Digital Twins for Robot Systems in Manufacturing

Ali Ahmad Malik, Guodong Shao, and Jane Tarakhovsky

Abstract The increasing need for industrial automation is driving the adoption of robotics, with new developments such as human–robot collaboration through autonomous mobile robots and collaborative robotic arms. While automation improves product quality and working conditions and lowers manufacturing costs, it can also limit manufacturing adaptability. Therefore, when integrating robots in manufacturing, there is a pressing need to simplify the methods to develop, install, reconfigure, and operate robot systems to achieve greater adaptability. This is where the concept of Digital Twin, which replicates the behavior of a complex system in a virtual environment for analysis and optimization, comes into play. In robotics, the Digital Twin technology is expected to address the challenges associated with designing, testing, commissioning, and reconfigurations. This requires a Digital Twin to accurately represent various dimensions of a robotic system under production variables. This study characterizes the components of a robot system that need to be modeled in a Digital Twin to create a trustworthy virtual replica of a physical robot system. A Digital Twin of this kind can be utilized throughout the lifecycle of the physical robot installation across various use cases.

Keywords Robotics · Digital Twin · Flexible automation · Manufacturing systems · Simulation · System design

A. A. Malik (✉) · J. Tarakhovsky
Department of Industrial and Systems Engineering, Oakland University, Rochester, MI 48309, USA
e-mail: aliahmadmalik@oakland.edu

J. Tarakhovsky
e-mail: janetarakhovsky@oakland.edu

G. Shao
Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
e-mail: guodong.shao@nist.gov

M. Grieves and E. Hua (eds.), *Digital Twins, Simulation, and the Metaverse*, Simulation Foundations, Methods and Applications, https://doi.org/10.1007/978-3-031-69107-2_13

1 Introduction

Modern manufacturing systems are complex, with facilities evolving into large networks of data-connected mechatronic components [1]. The complexity of these systems stems from the quantity of information that spans various lifecycle phases, including design, development, commissioning, operations, and end-of-life [2, 3]. The elevated complexity and interconnectivity make the lifecycle management of modern-day manufacturing systems more challenging. Conversely, demand is increasing for manufacturing systems to possess resilience and adaptability [4]. Addressing these challenges in complex scenarios requires enabling smart manufacturing through digitalization, data connectivity, and the integration of machine learning [5]. Smart manufacturing, besides resilience, can bring cost reduction, enhance workers' well-being, and result in a better return on investment (ROI).

Industry 4.0, or the fourth industrial revolution, is the net sociotechnological impact of infusing emerging technologies such as additive manufacturing, machine learning, robotics, simulations, and the Internet of Things in products and their manufacturing systems. Advanced robotic automation stands out as one of the enablers for Industry 4.0 [6]. Modern installations strive to make robotic automation more flexible, adaptable, safe, and cost-effective than traditional robotics implementations. However, flexible approaches are lacking in developing plug-and-play hardware, programming the robots, control program generation, task scheduling, layout planning, safety assessment, and alignment with production plans.

Advancements in virtualization, sensing technologies, and computing power facilitate the realization of Digital Twins (DTs), which enable the testing and validation throughout the design, development, and control phases of a complex system in a virtual space. Different scientific domains increasingly recognize the potential value of DTs for managing complexity in areas such as manufacturing, transportation, aircraft, and space missions [7]. Manufacturing customization and reconfigurability are vital domains to manage through DTs [7].

Computer models provide a means to shorten the time needed to design, redesign, and deploy robot systems. Computer-based virtual models of physical systems can be beneficial for testing and validating the production before implementation [8]. While this method is consistent with traditional virtual modeling, the emerging "lifecycle" approach and real-time communication between physical and virtual systems are pivotal concepts of DTs [9].

Many studies have documented the potential advantages and relevance of employing DTs for robot systems [10–12]. It has also been observed that developing a trustworthy virtual replica of a robot system is time-consuming and demands advanced engineering skills and investment in different engineering software. Creating and deploying a DT of a robot system should be structured, simplified, and standardized to realize the needed ROI. It requires identifying the components of a robot system that are relevant to the purpose of its DT. Moreover, the flexibility of the DT itself is critical to ensure that the DT can effortlessly be adapted to evolving circumstances.

This chapter presents the importance of DTs in robotic installations within manufacturing systems. The components outlined in a DT of a robot system can assist researchers and practitioners in developing cost-effective, modular, and flexible DTs, thereby improving the resilience of robot installations. This is an essential step toward achieving adaptable manufacturing systems.

The key contributions of this chapter are to:

1. Present the components of a DT of a robot system for flexibility
2. Examine the lifecycle phases of a robot system that a DT can support
3. Apply DTs in robot systems in manufacturing settings
4. Present use cases that demonstrate the utilization of DTs in robot systems.

2 Challenges and Opportunities in Contemporary Manufacturing

The continuous drive to shorten product life cycles emerges as a significant transformation in the contemporary business landscape [13]. Emerging sociotechnological trends require shorter product development and launch timelines. In this setting, manufacturing companies leverage emerging hardware and software technologies and their potential opportunities [14, 15].

Aside from the rapid pace of changes, manufacturers face a shortage of skilled workers. The recent global exposure to the COVID-19 pandemic also displayed widespread disruptions in supply chains [16] partly because of a shortage of workers due to social distancing measures. Research studies identified that future factories could better address such challenges by adopting modular, flexible, and human-friendly automation solutions [17].

A way to develop human-friendly automation solutions is through flexible, collaborative robots. Technologies that facilitate the swift validation of new manufacturing strategies are also needed. Therefore, future manufacturing systems must not only be repurposable but also be designed, developed, commissioned, and reconfigured at a significantly faster pace [18].

DTs can be utilized to address the resilience requirements within a manufacturing system. For example, DTs can help reduce the time required to validate new manufacturing strategies, generate automation programs, and provide maintenance support. Additionally, DTs can harness real-time and historical data to offer insights for process optimization. Such assistance can potentially enhance the level of resilience that a manufacturing system can provide.

3 Robotic Automation in Manufacturing

Automation describes assigning physical and cognitive tasks to machines and software to boost production and decrease human effort [19] In manufacturing, adopting automation brings advantages such as enhancing workplace safety, efficiency, quality, and cost-effectiveness [20, 21]. However, this often comes at the cost of reduced production flexibility. At the heart of industrial automation lies industrial robots. The subsequent sections elaborate on the diverse types of robots employed in manufacturing facilities. Figure 1 shows various industrial robot types, including spherical, SCARA (Selective Compliance Assembly Robot Arm), delta, Cartesian, and humanoid robots [22]. The robot selection for a specific task is based on the nature of the tasks to be automated, available space, financial constraints, and process-related considerations. While these robots enhance manufacturing efficiency, their applications are limited in certain operations, such as assembly, which only constitutes 7.3% of robotic use [23].

3.1 *Traditional Industrial Robots*

Robots are the predominant force driving the industrial automation of physical tasks [22, 24]. These robots, characterized by fixed positioning, operation within enclosures, and time-consuming reconfiguration processes [25], fall into the category of fixed automation solutions. They can help achieve high production volumes but must strictly be separated from human interaction. They also demonstrate limited flexibility [26]. Industrial robots have proven successful in various sectors, including automotive, medicine, food, and electronics manufacturing [27]. The primary reason for the unsuitability of robots in assembly is human safety and the challenges of their reconfiguration [28].

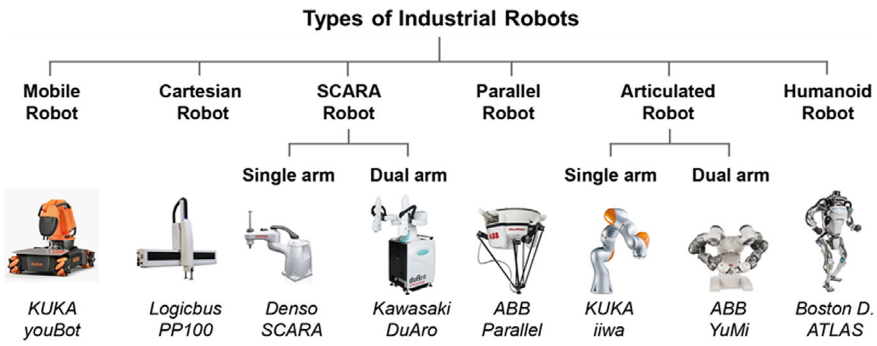

Fig. 1 Various types of industrial robots

Fig. 2 A human and robot coexisting in manufacturing [36]

3.2 Collaborative Robots

Modern industrial robots are lighter, portable, easy to program, and safe. This change can meet the need for flexibility in terms of mobility, capability, and capacity [29]. These robots, designed for collaboration and coexistence with humans (Fig. 2), are commonly known as “cobots” or collaborative robots [30]. A collaborative robot can be defined as a mechanical device intended for direct physical interaction with humans, a concept first introduced by Colgate [31] and further developed by Kruger [32]. Cobots allow humans and robots to work together to harness the strengths of humans and machines. This concept, often called lean automation, exists at the convergence of human flexibility and machine efficiency [33].

Literature showcases diverse applications of cobots, spanning pick-and-place operations, assembly tasks, welding, inspection processes, and packing [34]. Moreover, cobots have been explored as a viable solution for rapidly repurposing factories in emergencies [17]. The predominant use of cobots has been in manufacturing small components such as those assembled into electronics, appliances, and electronic actuators [28, 35]. With the advancement of sensing and safety technologies, cobots are being considered to automate large and heavy components.

3.3 Autonomous Mobile Robots

Autonomous mobile robots (AMRs) represent a distinctive category within collaborative robots [37]. They have proven highly effective in material handling applications in manufacturing settings [40]. Their adaptability and versatility make them well-suited for tasks requiring interactions with humans. Beyond manufacturing, AMRs have found applications in warehouses, military operations, healthcare, search and rescue missions, security, and home environments [38]. This versatility underscores the potential of mobile robots to automate operations in diverse fields.

Different robot types have standard features such as mechanical multijointed reprogrammable actuators, end-of-arm tooling, machine vision, positioning technology, and control programs. Adaptability is recognized as necessary for most modern-day robots. The following section presents a typical physical architecture of a robot installation.

4 Architecture of a Robot System in Manufacturing

Robotic systems in manufacturing settings are available in various designs, layouts, and configurations, influenced by specific use cases. A typical robot cell comprises multiple hardware and software components (Fig. 3). Articulated robot arms, with one or more reprogrammable mechanical joints, represent most robot installations [39]. One or more tools (end effectors) are attached to a robot manipulator's tool post to perform various functions. A robot controller oversees the operations of the robot system, connecting all external hardware through the input/output (I/O) interfaces of the controller. Various sensors are embedded in the robot body and integrated externally to monitor its performance and respond to emerging situations.

Robotic arms designed for human–robot collaboration (HRC) typically have power and force-limiting bodies, speed and separation monitoring, hand guiding, and emergency stop as stipulated in the ISO15066 safety standard for HRC [21]. These attributes ensure safe interaction between robotic arms and humans [40]. AMRs can

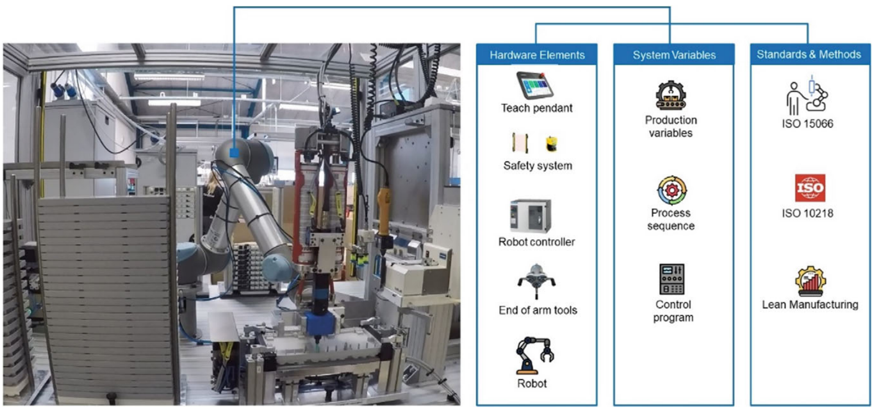

Fig. 3 Typical components of a robot system in a manufacturing setting

also facilitate the mobility of a robotic arm within the robot system. Furthermore, collaborative robots must comply with the ISO19649 standard [41], which establishes terms related to mobile robots operating on solid surfaces and engaging in industrial robot applications. To effectively employ the concept of DTs, it is vital to model most, if not all, of these features of robot systems in their digital models.

5 DTs for Robots in Manufacturing

A DT is a virtual representation of the components and dynamics of an observable physical system [44]. DTs can mirror real-time operating conditions and predict the future behavior of a physical system [45]. The core concept of a DT involves creating a digital model of a physical system and linking each component of the digital model to its corresponding physical assets. In return, the virtual model must act as a front-runner of the physical system to predict or estimate its future behavior.

The present understanding of the DT concept originates from the idea of a "Conceptual Ideal for PLM" (Product Lifecycle Management) [42]. It proposes that every system is a subset of two other systems: the physical system in the physical world and a virtual system existing in virtual space, containing all necessary information about the physical system. The bidirectional relationship between the physical and digital systems can enhance product design, manufacturing, and service throughout the system's life cycle [43].

The methods of using an informational virtual model to represent the complexity of a physical system have evolved. In earlier times, the virtual model existed as a mental image [1], limited in its capacity to address questions about the system's performance. In the mid-twentieth century, creating virtual models became possible, starting with 2D CAD (computer-aided design) objects and advancing to 3D models and dynamic simulations. These virtual models are typically developed early in the system's lifecycle, i.e., during design. These models often become useless when the system transitions to the operation phase.

The linkage of digital models to their physical counterparts and the integrated intelligence throughout their lifecycle are now achievable (Fig. 4). This enables them to understand operational behavior and assist in addressing day-to-day production constraints. In this context, DTs can be categorized into DT prototypes and DT instances [44]. A DT prototype is used to refine system design, presenting optimal static and dynamic information to achieve desired outcomes. Meanwhile, a DT instance integrates monitoring, service, sensing, and behavioral information about the physical twin during its operations. DT instances exhibit predictive and interrogative behaviors, which prove beneficial during the operational and maintenance phases.

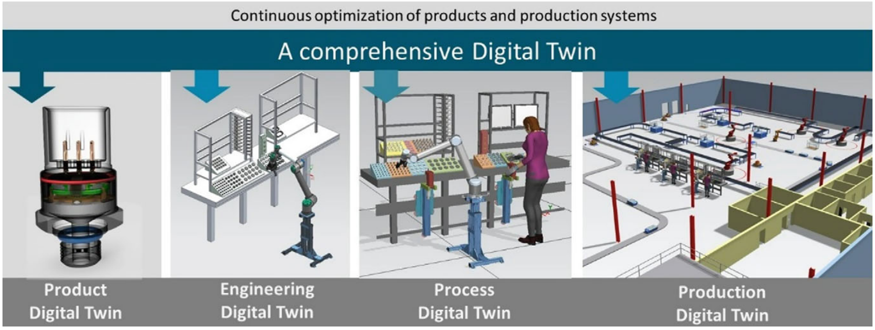

Fig. 4 Scope of DTs in manufacturing systems

6 Lifecycle Phases of Robot Systems

A robotic system undergoes a comprehensive life cycle, commencing with its design and concluding at its end-of-life stage. Correspondingly, its DT follows a parallel life cycle, adapting to various scenarios and system evolution throughout the lifecycle (Fig. 5). The subsequent section describes the functions of a DT across multiple stages in a robotic system's life cycle.

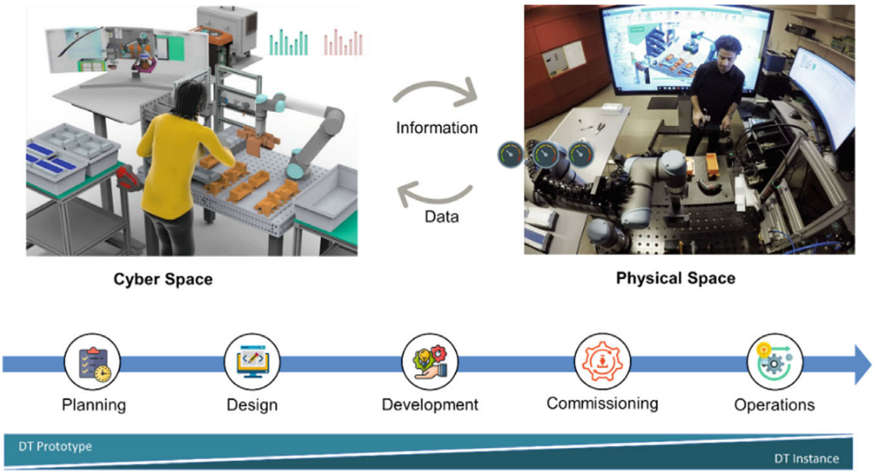

Fig. 5 Concept of a Digital Twin system in human–robot collaboration

6.1 Design of the Robot System

In developing a new robot system, it is customary to construct virtual models before the actual physical counterpart is built. This virtual representation, which can also be referred to as a DT prototype, is conceived to conceptualize and finalize the system's appearance, specifications, the selection of off-the-shelf components, and the overall layout. Despite the absence of the corresponding physical counterpart during the design phase, the DT represents the intended physical twin. It enables the exploration of various what-if scenarios, facilitating swift, secure, and reliable design outcomes. The choice of robot manipulators, workstation design, layout, fixtures, and financial assessments are critical questions that must be addressed at the design stage.

6.2 Commissioning the Robot System

The results derived from the design phase provide information for developing the components of the physical system. The developed system then moves to the commissioning stage. In the case of a robot system, this stage may entail the creation of workstations, fixtures, feeding devices, and other hardware elements. The Bill of Materials (BOM) and Bill of Processes (BOP) can be generated, guiding the development of the physical system. Throughout this phase, the connection between the physical systems and their DTs can be established by linking the DT to an actual controller or programmable logic controller (PLC) to identify potential errors. This methodology is analogous to virtual commissioning (VC). VC, or hardware-in-the-loop simulations, reduces development time by facilitating virtual testing and integration well before actual commissioning. The physical robot can be live connected with its DT, allowing it to execute tasks as designed in the DT.

6.3 Scheduled and Preventive Maintenance

Maintenance is an essential component of most production systems. Emerging technologies such as augmented reality (AR) or chatbots can be integrated with a DT to optimize maintenance procedures, which can better assist maintenance personnel with enhanced visualization tools for fault detection and training tasks. Virtual reality (VR) is another visualization technology that can be integrated with the DT, particularly for training.

Maintenance can benefit from the DT technology in ways such as:

- Real-time Monitoring: Data capturing operating parameters, energy consumption, and system health.
- Predictive Maintenance: Use of machine learning within DT to predict potential failures or maintenance needs based on performance trends.

- Condition Monitoring: IoT sensors provide data on system health indicators, which can be integrated with DT for continuous condition monitoring.
- Asset Tracking: The usage and lifecycle of robotics assets, such as operating hours, replacement history, etc., can be tracked and help with proactive maintenance scheduling.
- Remote Diagnostics and Troubleshooting: Identifying issues remotely can help reduce downtime and improve overall efficiency.

6.4 Operations and Changeovers

The most compelling application of DT technology lies in its application throughout the operational life of a robot system. Over time, a robot system may need changeovers, safety assessments, production analyses, and modifications. Assessing the overall equipment effectiveness (OEE) is another practical facet when evaluating a production system for continuous performance optimization. A DT plays a pivotal role in elevating the quality of these processes, thereby enhancing the performance and reliability of the robot system. This helps justify the investment in the creation and maintenance of its DT.

The DT developed during the design phase is extended to facilitate real-time communication with the physical system during operation, enabling behavioral analysis and performance optimization. At this stage, the system synchronizes the real-world data with the DT, enabling automated assessment cycles. This cyber-physical system integrates production planning and control databases to support scheduling production orders and changeovers. The DT is valuable in simplifying the reconfiguration or repurposing of the robot system in response to demand fluctuations.

7 Components of a DT for a Robot System

This section presents the fundamental components or modules comprising a robotic system's DT, as illustrated in Fig. 6. Traditionally, various tools are required to simulate each of these components. Connectivity protocols can enable near real-time communication between these components, streamlining the development of an accurate DT for a robotic system.

7.1 Static CAD Modeling

The initial step in constructing a virtual manufacturing system is to create a 3D visualization using CAD software. There is a multitude of tools available for this

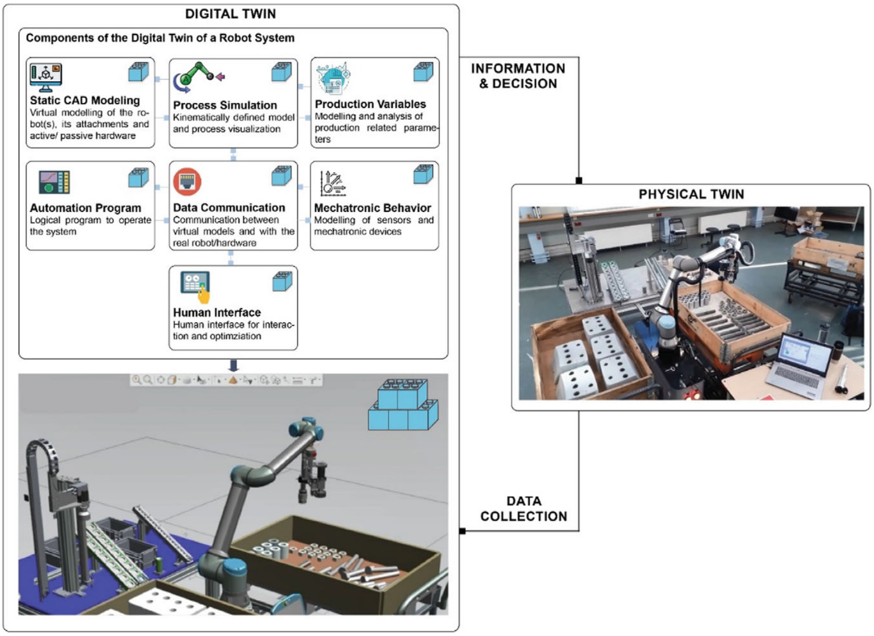

Fig. 6 Components of DT of robot systems

purpose. This CAD data can be obtained directly from the equipment manufacturer, often in standard exchangeable formats such as STEP (Standard for the Exchange of Product Data) [45]. Robot manufacturers offer CAD models of their robots, and a similar practice is followed by manufacturers of related equipment, such as grippers, fixtures, feeders, and tables. Furthermore, many simulation tools feature a built-in library of proprietary and generic factory resource CAD models.

A critical step in preparing the CAD data is creating an assembly file and consolidating the individual CAD models of various devices and equipment. The virtual assembly model must represent the complete physical robot system being investigated. Each component can be assigned material properties and visualization to aid in subsequent analyses. This file can be exported to various exchangeable formats, with STEP being the most common standard format.

7.2 *Process Simulation*

The CAD data can be imported into a continuous simulation environment. Creating a dynamic simulation starts with defining the kinematics of each active resource within the system. It involves specifying position and location constraints, joint types, joint limits, and velocity limits. For example, a gripper may need to be defined for its motion kinematic joint types, limits, and action poses. The visualization/simulation of a DT is achieved through three steps: (1) creating the simulation model of a robot system along with its operation sequences, akin to a Gantt chart, (2) an event-driven continuous simulation that runs for a pre-determined time and controlled by an internal logic engine, and (3) the simulation is controlled through signals from a virtual PLC and other emulators. This simulation becomes the primary component of the DT for visualization, experimentation, and analysis. After the simulation, it can perform analyses (e.g., collision detection, layout assessment, cycle time estimates) and optimizations. Numerous proprietary tools are available to create this type of simulation, while open-source engines can also be utilized.

7.3 Automation Program

PLCs serve as industrial computers for programming and monitoring industrial robot systems. A critical step in commissioning a robot-based manufacturing system is creating and validating the automation program. Usually, this program is created later in the development stages. Developing, testing, and validating the automation program in a virtual space, along with process simulation, enhances the reliability of the system's performance. Each PLC has its programming tool, and open-source program development tools are also available. To ensure interoperability, PLC programs follow the IEC 61131 standard [46]. The IEC 61131-3, developed by the International Electrotechnical Commission (IEC), sets the standard for PLCs' syntax, semantics, and interoperability. The developed programs are downloaded onto a virtual PLC and interfaced with the simulation.

7.4 Mechatronic Behavior

A robot system includes sensors, actuators, feeders, fixtures, and other mechatronic elements (Fig. 3). Behavioral modeling of these devices enables an accurate virtual model of the entire system. The Functional Mock-up Unit (FMU) is a tool-independent, free standard crafted for dynamic model exchange and co-simulation. FMUs define a container and an interface for sharing dynamic simulation models through a combination of Extensible Markup Language (XML) files, binaries, and C-code. Both commercial and open-source tools are accessible for simulating the behavior of each device and interfacing it with the process simulation.

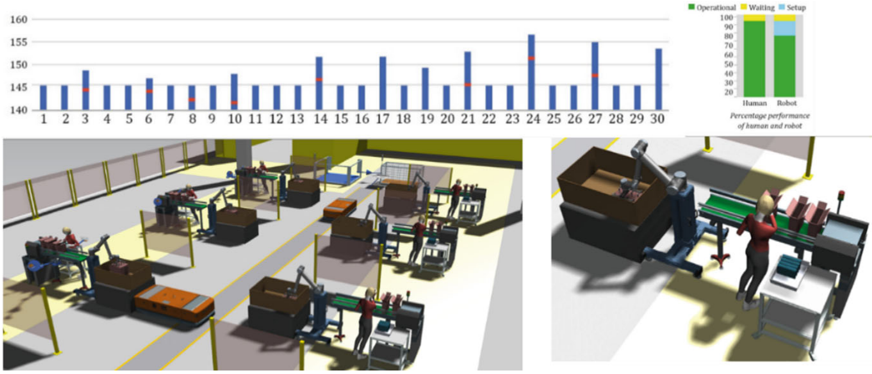

Fig. 7 Production assessments through simulations

7.5 *Production Variables*

The evaluation of production variables based on historical statistical data is not always required in the process modeling of a robot system. However, it is a component that can be added to a DT of a robot system for production-related analysis. In this phase, production-related parameters and throughput specifications are defined. Since these analyses are done in a stochastic simulation, a different tool is often required to perform stochastic modeling and interface it with the existing continuous process simulation model. This model simulates cycle time, startup time, setup time, potential failure scenarios, repair and maintenance requirements, shifts, worker allocation, and other relevant factors with statistical probabilities. An example of such a simulation is shown in Fig. 7, where six human–robot packaging stations are shown, and the simulation presents the operational time and waiting time for each resource. Discrete simulations can run thousands of trials based on probabilistic distributions derived from historical data. This analysis enables the prediction of the throughput of a robot system under the design variables.

7.6 *Human–machine Interface*

In industrial settings, human–machine interfaces (HMIs) enable workers to interact with manufacturing systems or robots. This interaction involves conveying instructions such as start/stop commands, speed adjustments, and troubleshooting. Touchscreen HMIs are commonly employed in industrial settings for this purpose. An HMI is essential for facilitating continuous user interaction with the robot system in most robot work cells. Depending on the process and system design, modeling and integrating an HMI with the process simulation may be needed in a DT. A simulated HMI can communicate with PLCs and the process simulation. Using a virtual HMI allows end users to interact with the robot system in a way that is similar to its actual application. HMIs are designed following the ISA 101 standard, and validating them may require a DT model for thorough validation. A virtual HMI may be accessed on a computer screen or a handheld computing device communicating with the process simulation. The HMI developed during this step is downloadable to real HMIs for practical field applications.

7.7 Data Communication and Management

In robot system DTs, real-world data are integrated into the simulation. This integration enables continuous assessments under variable conditions, enhancing the accuracy and responsiveness of the DT. System performance data, including logs and alerts, can be stored in a data repository for ongoing evaluations. Various sensors, tailored to specific requirements, can be employed in robotic systems to log parameters such as robot joint positions, machine vision data, collision events, task completion status, safety breaches, and cycle time. As exemplified by [1], a robot assembly system is connected to a cloud data repository through an internet-based router for data logging. It is an HRC assembly cell using a UR-5 robot. The performance-related logs from the assembly cell are stored and used in the simulation for design optimization (Fig. 8). These performance factors include the idle time for both the operator and the robot, human operator safety (collision occurrences), and completed cycle counts. The recorded data is then used for layout and robot path optimization in the simulation.

Data management organizes data into meaningful information, focusing on creating "Golden datasets" that undergo cleaning, transformation, validation, integration, and standardization. The data management lifecycle encompasses key stages:

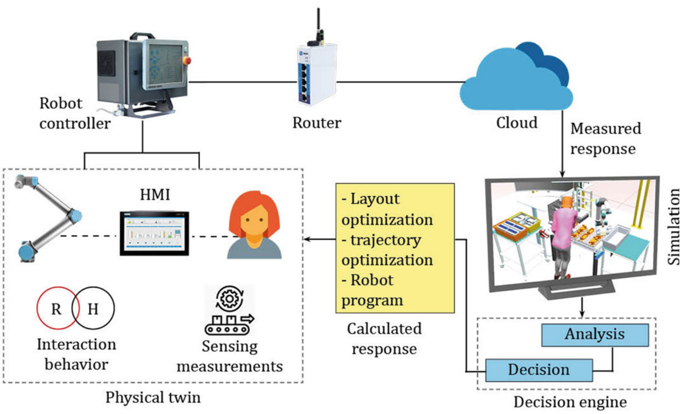

Fig. 8 Communication of data logs from robot system [47]

data collection, transmission, storage, processing, fusion, and visualization. During data collection, hardware, software, and network resources are integrated. Data transmission involves various wireless and wired technologies. Data storage, required for processing and analysis, utilizes technologies such as cloud storage, NewSQL databases, NoSQL databases, and distributed file storage (DFS). After processing data, data visualization can be made available in formats required by AR or VR [48].

8 Applications of DTs in Robots

Deploying and utilizing DTs alongside robot systems in manufacturing facilities offers a range of benefits. This section presents various advantages of robot systems contributing to robot installations' flexibility, reliability, and safety.

8.1 Safety Assessment and Validation

Manufacturing-related robot installations comply with safety standards, notably ISO 10218 [49] and ISO 13849 [50], which outline safety requirements for industrial robots. Moreover, collaborative robots align with safety specifications outlined in ISO 15066 [51], which is dedicated to collaborative robotic devices. Various safety measures, including emergency stops, human movement monitoring, and active collision avoidance, are integrated into robot cells to safeguard coexisting humans. The assessment and validation of robot systems for compliance with safety requirements are essential.

The DT model should accurately replicate the robotic system's physical characteristics, behaviors, and interactions (movements, sensors, and environment) to be valid. Under ISO 15066, a safety risk assessment is required following any physical alterations to the system. The risk assessment process can be streamlined using DTs within a controlled and risk-free environment. Risk identification can be conducted in the DT, maintaining a live connection with the physical robot. This approach identifies potential collisions in the virtual environment before the physical system is populated with hardware resources.

Evaluating potential accidents or injuries is essential in the context of HRC. Dynamic simulations within DT can evaluate safety performance under different operating scenarios (emergency, failure modes, and normal operations). Collision detection algorithms within the DT can identify potential failures and develop strategies for avoidance or mitigation to enhance safety.

Continuous monitoring using collision-related data logs can enable the assessment of the frequency of collisions between humans and robots over time, facilitating the optimization of robot paths to avoid such incidents. Fault tolerance mechanisms and redundancy in a DT can enhance safety and reliability. The DT can also offer training and awareness programs for operators, maintenance personnel, and other stakeholders. The DT models can also simulate the safety training scenarios within a virtual environment to enhance learning and preparedness.

8.2 Reduced Development Time

Studies have found that robotic automation projects frequently exceed the initially projected timeline [52]. This duration can be further extended, particularly with more complex tasks such as assembly and battery pack manufacturing. Challenges that emerge unexpectedly in the planning stage, impacting the project timeline, include issues related to process balancing, task scheduling, feeding methods, fixtures required, the necessity for multiple grippers, and safety complications. This prolonged integration timeframe is attributed to the nature of robot operations. Robots must coordinate their movements with other hardware (machine tools, equipment, end-of-arm tooling), peripherals (vision systems, force sensors), and humans, contributing to increased integration and operational complexity.

Various methods and frameworks have been documented for developing robot systems [53–55]. However, there is a growing need for novel approaches that focus on minimizing the time and effort required for integration, validation, and reconfiguration. DT prototypes can offer a high-fidelity and trustworthy digital model of the real system to reduce the chances of any errors that may arise at a later stage.

8.3 Robot Programming

Robot programming involves defining the paths, actions, and logical procedures for robots to perform the assigned tasks. Industrial robotic applications often require significant expertise and effort. Despite the promise of more accessible programming in the latest robots, manually programming complex robot paths remains time-consuming. With the continuous desire for customization and changing market dynamics, robot programming is not a one-time activity in their operational life. The needed flexibility and adaptability require easy ways of programming the robots.

To tackle this challenge, a DT can facilitate the intuitive development of robot programs offline within a graphical environment (Fig. 9). The robot program can be seamlessly downloaded from the DT directly to the connected robot by virtually testing the desired operation, complete with defined robot trajectories and logic. This approach streamlines the programming process, leading to a significant enhancement in efficiency during robot deployment.

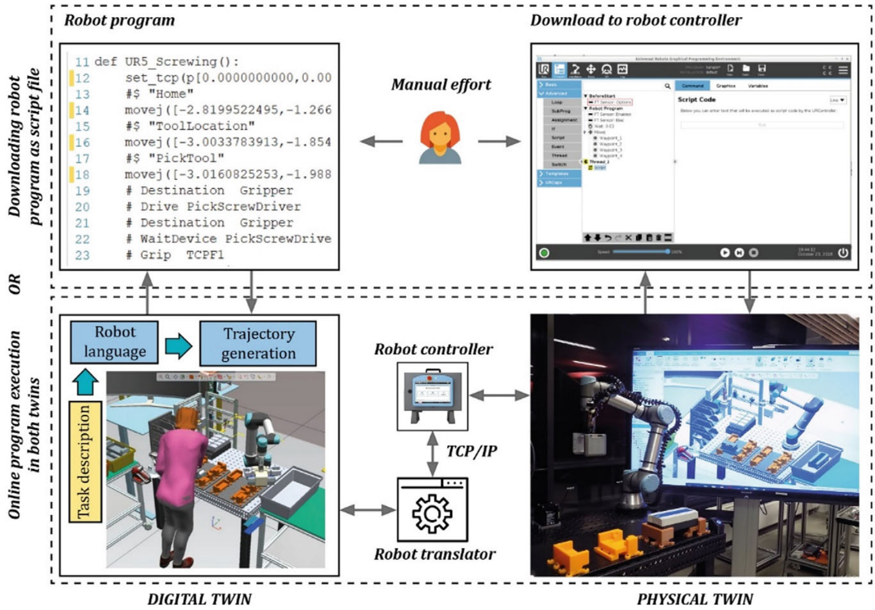

Fig. 9 Generating robot program and controlling robot arm through its DT [47]

8.4 *Simplified Reconfigurations*

The demand for variety in manufacturing is rising, and assembly is recognized as a prime area with significant potential for introducing product diversity [56]. As we navigate the transition phase of the fourth industrial revolution, the notion of batch size one, focusing on personalized manufacturing, is increasingly gaining relevance. However, a challenge is that current robots often lack the flexibility necessary for rapid reconfiguration.

To realize the vision of batch size one, manufacturers require robots with features, hardware, and software solutions that facilitate effortless adaptation to changes and variations in product design. Swift reconfiguration of robots is indispensable for staying in sync with the dynamic demands of modern manufacturing, where rapid shifts in product specifications and design variations are commonplace. DT models emerge as a valuable tool in expediting these reconfigurations by automatically evaluating the automation potential for specific tasks. This includes generating a process sequence, automation programs, robot codes, and worker training opportunities. DT models contribute to streamlining the adaptation process, ensuring efficiency and agility in response to evolving manufacturing requirements.

8.5 Layout Planning and Optimization

In a robot installation, achieving an optimal arrangement of robots, fixtures, assembly parts, and associated hardware is critical to minimize footprints and shorten cycle times. In the case of collaborative robots, additional safety layers need attention. To enhance the design of the workstation layout, the following experiments can play a pivotal role:

Collision analysis: Identifying and mitigating collisions become paramount in the robotic process in scenarios involving confined spaces with multiple robots and associated hardware. Conducting a thorough collision analysis serves to identify potential collisions, allowing for the optimization of robot trajectories and equipment placement. Given the frequent changeovers and reconfigurations inherent in such environments, this collision analysis may need to be a routine activity. A DT emerges as a valuable tool for generating safe robot paths that circumvent potential collisions (see Fig. 10). By using DTs, robot paths can be proactively optimized. The result is a more efficient and collision-free operation, even in dynamically changing scenarios.

Reach test: The reach test is instrumental in determining whether a robot can access all desired locations within its workspace. This test aids in defining the most optimal locations for placing robots and relevant production equipment. Specific location points for robots are established, evaluating whether the robot can safely reach all desired locations. A grasp envelope is created for a human reach test to demonstrate the human arms' reachability without adopting unsafe body postures.

Placement test: The placement test seeks to identify optimal locations for robots, humans, and production equipment. The goal is to minimize cycle times, prevent

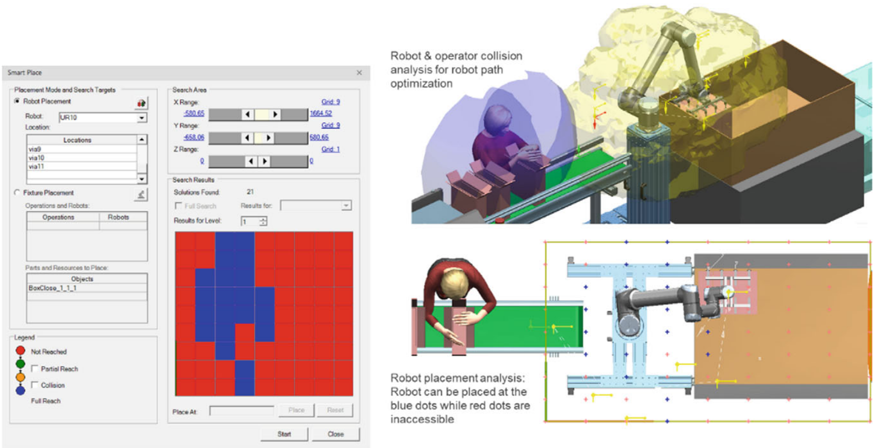

Fig. 10 Layout planning of a robot cell in simulation

collisions, and ensure a safe working environment. The test can define a range of points from which a robot can reach a selected set of locations.

Other considerations may include designing the layout with flexibility and scalability to accommodate future changes and expansions. Modular design approaches and flexible workspace configurations enable easier reconfiguration and adaptation to evolving production needs. Another important consideration is ensuring the seamless integration of robotic installations with existing manufacturing systems, including conveyor systems and automated guided vehicles. Coordinating the layout design with other production processes (inventory management systems) is essential to optimize workflow integration and synchronization.

8.6 Process Visualization

A comprehensive simulation enables high-accuracy visualization of the detailed process. Even without making any computer-based analysis of collisions, robot path, or layout visualization, visualization allows visual assessment of the process. Potential errors are identified, and the required modifications are determined. As shown in Fig. 11, a simulation of a robotic process presents the assembly of medical ventilators.

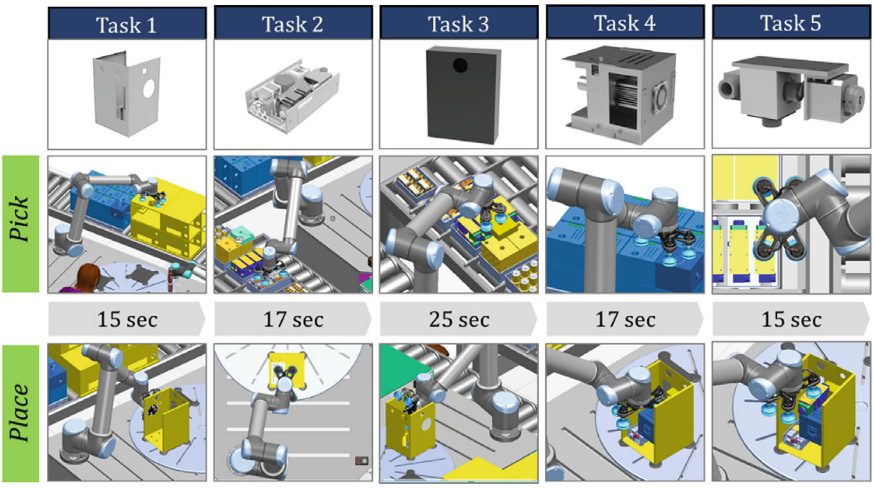

Fig. 11 Sketch shows the assembly process sequence in a robotic assembly process

8.7 Control Program Generation

Robot systems with multiple robotic arms, sensors, actuators, feeders, and hardware devices typically operate based on a logical control program. Traditionally, the development and verification of this logical program are carried out during the commissioning phase. The validation and error-proofing procedures can be time-consuming and may uncover errors that could set the project back to earlier stages. However, leveraging a DT allows for a more streamlined approach. The control program can be generated directly from the simulation model and verified several times during the system development. This generated program is then downloaded to a PLC. The advantage of this approach is that, with each change in the system design, a new control program can be rapidly created, validated within the DT simulation, and then efficiently downloaded to the PLC. This dynamic adaptability enhances the efficiency and agility of the robot system, reducing the time and effort traditionally associated with the commissioning process.

8.8 Assessment of Return on Investment

ROI analysis is crucial for decision-making when implementing a robot system to automate a specific process. Without a detailed visualization, analysis, and understanding of operational behavior, accurately assessing the financial gains from investing in a robotic system becomes challenging. A comprehensive simulation-based DT offers an in-depth perspective on various phases of a robot system's life-cycle. It provides a more accurate and thorough assessment of ROI throughout its entire operational lifespan.

9 Practical Use Cases

This section presents two use cases from industrial practices that exemplify the practical application of DTs in robot systems.

9.1 DT-Based Development of a Robot Assistant in Wind Turbine Manufacturing

This case exemplifies the creation and utilization of a DT for a collaborative mobile robot aiming to automate assembly tasks in the manufacturing of wind turbines. Applying a mobile robot assistant for hybrid automation of wind turbine manufacturing is expected to give benefits such as reduced production costs, enhanced product

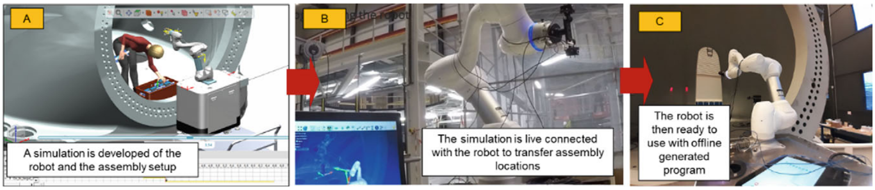

Fig. 12 DT-supported deployment of a robot assistant in wind turbine manufacturing

quality, and improved working conditions. The DT technology was employed for the commissioning and reconfiguring the mobile robot, contributing to expedited design and validation.

The growing demand for higher rating capacity in wind turbines has driven the production of larger generators, extended blades, and taller towers. The assembly of these turbines entails the manipulation of large-sized components. Traditional automation is impractical due to frequent design alterations and diverse tasks, rendering it labor-intensive. However, human capabilities fall short in managing the assembly of these substantial components, resulting in extended lead times and increased overall costs for sustainable energy. To address these automation challenges, the case presents a solution consisting of a mobile robot equipped with a robotic arm that uses laser beams to assist operators in precisely positioning assembly components. This approach streamlined the assembly process and reduced the assembly time.

The simulated robot was connected to the physical robot in real time using an Ethernet connection (see Fig. 12). The robot's IP address was utilized in the simulation to establish this connection. A post-processor for Doosan Robotics was used. A robot post-processor defines how robot programs are generated for a specific robot controller.

During the design phase, a comprehensive workspace with the robot system was modeled in simulation-based DT. The DT model served as a design validation tool for each reconfiguration. During the development phase, the DT model was a reference for programming the robot. Assembly locations were extracted from the DT model and encoded in the robot program. Vision tests and safety risk assessments were performed using the DT. The DT was operational with the robot system to verify the changes and robot programming.

9.2 DT of a Human-Robot Collaborative Assembly Cell

This section illustrates the application of a DT in developing and operating a collaborative assembly cell (Fig. 13), emphasizing its significance in designing, developing, and operating human–robot production systems. In the design phase, the DT was

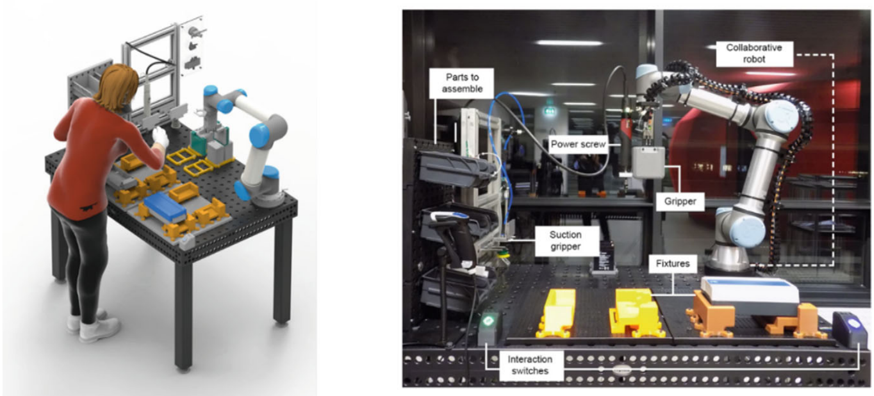

Fig. 13 Humans and robots working collaboratively [47]

used to create and select the elements of the assembly system according to production requirements and its integration with the overall system. Dynamic simulation facilitated a quantitative assessment and a business value proposition for the proposed solution. The Task Simulation Builder in TPS was used to model human tasks for ergonomic assessments.

During the operational phase, using data loggers, the DT transitioned from manual data syncing to automated and real-time data syncing, enhancing its utility for error identifications. The DT proved valuable in dynamic task distribution based on task complexity rating and event-driven simulation. Other benefits included intuitive robot programming to reduce manual efforts, human safety assessments, the generation of data logs for critical actions through sensor integration, and the incorporation of artificial intelligence to enable the system to self-learn and make decisions based on past experiences.

10 Future Research Directions

Interoperability stands out as a critical challenge in the current state of creating DTs for robot systems. The various aspects of a robot system (geometry, kinematics, robot program, automation logic, etc.) can be modeled using different tools (e.g., Robot Operating System (ROS) [57], OpenPLC [58], Unreal Engine [59], etc.). However, exchanging data between these tools is often complicated and sometimes impossible. Additionally, commercial tools from one vendor may not exchange data with those from another. Consequently, there's a pressing need for standardized, exchangeable data formats for DT devices and assets, particularly their connectivity with open-source tools. Initial standards developments such as the IEC 63278—Asset Administration Shell [60] have been made. Still, they are at an early stage of development, and their widespread adoption needs to address their suitability for various scenarios.

Creating and operating a DT necessitates investment in software tools, human resources, data processing ability, and communication technologies. However, it is essential to recognize that not every robot installation requires a DT. Fundamentally, a DT benefits robotic systems as it facilitates flexibility, reconfigurability, seamless deployment, predictive maintenance, and safe human–robot interaction, among other benefits. Assessment methods must be available to identify the need and value of a DT in a given context and asses the ROI of creating and using a DT.

In manufacturing systems, hardware modularization involves incorporating parallel modules for capacity or capability adjustments. Combining flexible automation with human skills, this modular approach facilitates reconfigurability and agility. Achieving a high degree of customization involves adding, replacing, or eliminating modules. A similar modular approach is needed in DTs. Given that the current approach to developing DTs is time-consuming, the creation of libraries of modular DTs of assets and information blocks can pave the way for the formation of reusable and exchangeable DTs.

Flexible robot installations face the challenge of effective and dynamic task scheduling. Task scheduling for robots involves the creation of an optimal schedule within a system. This schedule specifies which robot is assigned to each task and how the tasks will be processed. Dynamic task allocation goes a step further, encompassing the planning of automation processes and allowing robots to adapt during operations. To address this challenge, a comprehensive approach that integrates event-based logical simulation, probabilistic analysis, and statistical data analysis into a DT model is needed. This integration can enhance the DT's capability to facilitate dynamic and efficient task scheduling, ensuring adaptability to changing operational needs.

11 Conclusion

A manufacturing system can be characterized as a network of subsystems, including equipment, machines, humans, and robots, working together to transform raw materials into finished products. Robots have become integral components of modern manufacturing facilities and are increasingly gaining traction. However, designing, developing, deploying, and reconfiguring robot cells is time-consuming, spanning weeks to months. The extensive involvement of a larger workforce in the project contributes to higher overall system costs and results in a prolonged ROI. This extended timeframe is influenced by various factors, such as sequential development processes, complex programming techniques, tool development, and the need to adhere to safety standards.

This chapter outlines the fundamental elements or modules constituting a robotic system's DT. The research arena has documented the advantages of employing DTs for robot systems. However, realizing the full potential of DTs for robot work cells requires the creation of a reliable and comprehensive digital representation that accurately models the elements and dynamics of the observed robot system. Flexibility remains critical in ensuring the DT can seamlessly adapt to changing circumstances. This chapter underscores the significance of DTs in manufacturing robotic cells and outlines the essential criteria for developing these DTs.

The interoperability challenge arises in creating DTs for robot systems, as exchanging data between different tools proves difficult. Standardized and exchangeable data formats are essential, emphasizing compatibility with open-source tools. While investing in DT tools and resources is crucial, it's important to note that not every robot system requires a DT. Modularization is critical in manufacturing and DT development, offering flexibility and reconfigurability. Flexible robot installations encounter challenges in dynamic task scheduling, which can be addressed by integrating logical simulation and statistical analysis into DT models, ensuring adaptability to changing operational needs.

Disclaimer This research was conducted through the support of a NIST cooperative agreement [60NANB23D234]. Specific commercial products and systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose. No approval or endorsement of any commercial product by NIST is intended or implied.

References

1. Malik AA, Brem A (2021) Digital twins for collaborative robots: a case study in human-robot interaction. Robot Comput Integr Manuf 68:102092. https://doi.org/10.1016/j.rcim.2020.102092
2. Rios J, Bernard A, Bouras A, Foufou S (2017) Product lifecycle management and the industry of the future. In: 14th IFIP WG 5.1 international conference. Springer, Seville, Spain
3. Morgan J, Halton M, Qiao Y, Breslin JG (2021) Industry 4.0 smart reconfigurable manufacturing machines. J Manuf Syst 59:481–506. https://doi.org/10.1016/j.jmsy.2021.03.001
4. Yazdani MA, Khezri A, Benyoucef L (2022) Process and production planning for sustainable reconfigurable manufacturing systems (SRMSs): multi-objective exact and heuristic-based approaches. Int J Adv Manuf Technol 119:4519–4540. https://doi.org/10.1007/s00170-021-08409-0
5. Shao G, Helu M (2020) Framework for a digital twin in manufacturing: scope and requirements. Manuf Lett 24:105–107. https://doi.org/10.1016/j.mfglet.2020.04.004
6. Advanced Manufacturing (2022) National strategy for advanced manufacturing
7. Malik AA (2023) Simulation based high fidelity digital twins of manufacturing systems: an application model and industrial use case. In: Winter simulation conference 2023
8. Masood T, Weston R (2011) An integrated modelling approach in support of next generation reconfigurable manufacturing systems. Int J Comput Aided Eng Technol 3:372–398
9. Bilberg A, Malik AA (2019) Digital twin driven human–robot collaborative assembly. CIRP Ann 68:499–502. https://doi.org/10.1016/j.cirp.2019.04.011
10. Maruyama T, Ueshiba T, Tada M, Toda H, Endo Y, Domae Y (2021) Digital twin-driven human robot collaboration using a digital human 1–46. https://doi.org/10.3390/s21248266
11. Liu S, Wang XV, Wang L (2022) Digital twin-enabled advance execution for human-robot collaborative assembly. CIRP Ann 71:25–28. https://doi.org/10.1016/j.cirp.2022.03.024

12. Yao B, Xu W, Shen T, Ye X, Tian S (2023) Digital twin-based multi-level task rescheduling for robotic assembly line. Sci Rep 13:1–20. https://doi.org/10.1038/s41598-023-28630-z
13. Masood T, Kern M, John Clarkson P (2021) Characteristics of changeable systems across value chains. Int J Prod Res 59:1626–1648. https://doi.org/10.1080/00207543.2020.1791997
14. Giones F, Brem A (2017) From toys to tools: the co-evolution of technological and entrepreneurial developments in the drone industry. Bus Horiz 60:875–884
15. Stadnicka D, Antonelli D (2019) Human-robot collaborative work cell implementation through lean thinking. Int J Comput Integr Manuf 32:580–595. https://doi.org/10.1080/0951192X.2019.1599437
16. Malik AA, Masood T, Kousar R (2020) Repurposing factories with robotics in the face of COVID-19. Sci Robot 5, (2020) https://doi.org/10.1126/scirobotics.abc2782
17. Malik AA, Masood T, Kousar R (2021) Reconfiguring and ramping-up ventilator production in the face of COVID-19: can robots help? J Manuf Syst 60:864–875. https://doi.org/10.1016/j.jmsy.2020.09.008
18. Anumbe N, Saidy C, Harik R (2022) A primer on the factories of the future
19. Nof SY (2009) Springer handbook of automation. Springer, Berlin
20. Boy GA (2018) From automation to interaction design. Handb Hum-Mach Interact 431–443. https://doi.org/10.1201/9781315557380-22
21. Malik AA, Masood T, Management E, Brem A (2024) Intelligent humanoid robots in manufacturing: addressing the worker shortage and skill gaps in assembly cells. https://doi.org/10.1145/3610978.3640765
22. Kurfess TR (2004) Robotics and automation handbook
23. Shneier MO, Messina ER, Schlenoff CI, Proctor FM, Kramer TR, Falco JA (2015) Measuring and representing the performance of manufacturing assembly robots
24. Andersson SKL, Granlund A, Hedelind M, Bruch J (2020) Exploring the capabilities of industrial collaborative robot applications. Adv Transdisciplinary Eng 13:109–118. https://doi.org/10.3233/ATDE200148
25. Pedersen MR, Nalpantidis L, Andersen RS, Schou C, Bogh S, Krüger V, Madsen O (2016) Robot skills for manufacturing: From concept to industrial deployment. Robot Comput Integr Manuf 37:282–291
26. Ji S, Lee S, Yoo S, Suh I, Kwon I, Park FC, Lee S, Kim H (2021) Learning-based automation of robotic assembly for smart manufacturing. Proc IEEE 109:423–440. https://doi.org/10.1109/JPROC.2021.3063154
27. Buerkle A, Eaton W, Al-Yacoub A, Zimmer M, Kinnell P, Henshaw M, Coombes M, Chen WH, Lohse N (2023) Towards industrial robots as a service (IRaaS): flexibility, usability, safety and business models. Robot Comput Integr Manuf 81:102484. https://doi.org/10.1016/j.rcim.2022.102484
28. Malik AA, Bilberg A (2019) Complexity-based task allocation in human-robot collaborative assembly. Ind Robot 46:471–480. https://doi.org/10.1108/IR-11-2018-0231
29. Malik AA, Bilberg A (2019) Developing a reference model for human–robot interaction. Int J Interact Des Manuf 13:1541–1547. https://doi.org/10.1007/s12008-019-00591-6
30. Rahman SMM, Sadrfaridpour B, Wang Y, Walker ID, Mears L, Pak R, Remy S (2020) Trust-triggered robot-human handovers using flexible manufacturing, 1–8
31. Edward J, Wannasuphoprasit CW, Peshkin MA (1996) Cobots: robots for collaboration with human operators. In: International mechanical engineering congress and exposition, Atlanta
32. Krüger J, Lien TK, Verl A (2009) Cooperation of human and machines in assembly lines. CIRP Ann Manuf Technol 58:628–646
33. Malik AA, Bilberg A (2019) Human centered lean automation in assembly. Procedia CIRP 81:659–664. https://doi.org/10.1016/j.procir.2019.03.172
34. Ajoudani A, Zanchettin AM, Ivaldi S, Albu-Schäffer A, Kosuge K, Khatib O (2018) Progress and prospects of the human–robot collaboration. Auton Robots 42:957–975. https://doi.org/10.1007/s10514-017-9677-2
35. Povlsen K (2023) A new generation of robots can help small manufacturers. https://hbr.org/2023/11/a-new-generation-of-robots-can-help-small-manufacturers

36. BMW (2017) HRC system in production at BMW Dingolfing
37. Bänziger T, Kunz A, Wegener K (2017) A library of skills and behaviors for smart mobile assistant robots in automotive assembly lines. In: Proceedings of the companion of the 2017 ACM/IEEE international conference on human-robot interaction, pp 77–78
38. Kirova I (2020) Give me a hand—*The* potential of mobile assistive robots in automotive logistics and assembly applications Stefanie. Educ Technol J 11:329–331. https://doi.org/10.26883/2010.202.2349
39. Melissa R (2023) Articulated robot market size. https://statzon.com/insights/global-articulated-robot-market
40. Malik AA, Masood T (2022) Mobile robot assistants in wind turbines manufacturing. SSRN Electron J. https://doi.org/10.2139/ssrn.4241697
41. ISO: ISO 19649_2017(en) Mobile robots—Vocabulary
42. Grieves M (2002) Completing the cycle: using PLM information in the sales and service functions, Troy
43. De Oliveira Hansen JP, Da Silva ER, Bilberg A, Bro C (2021) Design and development of automation equipment based on digital twins and virtual commissioning. Procedia CIRP. 104:1167–1172. https://doi.org/10.1016/j.procir.2021.11.196
44. Grieves M, Vickers J (2017) Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In: Transdisciplinary perspectives on complex systems. Springer, pp 85–113
45. ISO: ISO 10303-242_2022—Industrial automation systems and integration—Product data representation and exchange—Part 242_Application protocol_Managed model-based 3D engineering
46. International Electrotechnical Commissioning (2003) Programmable controllers-Part 1: General information
47. Malik AA, Brem A (2021) Digital twins for collaborative robots: a case study in human-robot interaction. Robot Comput Integr Manuf. 68. https://doi.org/10.1016/j.rcim.2020.102092
48. Qi Q, Tao F, Hu T, Anwer N, Liu A, Wei Y, Wang L, Nee AYC (2021) Enabling technologies and tools for digital twin. J Manuf Syst 58:3–21. https://doi.org/10.1016/j.jmsy.2019.10.001
49. Collaborative Robots (2016) Eliminate the mystery around safety robot safety standards for collaborative operation ISO 10218 2016. Curr Saf Stan
50. ISO: ISO 13849-1_(2023)(en) Safety of machinery—Safety related parts of control systems, Part 1*:* General principles for design
51. Robots ISO (2016) Robotic devices--collaborative robots. ISO 15066: 2016
52. Bauer W, Bender M, Braun M, Rally P, Scholtz O. Lightweight robots in manual assembly—best to start simply! In: Examining companies' initial experiences with lightweight robots,. Frauenhofer-Institut für Arbeitswirtschaft und Organisation IAO, Stuttgart
53. Tan JTC, Duan F, Zhang Y, Watanabe K, Kato R, Arai T (2009) Human-robot collaboration in cellular manufacturing: design and development. In: intelligent robots and systems, 2009. IROS 2009. IEEE/RSJ International Conference on. pp. 29–34 (2009)
54. Francalanza E, Borg J, Constantinescu Deriving a systematic approach to changeable manufacturing system design. In: Procedia CIRP. pp 166–171. Elsevier B.V.
55. Malik AA, Bilberg A (2017) Framework to implement collaborative robots in manual assembly: a lean automation approach. In: Katalinic B. (Ed.) Proceedings of the 28th DAAAM international symposium, Published by DAAAM International, ISSN. pp 1726–9679
56. ElMaraghy H (2014) Managing variety in manufacturing. Procedia CIRP 1–2 (2014)
57. ROS: Robot Operating System, https://www.ros.org/
58. GitHub: OpenPLC_ an open source industrial controller. https://github.com/thiagoralves/OpenPLC
59. EPIC Games: Unreal Engine. https://www.unrealengine.com/en-US
60. IEC: IEC 63278-1 (2023) ED1 *Asset* Administration shell for industrial applications—Part 1: Asset administration shell structure. (2024)