simulate the effects of heat during welding [7]. With FEM analysis, the MC method can become overly time-consuming due to the large amount of iterative FEM simulations required, and the MIC (method of influencing coefficients) has been suggested as an alternative approach [8]. Novel welding simulation methods have been suggested to achieve faster simulation times [9]. Variation simulation can be carried out in either a dedicated computer-aided tolerancing software such as RD&T [10], or in a module integrated into the modeling software such as 3DSC [11].

1.2 Digital twins for individualized manufacturing

Recent years have seen an increasing interest in digitization and digital twins [12, 13]. A digital twin can be described as a virtual model of a real object. What separates a digital twin from a traditional simulation model is the possibility to continuously update the model with inspection data from the real object, and to feed the simulation result back to the real object in order to optimize it in some way [14]. The main focus of recent studies has been to develop and evolve the digital twin concept by improving how measurement data is collected and integrated in the virtual model, and how the analysis result is implemented in the real environment [15]. Studies have also examined the relation between digital twins and cyber–physical systems, highlighting their complementary roles in achieving smart, interconnected manufacturing environments [16, 17]. Digital twin modeling and simulation approaches have focused on hybrid data-driven methods and multi-domain frameworks to improve model fidelity and real-time synchronization [18, 19].

Digital twins are seen as a part of the work towards Industry 4.0 and smart manufacturing [20, 21]. In the manufacturing context, digital twins can be used to optimize some aspect of an operation by using inspection data from parts or manufacturing processes [22]. By generating models of parts or processes and feeding the digital twin with measurement data, the quality of the final product can be improved [23]. Studies have shown that data from multiple process steps can be integrated into a digital twin to optimize the result [24]. A digital thread has been proposed as a structure for data management for a digital twin [25]. Within the field of geometry assurance, one of the important use cases for digital twins is to achieve individualized production through the use of variation simulation tools [26, 27]. Rather than using a strictly statistical approach to model variation in parts and processes and finding a robust one-size-fits-all setup which is insensitive to variation, the variation can be directly measured as it is occurring and adaptive adjustments can be made to achieve the best possible results under current conditions [28]. This approach has been suggested to manage precision in sheet metal assemblies [24] and composite assemblies [29]. Research on variation and geometry management demonstrates that digital twins can enhance dimensional quality and process stability, though significant challenges remain in model updating and data consistency [25, 30].

In the case of a fabricated aero engine component assembly, two main approaches have been suggested for minimizing geometrical variation through the use of measurement data [31]. The main challenge is to optimize the fit in the interfaces between the parts based on the unique geometrical variation on each interfacing surface on the parts. The SA (Selective Assembly) approach is based on the idea that each part in the assembly can be selected from a group of available parts in storage [32]. Each of these parts will have a certain amount of geometrical variation, and by measuring this variation an optimal combination of parts can be selected for each assembly. Another alternative is the ILA (Individualized Locator Adjustment) approach, where each locator on the fixture is adjusted within a small range to minimize variation [33]. In a case study based on the automotive industry, ILA was found to be more efficient than SA for minimizing geometrical variation [34]. However, the case studies for ILA have focused on typical automotive use cases involving sheet metal parts joined with spot welding. In order to implement ILA for a fabricated aero engine assembly, the method needs to be configured for solid parts joined with full weld seams. This requires a model with solid elements and seam welding simulation, which is significantly more computationally demanding than the shell elements and spot welding simulation used in previous studies of ILA. The Steady-state Convex hull Volumetric shrinkage (SCV) method has been evaluated in physical welding tests and has shown good results, achieving a balance between accuracy and speed which is suitable for heavy simulation which needs to be carried out within a limited time frame [35]. However, the SCV method has not been evaluated for ILA applications.

In order to realize and implement a digital twin, an infrastructure is required for managing data flow [36] and feeding the digital twin with inspection data [22]. Effective digital twin implementation in manufacturing depends on robust data acquisition, processing, and fusion methods to enable an accurate and responsive virtual representation of the physical system [37, 38]. Recent studies have emphasized that the integration of Internet of Things, AI, and cloud computing technologies provides the computational and connectivity backbone necessary for scalable and real-time digital twin applications [39, 40], highlighting the need for efficient information frameworks. The increasing use of digital twins has also brought attention to the aspect of data security [41], emphasizing the need for common frameworks and routines for building information security into the entire digital twin workflow. A unified framework is required in order to connect the digital twin to the real environment [25], and achieving feedback control of the process is seen as an important research objective [42]. Digital twins for manufacturing have largely remained at the conceptual stage [43], and many companies have not yet been able to fully implement digital twins within their processes [12]. In a review, 55% of the digital twins studied were categorized as conceptual [14]. So far, there is no unanimous consensus on what tools and methods should be used for implementing digital twins [20]. In many cases, measurement data is being collected from the production process but the potential for analysis and optimization is not properly utilized [44]. To reach the goal of a fully implemented and realized digital twin for geometry assurance of welded assemblies, a framework is required which is fully compatible with the information models and data flows applied within the industrial manufacturing environment. A standardized framework has been suggested by the ISO (International Organization for Standardization) for digital twins for manufacturing [45]. Referred to as ISO 23247, the standard aims to provide a unified view on how digital twins for manufacturing should be structured in order to ensure interoperability and enable broad collaboration. Within the manufacturing environment, the ISA-95 standard is widely used for defining information flows between manufacturing activities. However, since the ISA-95 standard was introduced before the conception of digital twins for manufacturing, no clear methodology exists for accommodating the complex real-time information flows required by a digital twin. By defining and implementing a digital twin for welded assemblies into a standardized framework and ensuring compatibility with the industrial manufacturing environment, an important contribution can be made towards lighter and more efficient aero engine components.

1.3 Scope of paper

This paper focuses on how the ILA approach can be realized in a digital twin for welded aero engine assemblies. The aim is to propose a cohesive framework describing how digital twins for geometry assurance can be organized into the manufacturing environment using standardized frameworks and information models. The proposed digital twin implementation is first defined at the functional level, showing how ILA can be combined with a novel welding simulation method. The necessary activities are outlined and described. These activities are then sorted into the ISO 23247 framework for digital twins in manufacturing, showing how information flows between each task. Finally, a proposal is made for an extended activity model based on the well-established ISA-95 manufacturing system standard. In order to ensure compatibility with ISA-95-based manufacturing environments, the proposed activity model applies a networked structure containing the activities necessary for a digital twin implementation for welded assemblies.

Section 2 provides a frame of reference, defining the concepts that support the presented work. Section 3 describes the proposed digital twin for geometry assurance of welded aero structures. In Sect. 4, the proposed digital twin is implemented in the ISO 23247 framework. In Sect. 5, the defined activities and data flows are used to create an extended activity model based on the ISA-95 standard. Section 6 describes the proposed digital twin functionality in terms of the proposed framework, followed by a case study in Sect. 7 giving an example of how a digital twin can improve fit in a welded assembly. A discussion of the results is presented, followed by conclusions and suggested future work.

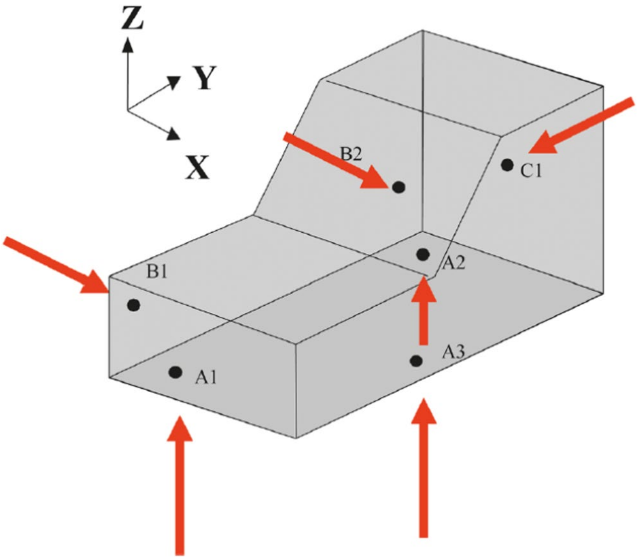

Fig. 2 A locating scheme with six locators to position a part

2 Theoretical background

This section provides an outline of the scientific concepts and industrial frameworks that support the work presented in this paper.

2.1 Digital twins for geometry assurance of welded assemblies

The digital twin proposed in this paper aims to improve the geometrical quality of welded assemblies by applying welding simulation and optimizing locators through a genetic algorithm. The theoretical foundations for this functionality are outlined below.

2.1.1 Locating systems

In order to fully define the positioning of a single rigid part, six locators are required as shown in Fig. 2. This is sometimes referred to as a 3-2-1 system: 3 locators A1, A2, A3 in the z-direction lock the part from translation along the z-axis and rotation around the x-axis and y-axis, enabling movement only in the x-y plane. 2 locators B1, B2 then lock translation along the x-axis and rotation around the z-axis, meaning that the part can now only move in the y-direction. Finally, the last locator C1 locks the remaining translation along the y-axis. However, if the part is non-rigid, flexibility will still allow it to deform and move even when constrained by a 3-2-1 system [46]. Depending on the how flexible the part and what types of forces that will be applied while it is mounted in the fixture, additional support points will be required to prevent movement in critical areas. A so called n-2-1 system includes multiple locators that makes the fixture over-constrained, requiring an FEM-analysis to compute part deformation.

Locator trimming is an approach where the locators in an assembly fixture are adjusted to improve geometrical quality [46]. This makes it possible to compensate ingoing variation on parts in the assembly. For parts that can be considered rigid, only the six locators shown in Fig. 2 need to be adjusted. For a non-rigid part, the additional clamps can be adjusted as well. There are two main methods for locator trimming. The first is *nominal trimming*, where the locators are adjusted so that the part comes as close to its nominal position as possible. In *relative trimming*, the interfaces towards adjacent parts in the assembly are instead considered. The aim is to minimize variation relative to the other parts, so that optimal fit is achieved. When considering the relative variation between multiple parts at the same time, it can be challenging to estimate the chain of cause and effect for adjustments made to each locator since multiple interfaces will be affected in various ways. *Virtual locator trimming* is a proposed method where software tools are used to help the operator understand how the assembly variation will be affected by any given locator adjustment. Still, finding an optimal solution for locator trimming of a large assembly is often difficult since there are so many variables to consider when making adjustments.

2.1.2 Genetic algorithms

Genetic algorithms are useful for solving problems with a large number of input variables, where traditional optimization methods struggle with the exponentially growing solution space [47]. The algorithm is inspired by genes and survival of the fittest, where genes correspond to a set of input variables and fitness is defined as the dependent variable to be optimized. To initialize the optimization, a starting generation is created by generating a set of individuals with random genes defined as a vector of input variables. For each individual, a fitness value is calculated based on the input variables for that individual. To generate new individuals, two main methods are used: *crossover* and *mutation*. Crossover is done by selecting two parents and generating two children based on the genes of the parents. This can be done in multiple ways depending on the use case, but a common approach is to calculate an arithmetic combination [48] of the parent genes as

$$z_1 = x\zeta + y(1-\zeta),\ z_2 = x(1-\zeta) + y\zeta$$

where x and and y are the parent vectors and z_1 and z_2 are the children vectors. To combine the two parent input vectors, a combination vector ζ with the same length as the parent vectors is generated with random values between 0 and 1. The first child vector z_1 will receive random percentages ζ of the genes of the first parent and a corresponding percentage $1-\zeta$ of the genes of the second parent. The second child vector is generated from the opposite percentages of the parent genes. To add a random element to the algorithm and explore the solution space more thoroughly, a number of new individuals are also generated by mutation. Several approaches exist, but the aim is to create new individuals that are slight variations of existing individuals with a high fitness value. One way to achieve this is to randomly select one gene from the original vector and add a random value between the upper and lower limit for that variable. If the new value is between the upper and lower limit it is kept, otherwise it is substituted with the upper or lower limit value respectively [48].

For both crossover and mutation, individuals need to be selected based on their fitness. A common approach is *roulette wheel selection*, where each individual can be imagined as a section on a roulette wheel. Individuals with high fitness receive a proportionately large sector and vice versa, meaning that any individual may be selected for crossover or mutation but high fitness individuals will be selected more frequently [49].

When mutation and crossover have been performed, the new individuals are added to the existing generation of individuals and their fitness values are calculated. To create a new generation, the individuals with the lowest fitness are discarded and the process of crossover and mutation is reiterated. Since the solution space for a genetic algorithm is usually very large, it is unlikely that the global optimal solution will be found within a reasonable number of generations. Ideally, the algorithm would be allowed to reach a fully converged state with an optimal solution. However, successful convergence is difficult to assess for genetic algorithms, as in some cases a certain improbable mutation might lead to a significantly improved result [47]. Instead, a convergence criteria can be selected based on the number of generations analyzed by the algorithm. This number can be chosen based on experience or time constraints, and it helps to establish a set simulation time for the genetic algorithm which can be important in many implementations.

2.1.3 Welding simulation

Welding is a widely used method for joining parts into assemblies. Different approaches for welding exist, but to join two parts together the interface must be heated up so that the metal melts and forms a bond. Introducing high heat in a local area causes a non-uniform temperature distribution, leading to residual stress and deformation [50]. Local thermal expansion followed by cooling and shrinkage causes plastic strains in the material [51]. These effects can be predicted through welding simulation, which is widely used in the design phase in order to assess how an assembly will react to the welding process. Studies have shown that the geometrical deformation caused by a welding process is coupled to the geometrical properties of the parts before welding [52]. It has therefore been suggested that welding simulation needs to be implemented into the geometry assurance analysis process in order to accurately predict how the geometrical deviations on a certain set of parts will affect the outcome of the welding process. This implementation creates a need for fast welding simulation capable of handling non-nominal geometries. The SCV (Steady-state Convex hull Volumetric shrinkage) method has been introduced for this purpose [51]. The method predicts shrinkage in a part by calculating the contraction of the melted material as it solidifies. It consists of three main steps. First, a steady state computation of the thermal distribution in the part, then a computation of a 2D melted zone, and finally an application of thermal loads on a 3D model. This is faster than a full transient welding simulation, and it can be applied discreetly on pre-defined segments of the weld seam to get better accuracy in areas with i.e. strong curvature. The SCV method has been evaluated with physical weld tests in [35], where it was applied on a non-nominal geometry and then compared to the real welding result.

2.2 The ISO 23247 digital twin framework

To facilitate efficient implementation and provide interoperability in Digital Twins, the ISO/TC 184 has developed and published the ISO 23247 (Part 1–4) [53–56] to provide a standard framework for creating Digital Twins in manufacturing applications. In ISO 23247-3 [55], the digital representation of manufacturing elements is defined with the Information Attributes (some mandatory, some optimal related to specific use case), which are required to create the data model and support interoperability. ISO 23247-4 [56] deals with the requirements for information exchange and how protocols and data formats should be used to achieve exchange of data and information between entities.

These standards also reference other standards for how data should be formatted to enable seamless exchange and interoperability. For example ISO 10,303 [57], which is a standard for exchanging design and production data in the manufacturing industry (also known as STEP), and IEC 62,264 series which is based upon ISA-95 [58–62], a standard for defining how manufacturing related activities and information should interface between enterprise and control systems. Those are important when designing an architecture and creating the digital infrastructure required for data management and communication, and identifies important interfaces to various industrial IS/IT systems.

The ISO 23247-4 standard also provide examples of different cases, e.g. for metrology, material removal processes and assembly, which provide guidance in setting up new applications in an industrial context. There are also new parts of the standard in preparation, ISO 23247 Part 5 & Part 6. When approved and released, it's expected to provide more holistic system perspectives on Data Integration (Digital Thread for Digital Twins) and Model Integration, how Digital Twins interact with each other (Digital Twin Composition), to scale up the use of Digital Twins.

2.3 The ISA-95 enterprise control standard

As already mentioned, the ISO 23247 is pointing to the use of the IEC 62,264 or ANSI/ISA-95 standard. Even if the design of industrial IS/IT systems per organization are usually unique and customized to some degree, and has a more or less long heritage with legacy solutions, there are some generic solutions and standards used to set the architectures and design such systems. The ANSI/ISA 95.00.01 [58] is typically used, at least as a reference model to define the different type of functions and related system software's. It is a well-accepted way to make definitions and classifications of the functions and services needed in an industrial system. In particular, organization of functional domains and functional flows ANSI/ISA 95.00.01 [58], and the related activity models ANSI/ISA 95.00.03 [60] are useful to make a clear common view and understanding of the complete system. The ANSI/ISA 95.00.02 & ANSI/ISA 95.00.04 [59, 61] also give the guidance for how the information and data structure should be designed using object models and their attributes, to create clear interfaces and opportunity for interoperability between functions and levels. However it is difficult to see and assess how that is implemented in reality. In many cases the system architecture becomes more ad-hoc, based on adaptation of different legacy systems and/or how they are built and implemented by different software suppliers.

As ISA-95 was developed and launched as a standard many years before Digital Twins was introduced, ISA-95 is not designed with a well-defined entity and environment for those, and therefore does not have such functions, activities or orchestration integrated. Even though the ISO 23247 standard provides some guidance, current MES/MOM (Manufacturing Execution System/Manufacturing Operations Management) and PLM/ERP (Product Life Cycle Management/Enterprise Resource Planning) systems are often based on ISA-95. There is a need to integrate dedicated functionality and activities that enables Digital Twin integration.

3 Proposed digital twin for welded aero structures

This paper proposes a digital twin for geometry assurance of welded high precision assemblies. The purpose of this digital twin is to optimize the geometrical quality of the final product based on the measured variation in the parts that are to be welded together.

As soon as measurement data for a set of parts is available, it is transferred to the digital twin and translated to a legible format. An analysis is initialized which generates a starting generation of individuals with random settings for the locators and clamps on the fixture. These different settings are delegated to one or multiple instances of a variation analysis software. In each instance, the parts are positioned according to the settings of an individual from the genetic algorithm and a non-nominal welding simulation is initialized. The result of the simulation is used to evaluate the feasibility of these specific settings. The individuals that present the highest predicted feasibility are used as parents for a new generation, and the individuals with the lowest feasibility are discarded. After a sufficient number of generations, the feasibility will begin to converge towards a set of optimized settings. These settings along with predicted final product variation are evaluated by an operator and are then transferred and implemented in the physical weld fixture.

The digital twin is reliant on multiple sets of geometrical data as shown in Fig. 3. The transfer of these data sets between different activities can be solved using a message broker that takes output from one activity and delivers it as input to another. The simulation itself is based on *as-built* inspection data that is collected from in-line scanning equipment. This data describes the geometry of the parts so that the predictive welding simulation can take all geometrical variation into account. The simulation also requires the *as-designed* nominal data as a baseline. The result of the simulation comes in the form of *as-simulated* prediction data, which is the best available estimation of the outcome of the welding process. In order for the digital twin to be useful, this data needs to be as accurate as possible under the current constraints on time and computational capacity. In order to evaluate the simulated prediction, it can be compared to as-built inspection data that is collected after the welding process is finished. This comparison should be made continuously to monitor and optimize the predictive accuracy of the digital twin.

4 Application of ISO 23247 Digital Twin Framework

In order to organize the digital twin into the ISO 23247 framework, each of its functions need to be sorted into four domains: Observable manufacturing domain, Device communication domain, Digital twin domain, and User domain. A full overview of the framework is shown in Fig. 4.

The observable manufacturing domain contains the set of parts that are to be welded together, as well as the manufacturing equipment including the fixture used to mount the parts before welding.

The device communication domain is where the measurement data is collected and transferred to the digital twin. It is also where the output of the digital twin is converted to an input for the assembly operation.

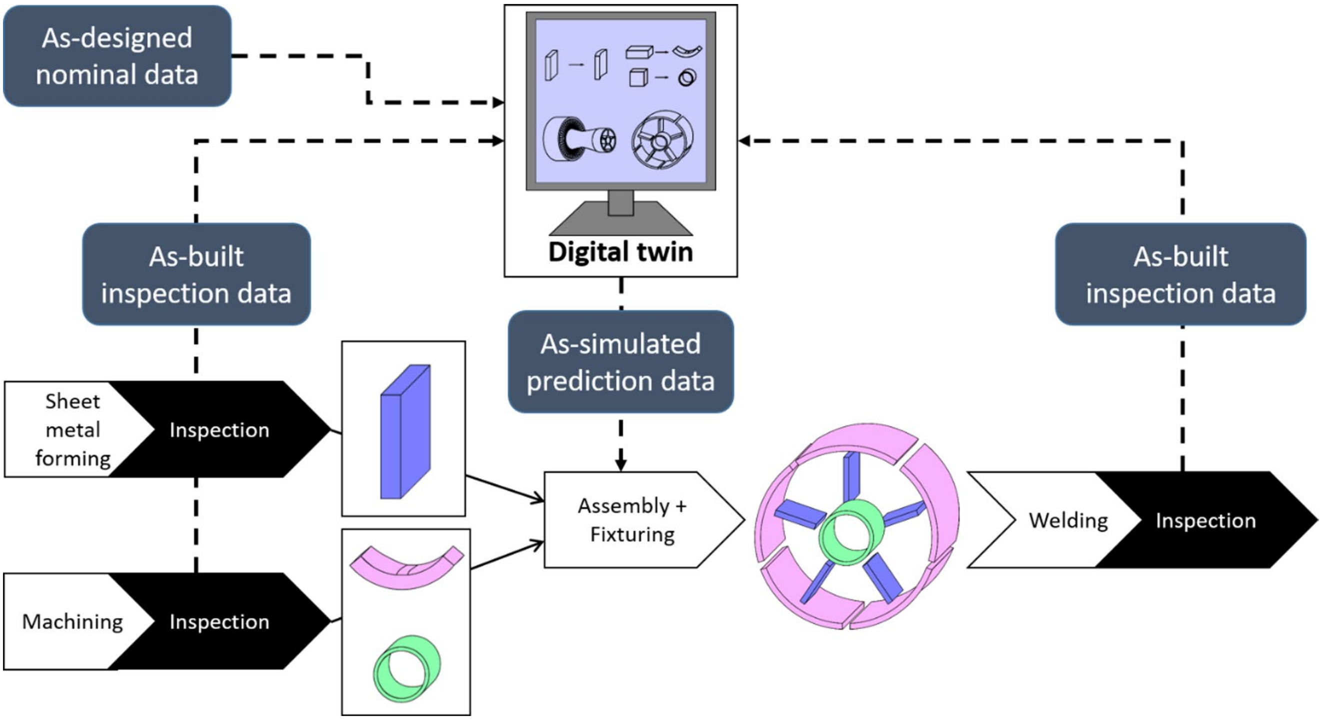

Fig. 3 Overview of inspection data flows within the digital twin

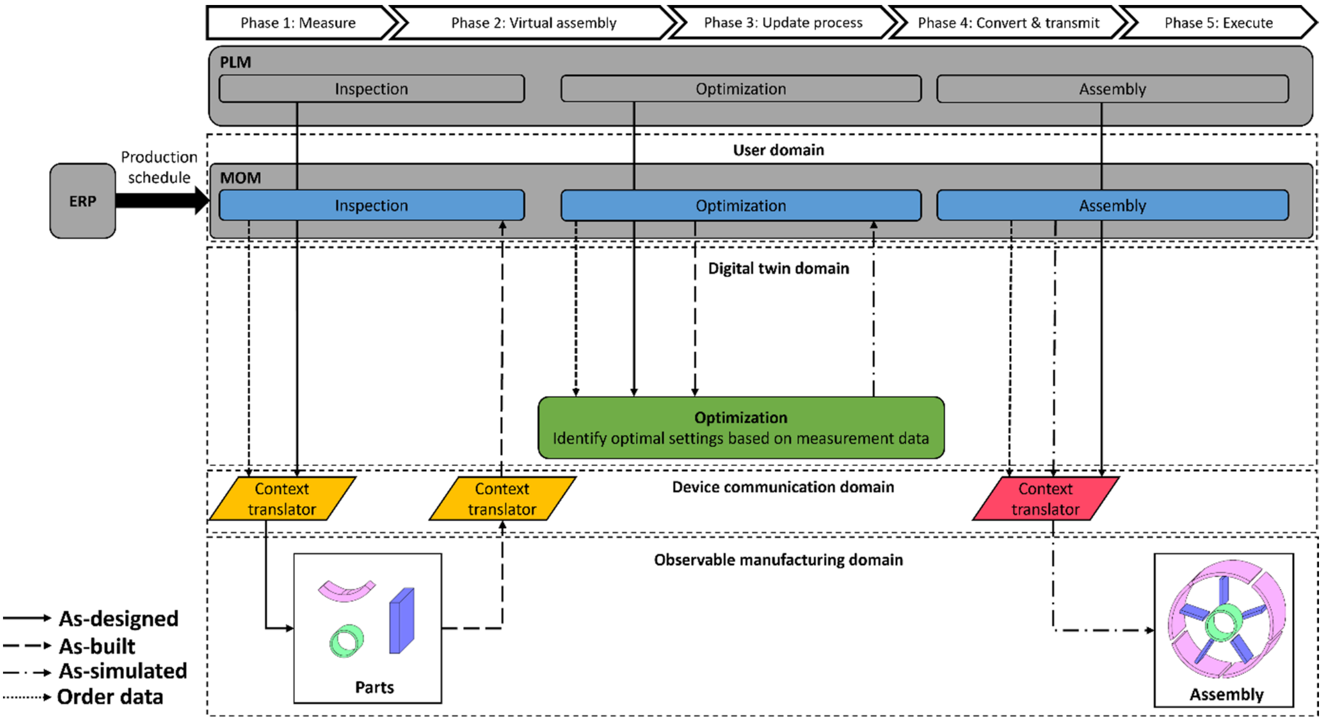

Fig. 4 The proposed digital twin functionality organized into the ISO 23247 framework

The digital twin domain contains the optimization software, where the scan data is used to create a non-nominal virtual assembly and evaluate different settings. This analysis has no physical presence and is therefore not counted as an observable element.

The user domain is where the digital twin simulation is initialized, visualized and controlled by the operator. The user can monitor and control the simulation to check for convergence and estimate simulation time. When the simulation is finished, a report is generated which shows how well the recommended settings are predicted to meet drawing requirements for the final product. After the user has reviewed the report, the settings are transferred to the fixturing equipment through the device communication domain. The MOM/MES system is here considered to be a part of the user domain, since it manages design and measurement data while orchestrating the activities in the digital twin. The PLM and ERP systems are placed outside of the framework since they do not contain any data specific to the individual set of parts being analyzed by the digital twin. They do however provide important information, with the ERP containing operation scheduling information and PLM providing design data which is then contextualized in the digital twin.

The information flows in the framework contain four types of data as shown in Fig. 4. **Order data** is used to initialize activities and assign an individual product ID. **As-designed data** is downloaded from the PLM system and contains nominal design data. **As-built data** contains measurements from individual parts, and **As-simulated data** is generated by simulating the as-built data to predict behaviors in the manufacturing process. The ISO 23247 standard is generally non-prescriptive when it comes to data formats and communication protocols for information transfers. The proposed functionality requires two types of communication: continuous operational data communicating the current state of different activities and heavier models containing a complete description of either as-designed, as-built, or as-simulated data. This requires both a lightweight messaging protocol for continuously tracking activity states with publish-subscribe, and a request-response protocol for querying heavier models.

5 Integration of digital twin framework into ISA-9compliant manufacturing environment

In order to integrate this digital twin workflow in an industrial manufacturing environment, the defined activities and information flow need to be organized into the context of a product lifecycle management system. The ISA-95 standard provides a semantic model and a set of ontologies commonly used within the manufacturing industry [63]. By using ISA-95 as a baseline for how activities and information are managed in the manufacturing environment, a strategy can be outlined for how a digital twin for manufacturing should be implemented.

The automation pyramid is often used as a model for how activities and information flows should be managed within ISA-95. The pyramid suggests a strict hierarchy with separate levels, where each activity belongs to a specific level. Information is transferred between adjacent levels in the pyramid. However, new manufacturing paradigms such as Industry 4.0 and smart manufacturing have brought significant changes to the way in which information is managed. Increased data storage means that more information about products and processes can be stored, increased computational power allows for complex data analysis, and technologies such as internet of things makes it possible to easily transfer data between devices through internet connections. It has been suggested that the automation pyramid and its strict hierarchy is not compatible with these changes [64]. Relevant information should be available wherever it is needed, data needs to be able to flow freely between all activities in the manufacturing system. A networked architecture is therefore much more suitable for modern manufacturing. This allows all activities to directly exchange information as required, rather than being limited to communication with neighboring layers in the pyramid. An illustration is shown in Fig. 5.

In addition to the pyramid, the ISA-95 standard also offers an activity model, shown in Fig. 6. In order to establish a networked architecture within the ISA-95 framework, this model can be used as a foundation. The activity model consists of eight main activities and prescribes an information flow between them illustrated by arrows. Within the model, three of these activities interface with lower level operations through the MOM/MES interface:

- Definition management handles data such as work masters and product definitions, which are usually stored within the PLM/ERP system. This data is made available in the MOM/MES environment by linking and downloading product definitions from PLM/ERP.
- Execution management coordinates the manufacturing process flow, receiving confirmation from finished tasks and initiating new tasks when appropriate.
- Data collection stores and provides data relevant to the manufacturing process, including measurements and work instructions for specific parts and operations.

By connecting additional activities to these interfaces, the activity model can be expanded with additional activities and information flows to support various kinds of functionality within the manufacturing system [64].

5.1 Mapping the digital twin framework to an extended ISA-95 activity model

To accommodate the workflow of the digital twin for manufacturing proposed in this work, the ISA-95 activity model needs to be extended based on the activities outlined in the previously shown digital twin framework. From the observable manufacturing level of the digital twin framework, activities are added for sensing and actuating respectively. Data from the sensing activity is received by the data collection activity, which sorts and labels the product data for further usage and makes it available to other activities through queries. The core component of the digital twin consists of an optimization activity which requests product data from the data collection unit and then performs a simulation task to search for optimal solutions. The results are shared with

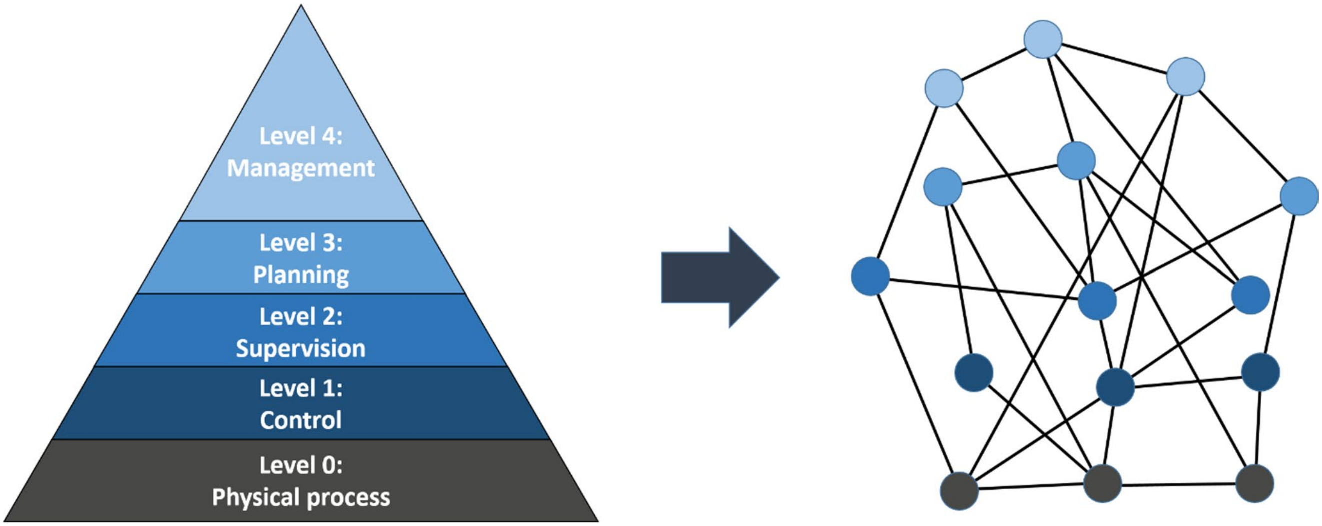

Fig. 5 Transitioning from a hierarchical structure to a networked structure, illustration inspired by [64]

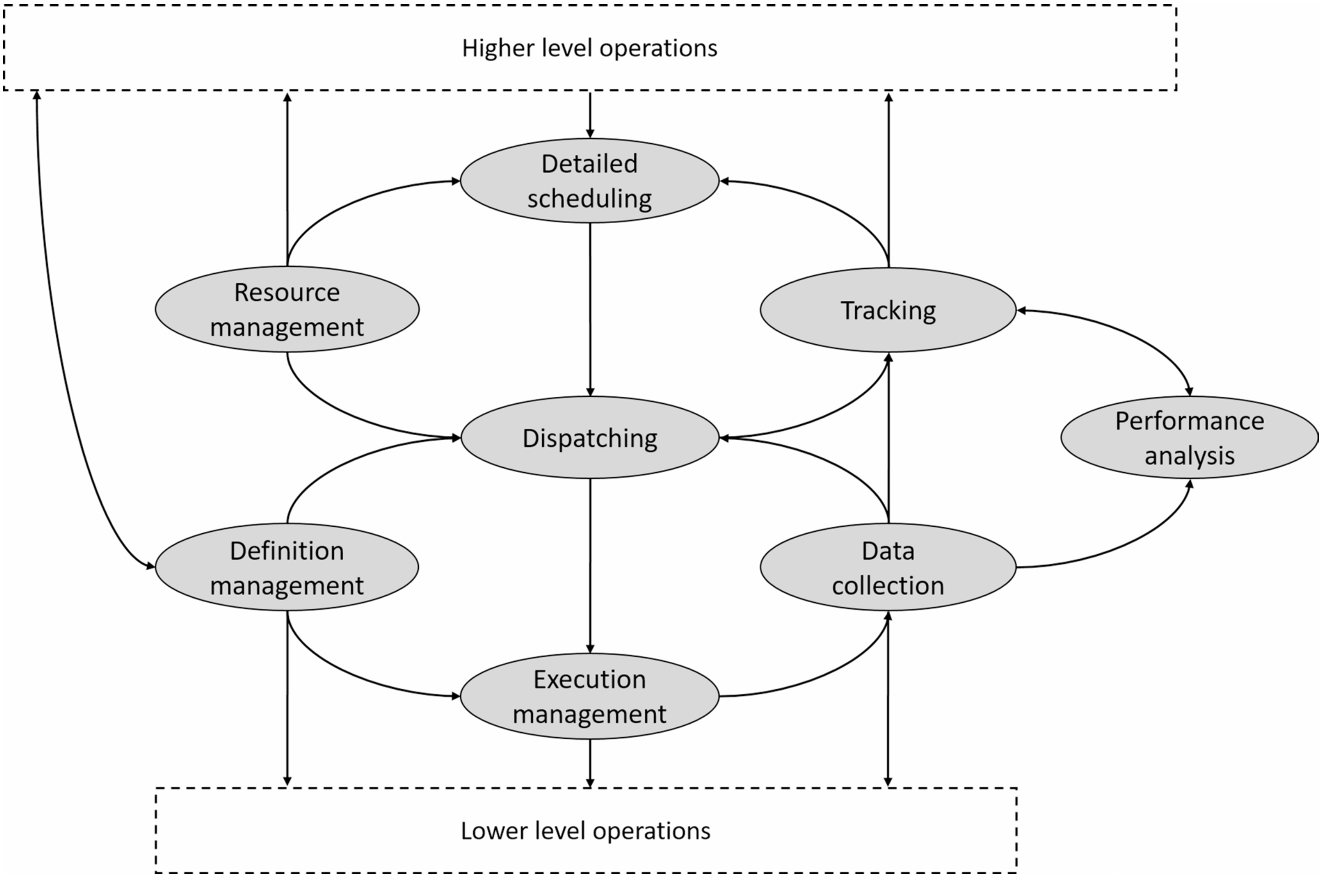

Fig. 6 The ISA-95 activity model, illustration based on [64]

an evaluation unit which allows an operator to monitor the optimization process and review the final result of the analysis. The optimized solution is then implemented through the actuating task. The extended activity model is shown in Fig. 7.

5.1.1 Sensing activity

Activities for sensing and actuating belong to the observable manufacturing domain in the ISO model. These activities are physically located close to the manufacturing process. In the proposed digital twin implementation, the sensing task uses 3D scanning to collect a point cloud which describes the part. The newly acquired as-built data is sent to the data collection activity, and a task confirmation is sent to execution management to confirm that this activity has finished successfully. The information exchange is shown in Fig. 8.

5.1.2 Optimization activity

When the sensing activity has finished, the optimization activity is initiated from execution management. As-built data from measured parts is received from data collection, and as-designed data is received from definition management including up-to-date nominal data, tooling and settings. The as-built and as-designed data are combined to generate a virtual assembly which can be used to predict the behavior of the next process step under current conditions. The output of the optimization is a set of suggested process settings. Results are sent to the evaluation activity, which returns a confirmation that the final suggested settings have been evaluated and verified. Optimized settings are then sent to definition management in the form of as-simulated data to update the product definition for the current set of parts. Finally, a confirmation is sent to execution management. The information flows are shown in Fig. 9.

5.1.3 Evaluation activity

Evaluation is required for multiple purposes within the proposed digital twin functionality. Before the settings proposed by the optimization task can be implemented, the predicted geometrical variation needs to be reviewed and compared against all relevant requirements on the welded assembly. These requirements are contained within the as-designed data, which can be compared to the as-simulated

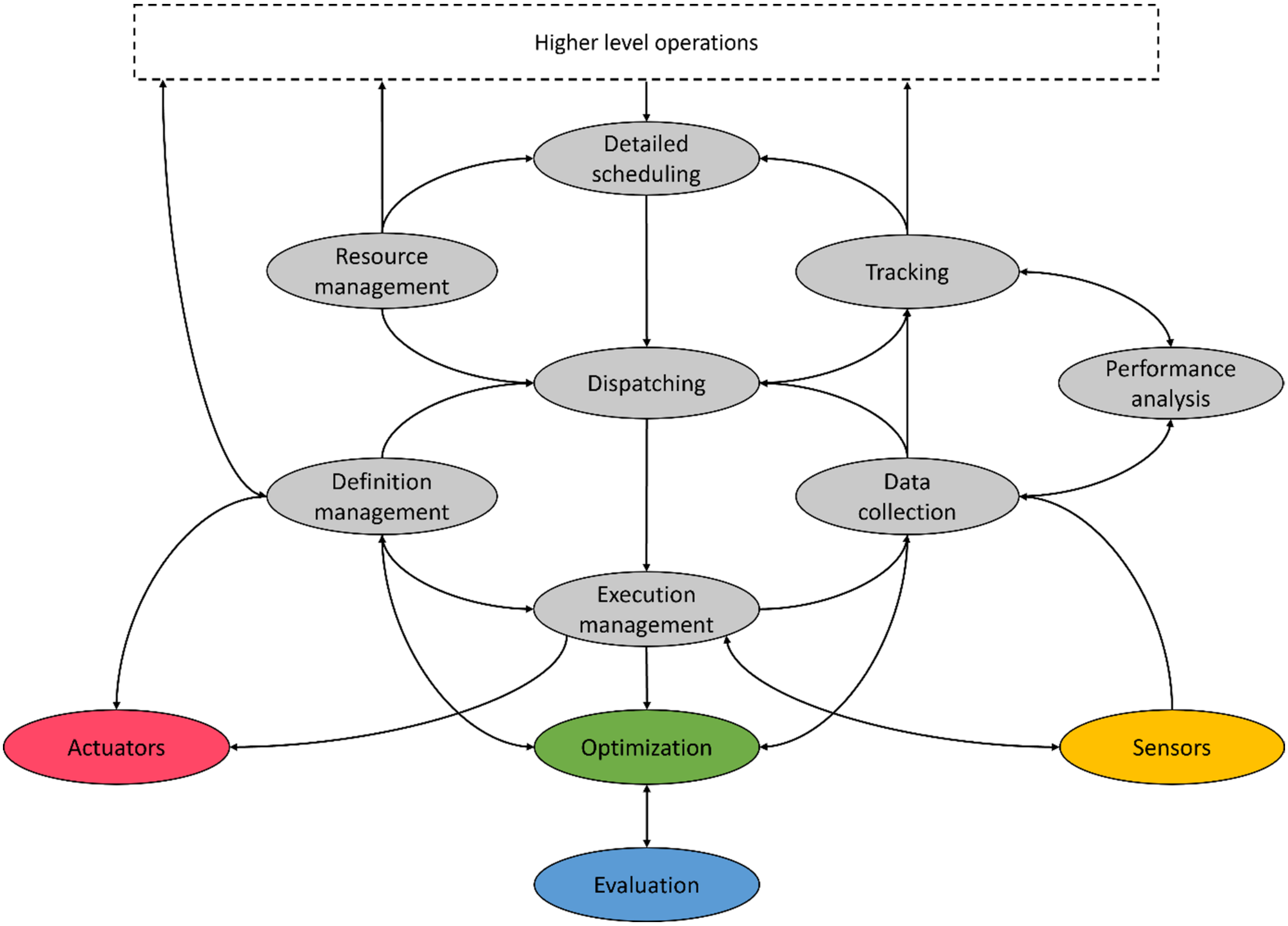

Fig. 7 Extended ISA-95 compliant activity model based on digital twin functional requirements

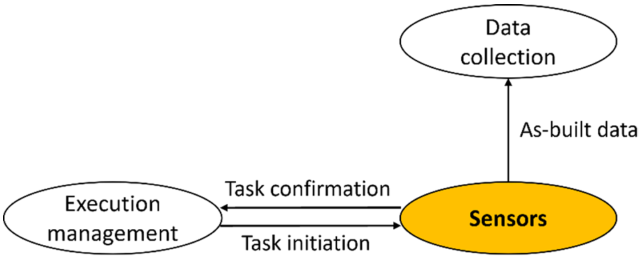

Fig. 8 Information exhange for sensing activities

data from the digital twin. Before the optimization activity can finish, it requires a confirmation from the evaluation activity that there are no errors in the optimized settings. Information flows for evaluation are shown in Fig. 10.

5.1.4 Actuating activity

The actuating activity is initialized when the optimization has finished, initiated by execution management. Optimized settings are sent to this activity from definition management. The purpose of the actuating activity is to implement these settings in the physical process to match the prediction made by the digital twin. The information flows are shown in Fig. 11.

6 Internal Digital Twin Functionality

In this section, an implementation of the proposed digital twin functionality is presented, based on the ISO 23247 and ISA95 standards.

6.1 Internal Functional Architecture

The proposed digital twin for welded assemblies is based on a virtual assembly which mirrors the real physical welding fixture setup. Nominal geometries for all parts in the assembly are meshed and imported into the RD&T software. In RD&T, a tolerance analysis is set up with a locating system for each part and measurement points on critical surfaces and interfaces. This model can be updated with scan data from real parts as it becomes available, and the position of

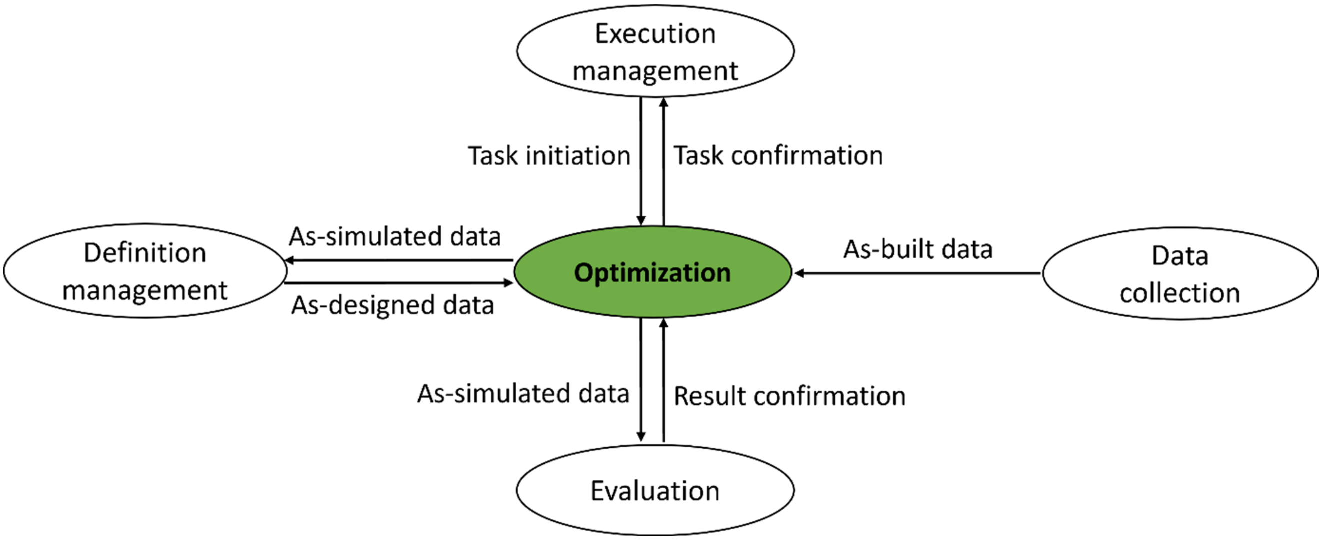

Fig. 9 Information exhange for optimization activities

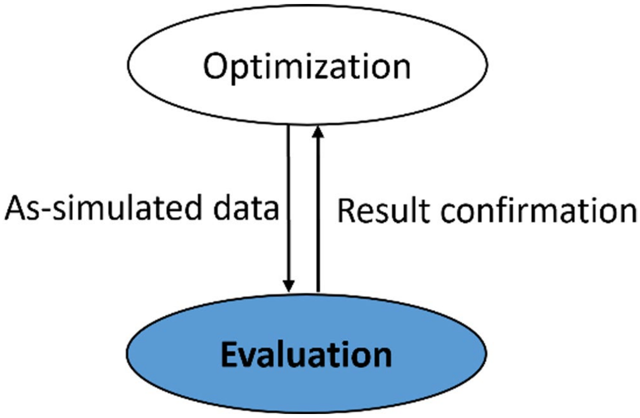

Fig. 10 Information exhange for evaluation activities

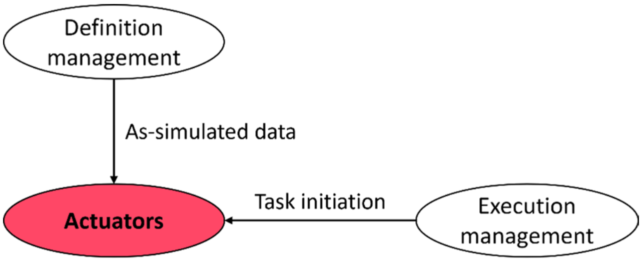

Fig. 11 Information exhange for actuating activities

each locator can be adjusted individually to analyze how it affects the measurement points given a specific set of scan data. The position of each locator mirrors the locating system in the real weld fixture. When scan data has been received for all parts in the assembly, the surfaces on the virtual parts are adapted to real measurements by warping the mesh and moving nodes to the closest point on the scanned surface. RD&T is then ready to make an individualized analysis for the measured assembly of parts.

In order to make a systematic search for optimal solutions in the large solution space of an adjustable weld fixture, a genetic algorithm is implemented in Matlab. The algorithm starts with a population of individuals with random settings for each locator in the fixture and then writes input files which can be read by RD&T. Multiple instances of RD&T can be used to analyze multiple individuals in parallel, so that individuals that belong to the same generation can be analyzed more quickly. When each analysis finishes, a result file containing the deviation in each measurement point is created which can be read by Matlab. When results have been read for all individuals in the starting generation, they are analyzed in Matlab. In order to prioritize compliant individuals, penalties can be added to measurements which are out tolerance. A root mean square (RMS) values is then calculated from all measurement points and assigned to each individual as a fitness value. The individuals with the best fitness are selected as parents for a new generation, and children are created by crossing parent genes. A small amount of mutation is randomly assigned to each child to explore a larger part of the solution space. This loop is then repeated until the population fitness starts to converge or until the manufacturing schedule demands that the weld process is started. The optimized locator settings are then exported, along with the adjusted and optimized virtual assembly, to be evaluated and implemented in the manufacturing process.

The requirements of the proposed digital twin regarding data and communication are mainly related to scan data and internal communication between RD&T and Matlab. The scan data is applied in RD&T with the STL format, and a wrapper can be used to translate standardized formats such as STEP 242 or QIF into an STL file. Communication between RD&T and Matlab depends on the implementation.

If RD&T and Matlab are running on a single computer, they can exchange information by writing and reading text files in a specified catalog. If multiple instances of RD&T are required beyond the capacity of a single computer, containerized instances of RD&T can be run in a cloud computing environment. In this case, the MQTT protocol can be used for communication by having Matlab and RD&T instances subscribe and publish to the same address.

6.2 Framework implementation

The first step towards an industrial implementation of the proposed digital twin is to organize the relevant activities into the ISO 23247 framework shown in Fig. 4. A full overview of the implementation is shown in Fig. 12. Here, MOM and PLM functionality is provided through Opcenter and Teamcenter respectively, and ERP functionality is implemented with SAP. Communication is managed in two ways: MQTT is used for transferring order data and initialize new activities, and REST API is used to transfer as-designed, as-built and as-simulated data in the STEP 242 format. Proprietary formats are used when necessary. The digital twin analysis loop is initiated from Operation 10 in Opcenter by sending order data to a context translator. A nominal scanning program in zinspect format is then downloaded directly from Teamcenter, and the zinspect file is contextualized with a unique product ID. The scan cell consists of a Zeiss GOM scanner which collects 3D scan data and writes an STL file with geometric data and a CSV file with evaluated drawing characteristics. These are translated to a STEP 242 file which is sent to Opcenter to finish the inspection operation. Operation 20 is then initialized by sending order data to the optimization activity, which downloads a rdt file with a nominal variation analysis program from Teamcenter and the newly collected as-built scan data from Opcenter. The variation analysis program is contextualized with scan data and the optimization is initialized through a genetic algorithm in Matlab. When the optimization has finished, it sends as-simulated data with recommended settings and predicted final variation to Opcenter where an operator reviews the as-simulated data and approves it to finish the operation. Operation 30 can now be started by sending order data to a context translator which downloads a nominal welding program from Teamcenter in rapid format and optimized locator settings from Opcenter. The nominal program is then contextualized with the optimized settings and product ID and passed on to the weld cell.

The workflow shown in the ISO 23247 framework can also be described with the extended activity model to outline the digital twin functionality in terms of an ISA-95 based industrial environment, as shown in Fig. 13. In this proposed implementation, Opcenter contains all contextualized data for individual parts in the manufacturing flow. Digital twin activities are initialized from execution management by sending out order data. When scan data and simulation data becomes available, the definition management activity is used to update nominal as-designed data with as-built and as-simulated data. Queries are made to

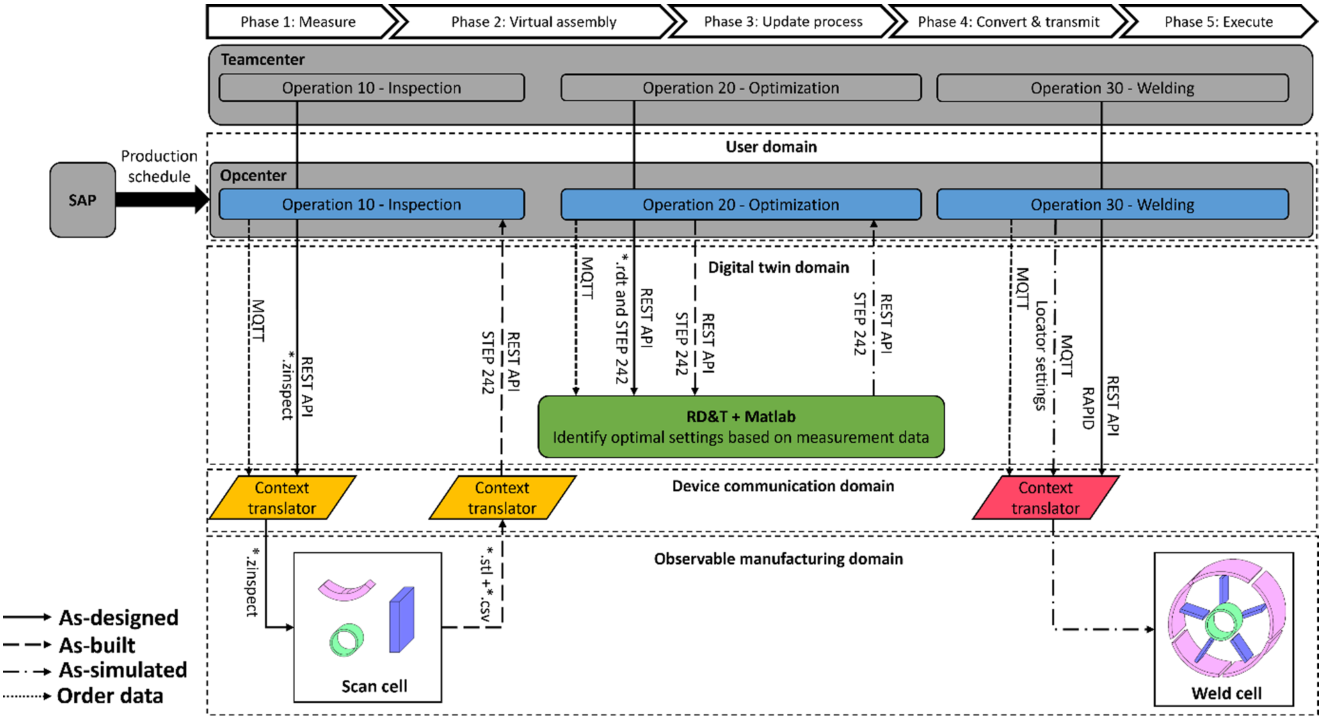

Fig. 12 ISO 23247 framework for the proposed digital twin for welded assemblies

Teamcenter when necessary to download nominal models and programs. However, no data is written to Teamcenter in this implementation to preserve the integrity of nominal design data.

7 Case study

This section presents a demonstration of the proposed digital twin for welded assemblies, showing how it can use measurement data to optimize settings in a weld fixture.

7.1 Case study description

The case study is based on an assembly consisting of 11 parts as shown in Fig. 14. The assembly is representative of those used for welded aero engine structures, and creates the same type of manufacturing challenge. In a nominal virtual model, the fit in each interface is perfect and it would be trivial to assemble and weld these parts into a compliant final product. However, on real physical parts there will always be small deviations on each surface of the parts which will slightly affect how the parts fit against each other. When assembling the parts in the weld fixture, these deviations need to be taken into account by making small adjustments to the locators in the fixture. Since each part has two interfaces against two other parts, the whole system is essentially coupled and it is often difficult to balance all adjustments to get optimal fit throughout the entire assembly. The purpose of this digital twin is to efficiently optimize these adjustments in a virtual environment and identify a set of locator positions that meets all geometric requirements while minimizing overall variation. In this case, the optimization focuses on getting an optimal fit and weld quality in the interfaces between the parts.

7.2 Execution of digital twin functionality

The virtual assembly is set up in RD&T by creating an assembly of 11 meshed parts and giving each part a 3-2-1

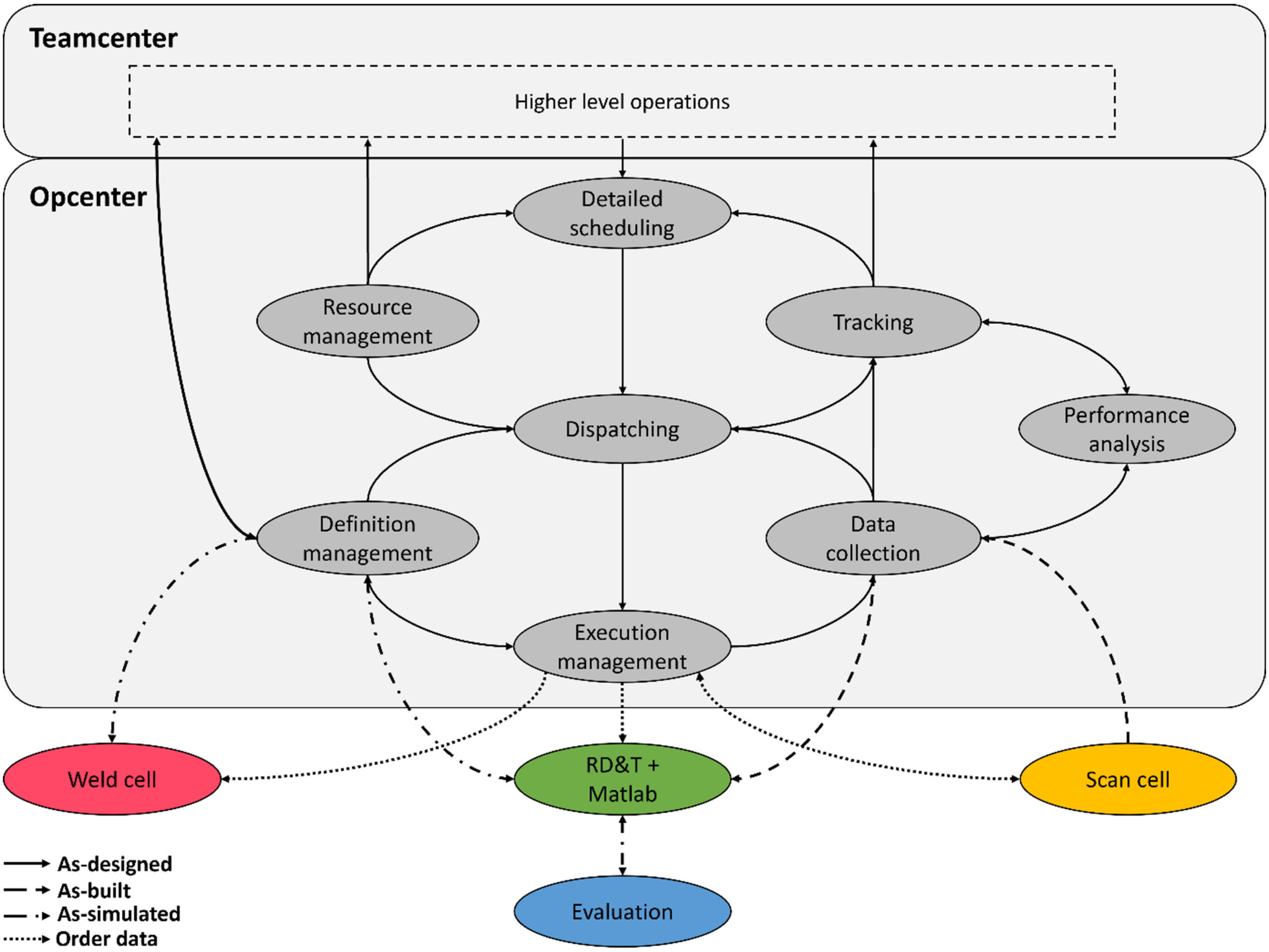

Fig. 13 Extended ISA-95 activity model for the proposed digital twin

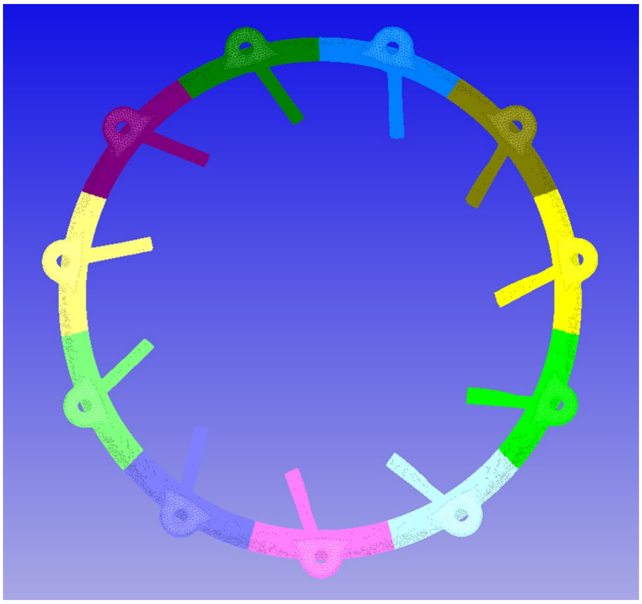

Fig. 14 Assembly used in the case study

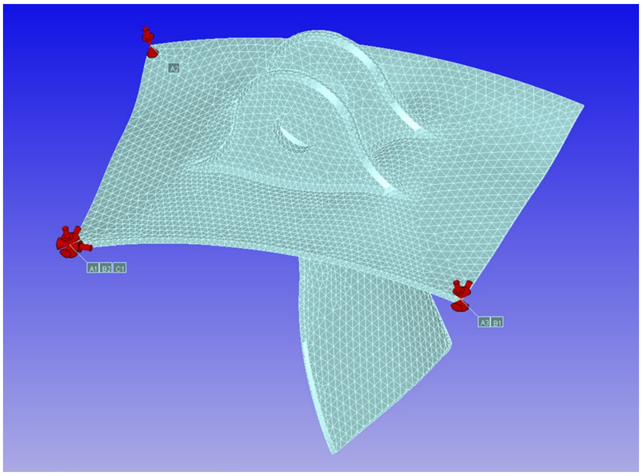

Fig. 15 Each part has 6 locators in a 3-2-1 scheme

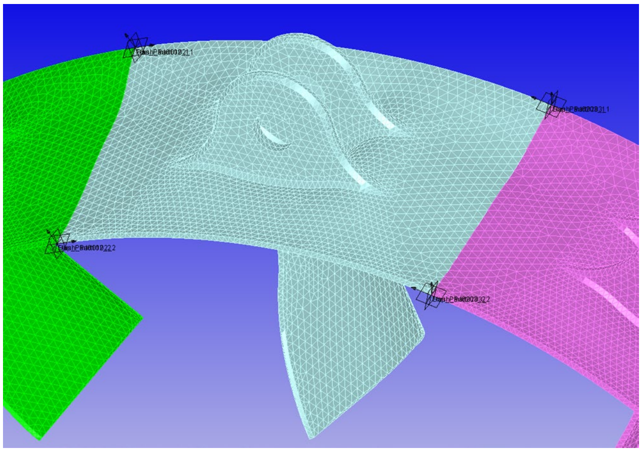

Fig. 16 Each interface has four measurement points, in two positions and in two directions

locating system as shown in Fig. 15, resulting in a total of 66 adjustable locators for the entire assembly. Four measurement points are created in each interface as shown in Fig. 16 to track gap and flush mismatch between parts, leading to 44 measurement points in total. To speed up the analysis, 20 instances of RD&T with the same model are set up on a single computer with a 16-core 1.40 GHz CPU and 64 GB RAM. A genetic algorithm is created in Matlab which searches for lowest possible RMS value based on all 44 measurement points. In this model, weld requirements are 0.1 mm for both gap and flush. A penalty value is added to all measurement points exceeding the +-0.1 mm range to further increase their RMS and make them less likely to survive. The algorithm is only allowed to adjust each locator position within a safe given range.

To initiate the analysis, STL files with geometric data are read for each of the 11 parts and the mesh is warped accordingly. The genetic algorithm is then initiated in Matlab, and the algorithm is allowed to run for 8 h. The result of the optimization is a set of optimized locator positions, and corresponding measurements which can be evaluated to check that all measurements are within tolerance. A comparison between the measurement results for nominal locator positions and results for the optimized positions can be seen in Fig. 17, showing that all gap and flush values are within the 0.1 mm tolerance limit.

8 Discussion

The proposed framework is an important step towards a full implementation of a digital twin for welded assemblies. By connecting individual parts and processes to the relevant MOM/MES and PLM/ERP systems, a digital thread is essentially generated to support the digital twin with necessary data. Further work will be required in order to scale up the digital twin to a fully integrated system within the manufacturing environment. Once the basic digital twin functionality is in place, there are many ways in which it could be expanded to cover more aspects of the manufacturing process.

While this paper focuses on welding simulation and fixture optimization, the proposed framework could support various types of analysis and process adjustments. Creating a virtual model of a physical product or process based on collected data has a broad spectrum of use cases. The simulation could focus on both geometrical and mechanical properties, such as prediction of residual stresses in a structure. The digital twin can be used to optimize different process settings as well as properties of the parts themselves. This could include strategies for adaptive machining of an

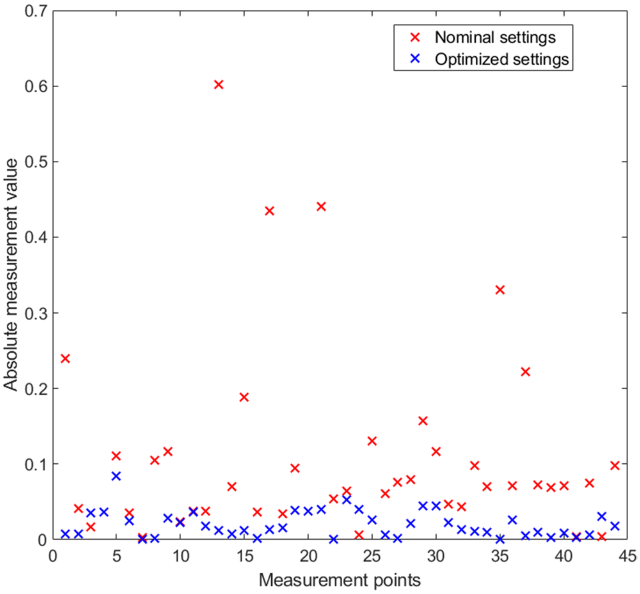

Fig. 17 Measurement values before and after optimization, shown as absolute values

interface to improve the fit of the final assembly, which would allow for further optimization of geometrical quality.

In the examples given in this paper, the digital twin focuses on the assembly process, which is a single operation in a longer manufacturing chain. Ideally, the digital twin should interact with every step in the manufacturing chain. This would allow for continuous optimization that is always based on the latest measurements, making sure that the final product has the highest possible quality based on current conditions.

Having a common framework enables interoperability between different digital twin applications by offering a semantic model and applicable ontologies. This enables collaboration between different actors working within the field. The goal is to avoid a situation where each digital twin is developed as a proprietary system for a single use case. Ideally, functionalities developed within separate projects should be able to be combined without extensive rework since they share the same basic data formats and protocols.

Moving from a strictly hierarchical and air-gaped structure towards an open networked structure will have implications when it comes to cyber security. Features such as API access to PLM and MOM systems from various software implementations will make these systems more vulnerable, however this is difficult to avoid when using digital twins for manufacturing since product data is an essential part of the digital twin. Even if the digital twin does not have writing access to the PLM system, it can freely access PLM information and it can also make changes in the MOM environment. The risk of malicious attacks will need to be managed and mitigated accordingly, and in some cases cloud computing solutions for heavy analysis tasks may need to be replaced with slower local computing to keep sensitive data safe. Solutions where the digital twin can only write data to MOM and not to PLM can also limit the potential harm of errors or attacks. Another risk is errors in the output of the digital twin leading to control signals outside of safe operation envelopes being sent to manufacturing equipment. This can be mitigated by having an operator review analysis results manually, and implementing safeguards in the equipment which rejects unsafe inputs.

9 Conclusion

A digital twin for welded assemblies has the potential to improve geometrical quality by individualizing the process and adapting it to measured part data. In order to implement and realize this system, it needs to be integrated into an industrial manufacturing system. In this paper, the ISO 23247 framework is used in order to structure the functionality of a digital twin for welded assemblies into a workflow of activities. This workflow is then established within an extended activity model based on the ISA-95 standard, showing how a digital twin could work as an integrated part of a manufacturing system. Finally, a case study shows how a digital twin implementation in Matlab and RD&T can decrease variation in a welded assembly. By collecting data from individual parts and processes and making it accessible to other activities, a digital thread is created to support the digital twin. The exact structure of the extended activity model shown in this paper should not be seen as prescriptive. Depending on the functionality and purpose of a digital twin, different activities and data flows may be required. An ISA-95 compliant digital twin framework can be generated by following the steps outlined in this paper:

- Define the functionality of the digital twin, including required inputs and outputs for the relevant analysis.
- Organize this functionality into the ISO 23247 framework to identify activities and information flows.
- Create an extended activity model by adding activities and defining their inputs and outputs.
- Use the activity model as a reference when integrating the digital twin into the manufacturing process.

For successful integration of a digital twin, full compatibility is required with the relevant MOM/MES and PLM/ERP systems used within the manufacturing environment. Important future work includes the development of standardized data formats and protocols to facilitate this interoperability.

Author Contributions All authors contributed to the conceptualization of the paper. Hugo Hultman wrote the first draft, with contributions

from Johan Vallhagen to the theoretical background section. All authors provided feedback on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Chalmers University of Technology. This work was funded by support from the Swedish Governmental Agency of Innovation Systems (VINNOVA) and the NFFP7 program.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

1. Runnemalm H, Tersing H, Isaksson O (2009) Virtual manufacturing of light weight aero engine components, International Symposium on Air Breathing Engines: 07/09/2009–11/09/2009
2. Madrid J, Söderberg R, Vallhagen J, Wärmefjord K (2016) Development of a Conceptual Framework to Assess Producibility for Fabricated Aerospace Components. Procedia CIRP 41:681–686
3. Lu C, Zhao H-W (2015) Fixture layout optimization for deformable sheet metal workpiece. Int J Adv Manuf Technol 78:85–98
4. Söderberg R, Lindkvist L, Wärmefjord K, Carlson JS (2016) Virtual geometry assurance process and toolbox. Procedia Cirp 43:3–12
5. Wärmefjord K, Söderberg R, Lindau B, Lindkvist L, Lorin S (2016) Joining in nonrigid variation simulation. Computer-aided Technologies–Applications in Engineering and Medicine
6. Lindau B, Wärmefjord K, Lindkvist L, Söderberg R (2014) Method for handling model growth in nonrigid variation simulation of sheet metal assemblies. J Comput Inf Sci Eng 14(3):031004
7. Choi W, Chung H (2015) Variation simulation of compliant metal plate assemblies considering welding distortion. J Manuf Sci Eng 137(3):031008
8. Lorin S, Lindkvist L, Söderberg R (2014) Variation simulation of stresses using the method of influence coefficients. J Comput Inf Sci Eng 14(1)
9. Lorin S, Cromvik C, Edelvik F, Lindkvist L, Söderberg R On the Robustness of the Volumetric Shrinkage Method in the Context of Variation Simulation, Proc. ASME 2014 International Mechanical Engineering Congress and ExpositionV02AT02A053
10. RD&T Technology, Robust Design and Tolerancing Software RD&T (2025) Available online: https://www.rdnt.se/. Accesse 23 Apr 2025.
11. 3DCS, Dimensional Control System 3DCS (2025) Available online: https://www.3dcs.com/. Accessed 23 Apr 2025.
12. Behrendt A, Duron A, Kelly R, Mussler S, Rettig R, Stoffregen S (2018) Digital manufacturing: escaping pilot purgatory, McKinsey & Company
13. Soori M, Arezoo B, Dastres R (2023) Digital twin for smart manufacturing, A review. Sustainable Manuf Service Econ 2:100017
14. Kritzinger W, Karner M, Traar G, Henjes J, Sihn W (2018) Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine 51(11):1016–1022
15. Kerremans M, Burke B, Cearley D, Velosa A (2019) Top 10 strategic technology trends for 2019: digital twins. Gartner Research, Document ID
16. Tao F, Qi Q, Wang L, Nee A (2019) Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. Engineering 5(4):653–661
17. Schleich B, Anwer N, Mathieu L, Wartzack S (2017) Shaping the digital twin for design and production engineering. CIRP Ann 66(1):141–144
18. Wagner R, Schleich B, Haefner B, Kuhnle A, Wartzack S, Lanza G (2019) Challenges and potentials of digital twins and industry 4.0 in product design and production for high performance products. Procedia CIRP 84:88–93
19. Tao F, Xiao B, Qi Q, Cheng J, Ji P (2022) Digital twin modeling. J Manuf Syst 64:372–389
20. Lattanzi L, Raffaeli R, Peruzzini M, Pellicciari M (2021) Digital twin for smart manufacturing: A review of concepts towards a practical industrial implementation. Int J Comput Integr Manuf 34(6):567–597
21. Li L, Lei B, Mao C (2022) Digital twin in smart manufacturing. J Industrial Inform Integr 26:100289
22. Wärmefjord K, Söderberg R, Lindkvist L, Lindau B, Carlson JS Inspection data to support a digital twin for geometry assurance, Proc. ASME 2017 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection
23. Sjöberg A, Önnheim M, Frost O, Cronrath C, Gustavsson E, Lennartson B, Jirstrand M (2023) Online geometry assurance in individualized production by feedback control and model calibration of digital twins. J Manuf Syst 66:71–81
24. Grégorio J-L, Lartigue C, Thiébaut F, Lebrun R (2021) A digital twin-based approach for the management of geometrical deviations during assembly processes. J Manuf Syst 58:108–117
25. Wärmefjord K, Söderberg R, Schleich B, Wang H (2020) Digital twin for variation management: A general framework and identification of industrial challenges related to the implementation. Appl Sci 10(10):3342
26. Söderberg R, Wärmefjord K, Carlson JS, Lindkvist L (2017) Toward a Digital Twin for real-time geometry assurance in individualized production. CIRP Ann 66(1):137–140
27. Söderberg R, Wärmefjord K, Madrid J, Lorin S, Forslund A, Lindkvist L (2018) An information and simulation framework for increased quality in welded components. CIRP Ann 67(1):165–168
28. Shahpar S Building digital twins to simulate manufacturing variation, Proc. Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers, p. V02AT32A049
29. Polini W, Corrado A (2020) Digital twin of composite assembly manufacturing process. Int J Prod Res 58(17):5238–5252
30. Schleich B, Wärmefjord K, Söderberg R, Wartzack S (2018) Geometrical variations management 4.0: towards next generation geometry assurance. Procedia CIRP 75:3–10
31. Forslund A, Lorin S, Lindkvist L, Wärmefjord K, Söderberg R (2018) Minimizing Weld Variation Effects Using Permutation Genetic Algorithms and Virtual Locator Trimming. J Comput Inf Sci Eng 18(4):041010–041010

32. Tabar RS, Wärmefjord K, Söderberg R (2022) Optimal part matching and joining sequence in non-rigid assemblies for improved geometric quality. Procedia CIRP 114:141–146
33. Rezaei Aderiani A, Wärmefjord K, Söderberg R, Lindkvist L (2019) Individualizing locator adjustments of assembly fixtures using a digital twin. J Comput Inf Sci Eng 19(4):041019
34. Aderiani AR, Wärmefjord K, Söderberg R (2021) Evaluating different strategies to achieve the highest geometric quality in self-adjusting smart assembly lines. Robot Comput Integr Manuf 71:102164
35. Hultman H, Cedergren S, Wärmefjord K, Söderberg R (2022) Predicting Geometrical Variation in Fabricated Assemblies Using a Digital Twin Approach Including a Novel Non-Nominal Welding Simulation. Aerospace 9(9):512
36. Bohlin R, Hagmar J, Bengtsson K, Lindkvist L, Carlson JS, Söderberg R Data flow and communication framework supporting digital twin for geometry assurance, Proc. ASME international mechanical engineering congress and exposition, American Society of Mechanical Engineers V002T002A110
37. Tao F, Zhang H, Zhang C (2024) Advancements and challenges of digital twins in industry. Nat Comput Sci 4(3):169–177
38. Zhang M, Tao F, Huang B, Liu A, Wang L, Anwer N, Nee AYC (2024) Digital twin data: methods and key technologies. Digit Twin 1(1):2
39. Wilking F, Schleich B, Wartzack S (2021) Digital twins-definitions, classes and business scenarios for different industry sectors. Proc Des Soc 1:1293–1302
40. Qi Q, Tao F, Hu T, Anwer N, Liu A, Wei Y, Wang L, Nee AY (2021) Enabling technologies and tools for digital twin. J Manuf Syst 58:3–21
41. de Azambuja AJG, Giese T, Schützer K, Anderl R, Schleich B, Almeida VR (2024) Digital twins in industry 4.0–opportunities and challenges related to cyber security. Procedia Cirp 121:25–30
42. Wang K, Liu D, Liu Z, Wang Q, Tan J (2021) An assembly precision analysis method based on a general part digital twin model. Robot Comput Integr Manuf 68:102089
43. Onaji I, Tiwari D, Soulatiantork P, Song B, Tiwari A (2022) Digital twin in manufacturing: conceptual framework and case studies. Int J Comput Integr Manuf 35(8):831–858
44. Madrid J, Vallhagen J, Söderberg R, Wärmefjord K (2016) Enabling reuse of inspection data to support robust design: a case in the aerospace industry. Procedia CIRP 43:41–46
45. Shao G, Frechette S, Srinivasan V An analysis of the new ISO 23247 series of standards on digital twin framework for manufacturing. Proc. Int Manuf Sci Eng Conf, Am Soc Mech Eng V002T007A001
46. Lindkvist L, Carlson JS, Söderberg R Virtual locator trimming in pre-production: rigid and non-rigid analysis. Proc. ASME Int Mech Eng Congr Exp 561–568
47. Simon D (2013) Evolutionary optimization algorithms. Wiley & Sons
48. Eshelman LJ, Schaffer JD (1993) Real-coded genetic algorithms and interval-schemata. Found Gen Algorithm 187–202
49. Whitley D The Genitor algorithm and selection pressure: why rank-based allocation of reproductive trials is best. Proc. Proce Third Int conf Gen Algorithm
50. Wang R, Zhang J, Serizawa H, Murakawa H (2009) Study of welding inherent deformations in thin plates based on finite element analysis using interactive substructure method. Mater Design 30(9):3474–3481
51. Lorin S, Cromvik C, Edelvik F, Lindkvist L, Söderberg R (2014) Variation Simulation of Welded Assemblies Using a Thermo-Elastic Finite Element Model. J Comput Inf Sci Eng 14(3)
52. Pahkamaa A, Wärmefjord K, Karlsson L, Söderberg R, Goldak J (2012) Combining variation simulation with welding simulation for prediction of deformation and variation of a final assembly. J Comput Inf Sci Eng 12(2)
53. (2021) ISO 23247-1: Automation systems and integration - digital twin framework for manufacturing – Part 1: overview and general principles. Int Org Stand
54. (2021) ISO 23247-2: Automation systems and integration - digital twin framework for manufacturing – Part 2: reference architecture. Int Org Stand
55. (2021) ISO 23247-3: Automation systems and integration - digital twin framework for manufacturing – Part 3: digital representation of manufacturing elements. Int Org Stand
56. (2021) ISO 23247-4: Automation Systems and Integration - Digital Twin Framework for Manufacturing – Part 4: Information exchange, International Organization for Standardization
57. (2024) ISO 10303-1:2024 Industrial automation systems and integration — Product data representation and exchange, Part 1: overview and fundamental principles. Int Org Stand
58. (2010) ANSI/ISA-95.00.01–2010 (IEC 62264-1 Mod) Enterprise-control system integration – Part 1: models and terminology. Int Soc Autom
59. (2010) ANSI/ISA-95.00.02–2010 (IEC 62264-2 Mod) Enterprise-control system integration – Part 2: object model attributes. Int Soc Autom
60. (2013) ANSI/ISA-95.00.03–2013 (IEC 62264-3 Modified) Enterprise-control system integration – Part 3: activity models of manufacturing operations management. Int Soc Autom
61. (2012) ANSI/ISA-95.00.04–2012 Enterprise-control system integration – Part 4: objects and attributes for manufacturing operations management integration. International society of automation
62. (2013) ANSI/ISA-95.00.05–2013 Enterprise-control system integration – Part 5: business-to-manufacturing transactions. Int Soc Autom
63. Seyedamir A, Ferrer BR, Lastra JLM An ISA-95 based ontology for manufacturing systems knowledge description extended with semantic rules. Proc. 2018 IEEE 16th Int Conf Ind Inf (INDIN), IEEE 374–380
64. Johnsson C, Brandl D (2021) Beyond the pyramid: Using ISA95 for industry 4.0/Smart manufacturing. Intech 14–20