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# THE ECONOMIC IMPACT OF DIGITAL TWIN TECHNOLOGY ON MANUFACTURING SYSTEMS

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## ABSTRACT

Digital Twin technology is rapidly advancing, offering a virtual representation that models and connects complex physical systems for diverse purposes like simulation, monitoring, maintenance, and optimization. In contrast to traditional approaches limited to simulating specific physical processes, simulations within a digital twin comprise polymorphic environments that accurately depict large-scale systems. These digital twins remain connected to their physical counterparts through real-time data and feedback loops. While the benefits of implementing digital twins are numerous, the resources, effort, and investment required can vary for each use case. Manufacturers often must assess the return on investment (ROI) before committing to these initiatives. However, digital twins' intricate, multidimensional nature poses challenges in accurately evaluating their ROIs. This research assesses the economic impact of developing digital twins for manufacturing systems and presents a practical framework for assessing ROI. This systematic approach can help stakeholders enhance the financial viability of digital twin projects.

## 1 INTRODUCTION

A system is an organized group of related resources that interact to form a whole for achieving a goal. Factories, often termed manufacturing systems, comprise various resources collaborating to produce a final product (Malik, 2023a). Establishing a new factory or its subsystems is challenging and complex; reconfiguring an existing factory poses similar challenges and could be time-consuming. Moreover, the advent of Industry 4.0 has further introduced complexity into manufacturing systems (Malik & Brem, 2021), referring to the system's information content and predictability. While modern manufacturing systems aim to be adaptable, reconfigurable, and resilient to market fluctuations (Wang et al., 2019), there's also a growing need for rapid and accurate development and reconfiguration of these systems (Jeon & Schuesslbauer, 2020).

A digital twin (DT) in manufacturing is a fit-for-purpose digital representation of an Observable Manufacturing Element (OME) with synchronized updates between the OME and its digital counterpart (ISO 23247, 2021). An OME encompasses various entities within a manufacturing environment, such as personnel, equipment, materials, processes, facilities, environments, products, or supporting documents. The digital representation accurately reflects the real-time operating conditions of its corresponding OME (Shao, 2021). This reciprocal relationship enables streamlined product design, manufacturing, and service across the system's life cycle.

DT in manufacturing applications is an evolution of computer simulations but adds a lifecycle approach, data connectivity (Shao et al., 2019), and a degree of intelligence. Different types of manufacturing simulations can be an integral part of DTs. Modern-day simulations are not limited to a specific physical process. They are often highly accurate, realistically rendered, polymorphic simulation environments of large-scale real-time systems connected to data and feedback. Implementing DTs has diverse benefits, and each DT may require different resources, effort, and investment depending on its scope and purpose.

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Developing a DT isn't straightforward due to various associated challenges. Primarily, there's no universally agreed-upon definition of a DT. Additionally, the nature and level of detail of a DT are determined by the specific use case for which it's intended. The DT's multi-dimensional and multi-perspective complexity challenges deriving its return on investment (ROI). To address this problem, our research assesses the economic impact and business value of developing DTs for manufacturing systems. We propose a practical framework to evaluate the cost components, a model to make a simulation complexity assessment, and a method for ROI calculation. This systematic process and the accompanying user interface application can assist practitioners, researchers, and policymakers decide the financial viability of developing a DT.

The objective of this study is to:

1. Introduce a method for evaluating the financial value of DT development.
2. Create a practical tool for estimating ROIs for DT applications.
3. Present three industrial scenarios demonstrating the assessment of financial value, focusing on developing DT applications for design, commissioning, and operational support.

## 2 DIGITAL TWINS FOR EVERY NEED

The global digital twin market is projected to reach $48.2 billion by 2026 (World Economic Forum, 2023). A survey by Gartner revealed that 75% of organizations worldwide intend to incorporate digital twins in the coming years. More than two-thirds of these businesses are expected to have integrated at least one digital twin into their operational workflows (Shao & Helu, 2020). However, a digital twin's characteristics, structure, and expenses will vary significantly based on individual business needs and circumstances. Each digital twin is required to be tailored to a specific use case. It is important that not every company needs to develop a DT from scratch. The following future scenarios can be considered for developing and implementing a DT.

### 2.1 DT Developers

These companies develop their DTs from the ground up, tailoring them to specific machinery, equipment, or systems unique to the organization. This bespoke approach has the highest development costs since every aspect must be built from scratch. Industries such as specialized equipment manufacturing, aircraft production, and space exploration may require this level of customization.

### 2.2 DT Integrators

This scenario concerns businesses that use standardized modules of DTs to construct a more extensive DT system. Automation system integrators can exemplify this type of situation. Manufacturing companies' development departments may also encounter this scenario. However, the digital twins must possess inherent interoperability and the capability to communicate with equipment from various OEMs. The DT will still have a high development cost but will enable flexibility to change it quickly.

### 2.3 DT Commissioners

Commissioners are the companies that procure a tailored DT solution from OEMs or system integrators and deploy it according to the system’s needs. They can acquire a fully developed DT system or one that is ready for deployment. Among these companies are the end users of diverse machinery and equipment. While this arrangement may appear particularly convenient for SMMs (Small and Medium-Sized Manufacturers), even large corporations may opt for this approach to reduce time and costs.

### 2.4 DT Users

Enterprises that choose to fully outsource their DT endeavors, encompassing tasks such as development, deployment, storage, and ongoing maintenance, whether at a remote facility or through cloud-based solutions, paving the way for the emergence of novel business models. This paradigm closely resembles the operational framework seen in web hosting services and AWS offerings for data storage. Such a strategy fosters efficiency and creates fertile ground for companies specializing in DT services to flourish and innovate.

## 3 DIGITAL TWINS AND LIFECYCLE OF MANUFACTURING SYSTEMS

Research conducted by the German Association of Machine Tool Builders (VDW) has revealed that the commissioning phase of a manufacturing system consumes up to 25 % of the total project cycle time (Reinhart & Wünsch, 2007). Almost 90 % of this commissioning time is consumed by delays and tasks associated with electrical and control devices. Furthermore, 70 % of these delays are directly linked to errors in control software. The ramp-up phase begins with the complete assembly of a manufacturing system and concludes when the system achieves full target quality at a specified cost and output rate (Malik et al., 2021). Maintenance represents a significant cost component in operating manufacturing systems. In 2016, maintenance expenditures and preventable losses in discrete manufacturing were estimated to total $193.6 billion in U.S. dollars (Thomas & Weiss, 2023).

A DT created during the design phase of a manufacturing system can support the system throughout its entire life cycle, including development, operation (such as maintenance and reconfigurations), and end-of-life phases. When targeted for industrial equipment and automation systems, a DT can utilize a virtual model that simulates mechanical, electrical, and control systems within a realistic 3D environment. This simulation validates the operation of a manufacturing system before physical implementation (De Oliveira Hansen et al., 2021). This DT can expedite commissioning efforts and prevent delays caused by unforeseen or unpredicted errors during commissioning.

## 4 RESEARCH METHODOLOGY

The proposed research is based on the authors' experiences, interviews with industrial practitioners, and existing peer-reviewed published research. The authors have developed several projects where simulation-based DTs, in some capacity, were designed for manufacturing applications. A few use cases are briefly presented below. Each use case has its objective, and different tools and technologies were used. Simulations were an integral part of all the listed DT projects. These projects provided insight into the time and effort required for building manufacturing DTs. These projects enabled the authors to estimate the cost and effort required to develop a DT and identify the business value of building one.

### 4.1 A digital twin of a human-robot collaborative assembly cell

This case studies human-robot interaction (Malik & Brem, 2021) in a collaborative assembly cell (Figure 1 (a)). The DT is intended for design support, safety assessment, and path optimization of the cooperative system. It consists of a continuous human-robot simulation, live joint position exchange between the physical and simulated robot, data log collection from the robot cell, and integration of data logs into the event-based simulation for performance optimization.

### 4.2 Digital twin of a machine vision system in a bolting robot

This study recognizes the importance of machine vision in a DT for robotic installations (Figure 1 (b)). It introduces a framework to model a machine vision-based parts-feeding system in DT of robotic installations. The industrial case presents the DT of a machine vision system using parts with material type, surface finish, geometry, and shape variability.

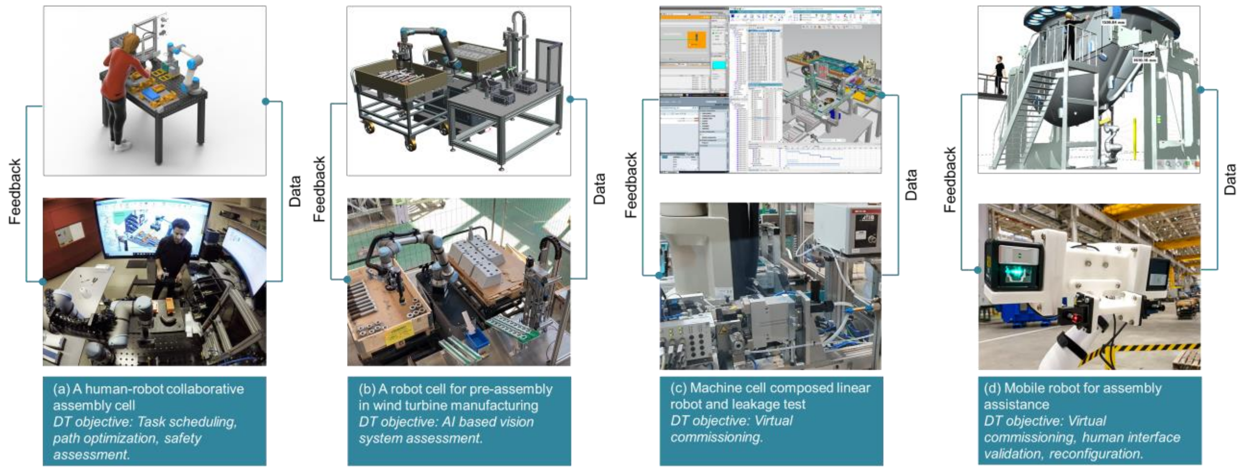


Figure 1: Different use cases of simulation-based digital twins developed for various purposes. These DTs represent individual scenarios utilized as case studies for this research.

### 4.3 Simulation-based digital twin for machine tool development

It is a unified DT (Figure 1 (c)) that facilitates verification, validation, and control throughout the development lifecycle of machine tools (Malik, 2023a). The DT supports virtual commissioning using hardware-in-the-loop and software-in-the-loop techniques. The use case proves a 35 % decrease in development time from the traditional approach. The approach also reduced reconfiguration efforts across the manufacturing system's lifecycle.

### 4.4 Digital twin-based development of mobile robot assistant

The case presents a mobile robot assistant (Figure 1 (d)), and its DT to help human operators assemble cable trays on the bedframe of wind turbines (Malik, 2023b). A complete process simulation was developed. A Programmable Logic Controller (PLC) emulation was integrated into the simulation. An active connection between the virtual and real robots was established. The DT system supports the mobile robot assistant's design, development, virtual commissioning, robot programming, and reconfigurations.

## 5 RELATED RESEARCH

DT is an emerging technology characterized by diverse interpretations and meanings in literature. This multifaceted nature of definitions poses a challenge in devising a methodology for calculating an ROI strategy for DT applications. The existing literature offers different approaches for ROI calculations for design and development, virtual commissioning (VC), and reconfigurations. Given the overlap between these aspects and DT techniques, the ROI assessment methods can potentially aid in formulating an ROI methodology for DT development.

The Efficiency Measuring Problem of using digital models in system development was discussed by Reinhart (Reinhart & Wünsch, 2007). Th authors documented a field study; there were 60 test participants, each independently developing a control program for a simple machine with a PLC. Half of the participants used standard development tools, whereas the other half of the participants used a simulation model to conduct a virtual commissioning of their control software. It was shown that the control software quality in terms of fulfilled requirements was improved by more than 100 %, whereas the commissioning time was reduced by 75 %. The virtual simulation models appeared to reduce the development time and number of errors.

Reinhart and Wünsch (2007) examine costs during the commissioning phase of a manufacturing system. They introduce a theoretical framework comprising four steps for economically applying VC. These steps encompass (1) breaking down the production system, (2) assessing the manufacturing system to quantify efforts and benefits for modeling each component, (3) analyzing the relationship between effort and benefits, and (4) adopting a VC strategy tailored to prioritize time, quality, or cost objectives.

A qualitative approach for the economic justification of simulation models was proposed by Shahim and Moller (2016). The authors evaluate the tangible and intangible costs and benefits of using virtual simulation models and apply the Fuzzy Analytical Hierarchy Process to quantify a score. To do so, the authors assess automation deployment in five companies to evaluate and justify value creation and the economic justification of simulation modeling in terms of time, cost, and quality. The project used a discrete event simulation (DES) along with some PLC emulators. The research material for this study consists of twelve interviews with design engineers, simulation and emulation experts, and development project leaders.

The study concludes that simulation models offer value by reducing onsite work, shortening ramp-up periods, and averting delays. The authors argue that the proposed approach is adaptable to numerous automation scenarios, including warehouses, manufacturing, assembly, distribution centers, mail, cargo, and baggage handling. However, qualitative research acknowledges the challenge of devising an ROI method. Moreover, understanding the complexity and specifics of the virtual models is challenging due to the absence of a description of the automation context. Additionally, the evaluation primarily focuses on using rather than developing the digital models.

A DT method for gauging the economic ramifications and potential ROI from implementing automation solutions within manufacturing settings was presented by Caccamo et al. ( 2022). The approach is argued to be beneficial for companies facing the prospect of costly automation solutions, where the potential ROI warrants more precise evaluation. The factors to evaluate the economic impact of a DT system on job-shop manufacturing can be assessed using four factors: ROI, compound annual growth rate, internal rate of return, and net present value (Banyai & Kovacs, 2023).

Although research has numerous qualitative and quantitative discussions and concepts regarding evaluating the monetary worth of simulation modeling for manufacturing systems, a cohesive framework for applying these methods to DT development is still lacking.

## 6 TWINECONOMICS: THE ECONOMIC ASSESSMENT OF DIGITAL TWIN DEVELOPMENT

This section presents the proposed method for evaluating the monetary worth of DT development. The method comprises four modules (Figure 2). Module 1 gauges the complexity of a manufacturing system, sorting it into simple, moderate, chaotic, or complex categories. Following this, Module 2 pinpoints the precise DT components that require modeling to ensure usability, thereby setting the desired level of detail for the DT. Subsequently, Module 3 estimates the person-hours needed for developing the DT system based on specified parameters. Module 4 then computes additional costs, such as hardware resources and software programs. Finally, Module 5 conducts a comparative analysis between DT-based and non-DT-based manufacturing systems, highlighting their advantages and disadvantages. An economic evaluation of DT integration within manufacturing systems can be accomplished by executing these modules.

### 6.1 Module 1: Scope of the digital twin

The first step involves identifying and specifying the purpose and scope of the intended DT. A DT can serve diverse objectives, but it's essential to clearly outline its development's purpose. According to the IEC 63278 standard (IEC, 2024), each DT must be associated with a specific use case. The ISO 23247 definition of DT also emphasizes “fit-for-purpose.” For instance, a DT for a robotic cell might be developed for tasks such as path optimization, scheduling, and virtual commissioning. The scope defines the required detail level of the DT.

### 6.2 Module 2: Complexity of the Manufacturing System

The next stage involves understanding the complexity of the manufacturing system, i.e., the OME for a DT. A manufacturing system functions as a set of structured resources operating cohesively. Complexity within such a system may stem from factors like the multitude and diversity of its constituent components. Nevertheless, it's important to note that not every element of the manufacturing system needs to be modeled in its DT based on the "fit-for-purpose" concept. The complexity of manufacturing systems pertinent to DTs can be gauged by assessing the abundance and diversity of its resources and processes.

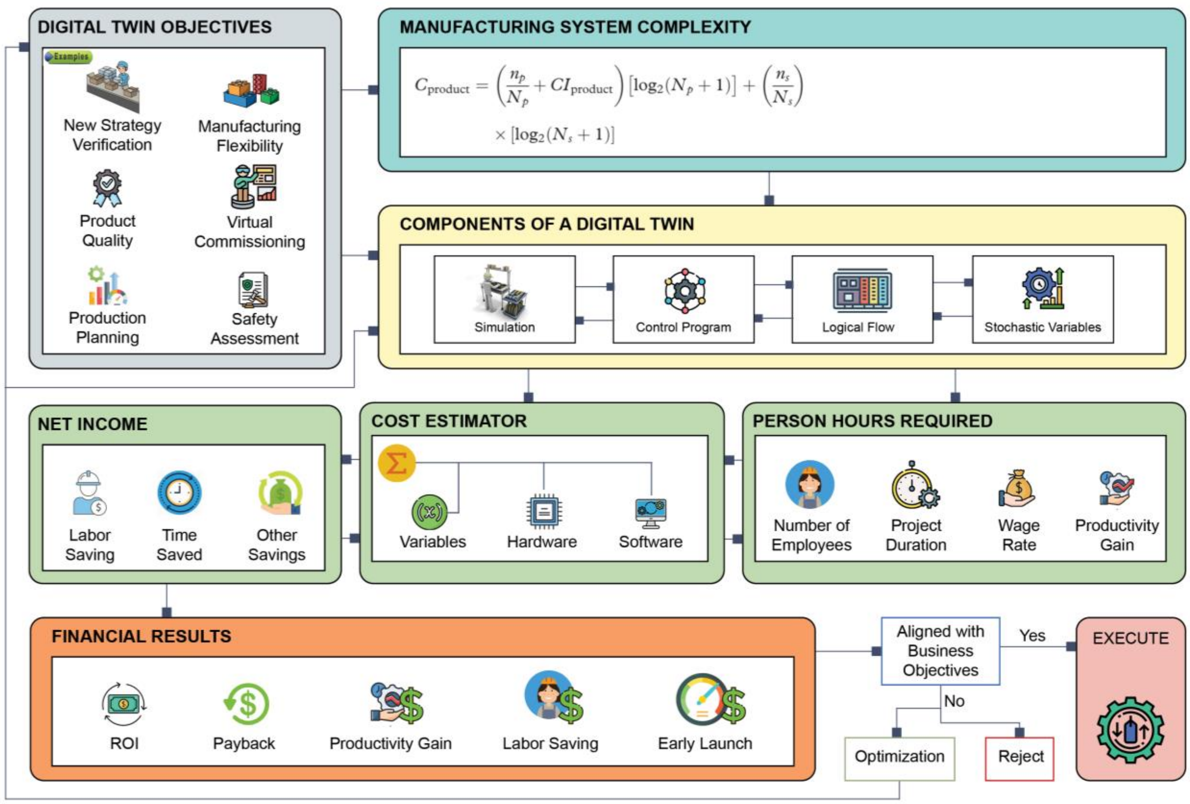


Figure 2: The method to calculate the ROI of digital twin development.

The cost component of the project is the cost associated with the physical system for which a DT is intended (Figure 3). A DT is supposed to serve some purpose in managing the complex manifestation of the physical system. That complexity manifestation will have a cost effect on manufacturers. Adopting DT will help minimize or eliminate that cost and will act as the benefit of investment in developing a DT. For example, changeovers and reconfigurations can be time-consuming and may involve severe problems if not carefully planned. A DT can help prepare them in a computer-based model, assess different scenarios, generate a control program, and operate the system according to the results.

The cost of investment in DT is fundamentally on the wages of skilled employees. It constitutes the primary cost component of developing a DT. The total person-hours required to create a DT can be estimated using the method described in the previous section. Therefore, the development cost of DT can vary from location to location. The second component is software cost. There are several open-source tools available to develop DTs. However, many tools developed in open-source tools may have robustness issues and may not be suitable for industrial applications in some situations. In these scenarios, commercial and proprietary tools can be used. However, they have challenges, such as limited to no data communication with other tools.

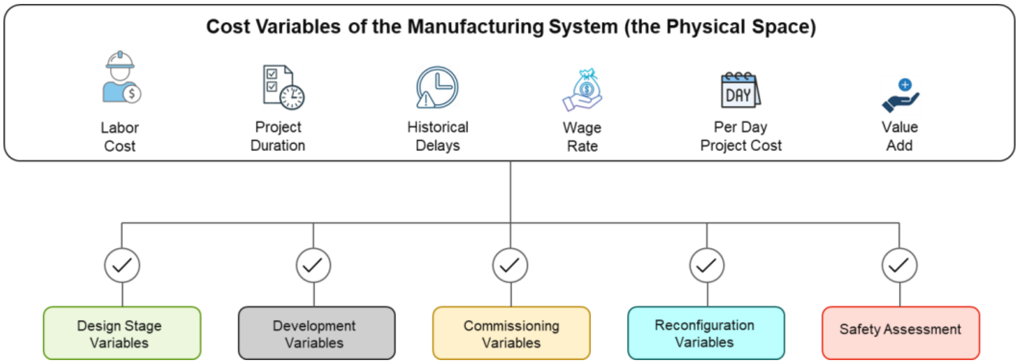


Figure 3: The scope of the DT and the associated cost variables.

The third significant cost component is the hardware cost. Though a DT is primarily a virtual environment, it is still composed of several hardware types. This hardware may include various types of sensors for process monitoring, data collection and logging, routers, servers, computers, and interaction devices such as AR/VR devices for DTs.

### 6.3 Module 3: Cost to develop a digital twin

A DT can encompass various components, though not all may be essential for every DT system. Considering the DT's objectives and the manufacturing system's complexity, a specific configuration for the DT is established. However, while modeling each component improves the accuracy of its results, developing each element requires an investment. The cost of developing a DT comprises several components, including person hours, hardware expenses, software expenses, and maintenance costs (Figure 4).

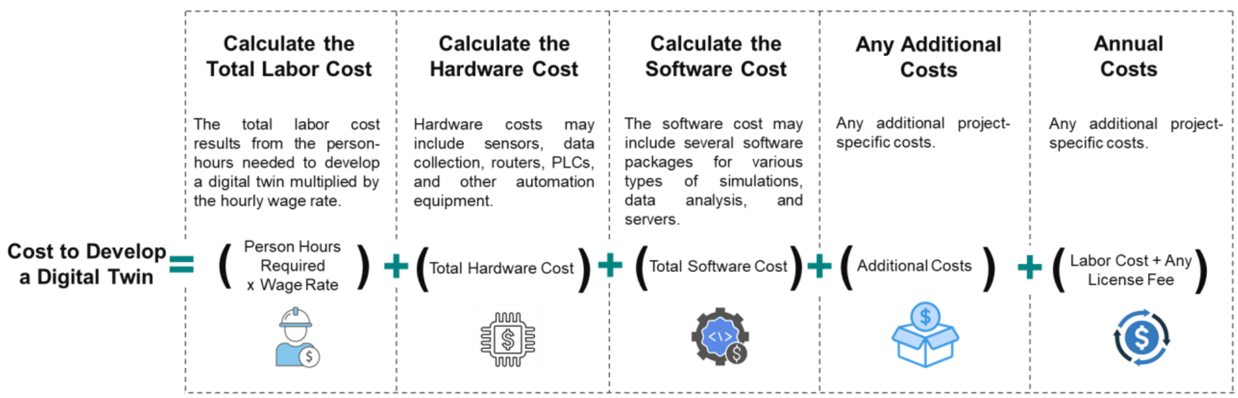


Figure 4: Cost variable of DT development.

While not mandatory, a primary simulation environment elucidates the dynamics of the observed manufacturing system and serves as the principal platform for visualizing the system's dynamics. Typically, this simulation employs continuous, discrete event, or stochastic simulation techniques. Numerous off-the-shelf tools, such as Tecnomatix, Delmia, RoboDK, and Visual Components, are available to develop this type of simulation. Open-source engines like Unity and Unreal Engine can also fulfill this role.

PLCs are industrial computing devices for programming and controlling industrial machinery and processes. They play a central role in managing machine operations based on logic-driven programs. Creating and validating an automation program is a foundational step in the commissioning and operations of a manufacturing system. PLC programs can be developed in specific software programs and downloaded onto emulated software-based PLCs. These software-based PLCs are linked to the simulation for logic-driven simulation.

To create a comprehensive DT, it may be necessary to simulate the electrical behavior of devices, such as drives, sensors, and actuators. These devices can be simulated within a behavior-modeling environment and linked with the primary simulation. This integration ensures a holistic representation of the system's functionality and interactions. A range of sensors may be integrated into the DT to gather necessary data, collecting information subsequently transmitted to a data repository. This repository is then linked to the simulation for further analysis and processing.

Developing a DT system is time-consuming. High-fidelity, high-resolution DTs demand increased time investment. Various skills, including software engineering, CAD, control logic understanding, interface design expertise, electrical engineering, measurement science, networking capabilities, and statistical analysis skills, are needed for DT modeling. A collaborative effort involving a team of engineers and subject matter experts typically undertakes such projects. This team composition significantly impacts the development costs, as individuals with diverse skill sets command differing salaries. The proposed method aims to quantify the person-hours required for constructing a functional DT from scratch, providing a structured approach to estimate the time and resources required for DT implementation (Figure 5).

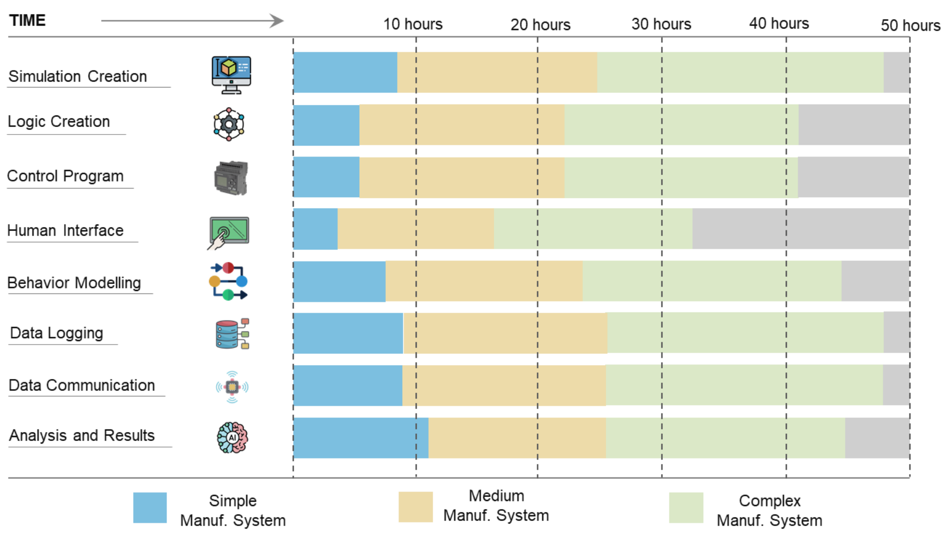


Figure 5: Time estimation to develop a digital twin.

The person-hours calculation can be generalized by assessing the complexity of a manufacturing system and identifying the components required to model. The figure presents a chart depicting the person-hours needed for modeling each aspect of a DT system. The estimation rationale draws upon the authors' experience with diverse DT projects and insights from interviews with industry professionals. Nevertheless, this time estimation can still vary based on the tools used, the skill level of the employees, work behavior, team structure, etc. If the total time to develop all the required DT modules is Ti, where i represents the module number. If n modules are considered in total, the equation for the sum of total time for all modules would be:

$$Time_{DT} = \sum_{i=1}^{n} T_i$$

Cost estimation can either rely on an average hourly rate for team members or improve accuracy by integrating precise wage rates for each individual. This cost assessment should encompass the hourly wage rate and an estimation of the overhead associated with employing each team member. Furthermore, the cost of implementing a DT should incorporate ongoing expenses for employees to manage, maintain, and utilize the DT throughout the lifecycle of the DT or the manufacturing system.

### 6.4 Module 4: Net gains of developing a digital twin

The preceding steps have provided an overview of the expenses involved in developing a DT and estimated the costs associated with designing, developing, maintaining, and operating a manufacturing system without a DT. Developing a DT of a manufacturing system can yield numerous advantages. These benefits include reductions in the number of person-hours needed to manage the system, prevent delays, accelerate time to market, and enhance manufacturing flexibility. It is necessary to quantify these advantages into financial figures to evaluate the benefits against the costs associated with developing and managing the DT. The comparison of the expenses versus benefits can be leveraged to generate an ROI estimation using the following equation:

$$DT_{ROI} = \frac{Net\ Benefits\ - Cost\ of\ Development}{Cost\ of\ Development}\ x\ 100\%$$

## 7 EXPERIMENT AND RESULTS

The method for assessing the ROI of DT development has been tested for the first case outlined in Chapter 4. The obtained results from the proposed *TwinEconomics* method were compared with existing findings on the financial viability of DT development. It was observed that while a system integrated with a DT incurs high initial costs, its long-term benefits become evident, as such a system proves to be more adaptable and requires less maintenance effort (Table 1). Moreover, the development of DTs primarily involves startup costs, with maintenance costs mainly associated with personnel hours. Most of the development cost is attributed to software licenses, which can be mitigated using free-to-use and open-source simulation environments.

Table 1: Financial results of developing DT for a collaborative assembly cell.

| Years | DT Development Cost ($) | DT Maintenance Cost ($) | Labor Saving ($) | Gains from Early Access to Market ($) | Other Savings ($) | Total Savings ($) | ROI (%) |
|---|---|---|---|---|---|---|---|
| 1 | 44,400 | 105,000 | 34,032 | 145,440 | - | 179,472 | 20 |
| 2 | 0 | 107,100 | 19,200 | 96,000 | - | 115,200 | 8 |
| 3 | 0 | 109,242 | 19,584 | 96,000 | - | 115,584 | 6 |
| 4 | 0 | 111,427 | 19,976 | 96,000 | - | 115,976 | 4 |
| 5 | 0 | 113,655 | 20,375 | 96,000 | - | 116,375 | 2 |

## 8 HANDS-ON TOOL FOR ROI ASSESSMENT

Microsoft Power Apps was used to create an intuitive graphical interface for the proposed TwinEconomics method (Figure 6). The developed app can be used on a smartphone or tablet to estimate DT's economic benefits. The user inputs values for the number of people involved, estimated time of the project, hourly wage of developers, and whether delays are likely to occur. As a result, it can be estimated how much time is being saved, how much cost can be reduced, and how much delay can be avoided.


Figure 6: An app-based user-friendly interface for quick ROI analysis of DT development.

## 9 DISCUSSION AND CONCLUSION

In the modern manufacturing landscape, the adaptability of manufacturing systems is required, necessitating the efficient adjustment of behaviors to meet evolving market demands and shrinking product life cycles. DT technology emerges as a solution to address the escalating complexity of automation systems and the pressing need for shorter ramp-up phases. However, manufacturers need to estimate the ROI for their DT investment before committing to these DT projects. Control software engineering, the concluding stage in the development process, predominantly occurs during the commissioning phase of production ramp-up. This research presented an initial practical framework for cost assessment of DT development along with a complexity model for simulation modeling. This systematic approach and a user-friendly interface can help stakeholders decide the financial viability of DT projects. The method has been evaluated for four industrial use cases. Future efforts include enhancing the framework and the tool to incorporate more factors (e.g., overheads), applying them to more industry cases, and considering standardizing the framework.

## DISCLAIMER

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