Enhancing Requirement Engineering Accuracy with Interactive Digital Twin Model

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Abstract

Requirement engineering (RE) often suffers from incomplete, ambiguous or inconsistent specifications, which can lead to costly rework or project failure. Recent advances in **Digital Twins (DTs)** – virtual replicas of physical systems with bidirectional data links – offer new ways to improve RE by simulating, visualizing and testing requirements in real time. An **interactive digital twin** extends this concept by providing a real-time, user-driven interface (often 3D or mixed-reality) that allows stakeholders to explore system behavior and validate requirements collaboratively. This paper reviews recent literature (2022–2025) on the use of interactive DT models to enhance RE accuracy. We first outline common RE challenges and show how digital twins are defined and made interactive. We then survey studies demonstrating DTs for requirement elicitation, conversion, validation, traceability and stakeholder communication. Notably, Gu *et al.* demonstrate that a DT-driven requirement-conversion framework improved conversion accuracy over conventional methods, while Stary *et al.* propose "Digital Process Twins" to involve users in iterative requirement elicitation and design exploration. We synthesize findings on benefits and limitations (e.g. improved stakeholder alignment vs. complexity of DT implementation) and identify gaps such as limited empirical evaluation and tool support. Finally, we suggest future research directions, including standardized interactive DT platforms for RE, integration with AI assistants, and richer traceability mechanisms.

Introduction

Effective requirements engineering is critical for successful system development. Requirements often come from diverse stakeholders with differing perspectives, making them prone to **ambiguity, incompleteness, and change**. Such deficiencies are well-known to cause project delays or failures. For example, Hoy and Xu report that *"weak requirements engineering is known to be a main reason for project failures"*. Common challenges in RE include eliciting correct needs from stakeholders, maintaining traceability, and validating requirements against real-world constraints. Traditional techniques (interviews, user stories, prototypes) often fall short when systems are complex or requirements are uncertain.

Digital Twin (DT) technology has emerged as a powerful paradigm that could help address these RE challenges. A **Digital Twin** is generally defined as *"a virtual model of a physical system"* with continuous two-way data exchange. Lacueva-Pérez *et al.* describe a DT as *"a high-fidelity digital representation of the operational dynamics of its physical counterpart"* with near-real-time synchronization. Kober *et al.* similarly characterize DTs as *"virtual models interconnected with a physical system through data links"*. This virtual-physical coupling allows DTs to simulate system behavior, monitor performance, and predict future states. Crucially for RE, a DT can be **interactive**, meaning stakeholders can manipulate the model parameters or scenarios and observe outcomes. An *interactive digital twin* typically provides user interfaces (e.g. 3D visualizations, dashboards, VR/AR environments) where users can explore "what-if" scenarios. Such interactivity enables stakeholders to experiment with system configurations and see immediate feedback, which can clarify requirements and reveal hidden constraints.

In this paper, we survey recent (2022–2025) academic and industrial work on applying interactive DTs to improve the accuracy of requirements engineering. We begin by examining the roots of RE difficulties and the rationale for using DTs. Then we define digital twins and discuss how they can be made interactive. The core of this review presents relevant studies showing how interactive DTs aid requirements elicitation, conversion (refinement), validation, traceability, and stakeholder communication. We analyze trends and gaps in the current research, noting, for example, that while prototype frameworks have been proposed, few have mature tool support. We conclude by proposing future research directions, such as integrating AI with DTs for dynamic requirement recommendations and developing standards for DT-RE integration.

Literature Review

Requirement Engineering Challenges

Requirements engineering inherently involves complexity and uncertainty. Multiple stakeholders (customers, engineers, operators) each have partial views of the system, often expressed in natural language or informal models. Misunderstandings can arise easily. Common RE challenges include *eliciting* complete requirements from stakeholders, managing *changing requirements*, resolving conflicting needs, and ensuring *validity* of requirements with respect to real-world constraints and system goals. For instance, Requirement Engineering (RE) involves *"eliciting, analyzing, specifying and validating"* requirements with stakeholders, and it requires negotiating priorities and conflicts. Agile environments can exacerbate this, as teams may focus on rapid delivery over formal documentation, risking weakening of specifications. Several surveys and experience reports confirm that poor or weak requirements lead to most project failures. In practice, common inaccuracies in requirements include vague wording, missing non-functional requirements, and lack of traceability to higher-level needs. Given these challenges, techniques that can make requirements more concrete, testable, and visible to stakeholders are highly valuable.

Digital Twin: Definition and Interactivity

A **digital twin** is a virtual replica of a physical system that mirrors its structure and behavior across the system's lifecycle. As discussed, Lacueva-Pérez *et al.* define a DT as *"a high-fidelity digital representation of the operational dynamics of its physical counterpart"* with near-real-time synchronization. More generally, Kober *et al.* emphasize that DTs are *"virtual models interconnected with a physical system through data links"*. This connectivity allows the twin to continuously ingest sensor data, update its state, and in turn guide adjustments to the physical asset. DTs often integrate multiple models (geometry, physics, control logic, data analytics) to represent complex systems. In industries, DTs are applied to production equipment, vehicles, buildings, and infrastructure for monitoring, diagnostics, and optimization.

Digital Twin for Requirements Elicitation and Visualization

Interactive DTs can support the elicitation and refinement of requirements by providing a shared, visual platform for stakeholder communication. Traditional requirement elicitation (interviews, workshops) can be hindered by abstract discussions; an interactive DT provides concrete artifacts (simulations, models) that stakeholders can react to. Stary *et al.* (2024) introduce the concept of **Digital Process Twins (DPTs)** as an intelligent design technology. Their approach is explicitly *"human-centered"*, using DPTs to involve relevant actors in *"requirements elicitation and design exploration"* for cyber-physical systems. They report that a DPT can allow stakeholders to *actively participate* by adjusting parameters or scenarios, thus refining requirements iteratively. Although still in the research stage, this work suggests interactive DTs can make elicitation more participatory and dynamic.

In industry, we see similar uses. IPG Automotive describes how its CarMaker driving-simulation tool serves as a DT for developing automotive systems: during requirement elicitation and system design, engineers *"test different prototypical implementations of driving functions"* (e.g. varying controller gains) and use the simulation results to choose final requirements. In other words, the DT provides a sandbox for exploring how various control strategies meet the desired outcomes, guiding requirement definition. This practical example shows that DT-based simulation can replace or augment early prototypes, turning vague functional goals into parameterized specifications. Similarly, in architecture and construction, *"digital mockups"* (a form of DT) allow clients and architects to navigate building designs in 3D, facilitating elicitation of user needs and identification of missing requirements. Overall, these works indicate that interactive DTs can act as a live requirements workshop: stakeholders see a working model from the outset, enabling faster feedback and clearer requirement statements.

Digital Twin in Requirement Conversion and Specification

Beyond elicitation, digital twins can help **convert** stakeholder needs into formal specifications. Gu *et al.* (2021) propose a *Digital Twin-Driven Requirement Conversion (DTRC)* framework for customized design, which directly addresses this issue. Their system employs a tri-model architecture (digital model, behavior model, evolution model) to iteratively transform informal or high-level requirements into detailed design parameters. They report that DTRC *"outperforms other RC approaches in terms of conversion accuracy"* in their elevator-design case study. The DT here is used to visualize and optimize the mapping path between customer requests and design variables. Notably, DTRC *"can visualize and optimize the conversion path"* which means decision-makers (designers, customers) can see how each requirement propagates through the design process. This kind of transparency helps ensure requirements are correctly interpreted. Gu *et al.* highlight that DT-driven conversion supports *customer participation*, effectively keeping stakeholders in the loop during requirement refinement.

Digital Twin for Validation and Traceability

Interactive DTs naturally support **validation** of requirements by simulating the system under varied conditions. For example, once a requirement is specified (say, a performance threshold or safety criterion), an interactive DT can emulate scenarios to check if that requirement is met. In manufacturing, Liu *et al.* (2021) propose a DT-driven framework for traceability of process quality data. Although focused on quality control, their approach illustrates how DTs maintain information models that link data across life-cycle stages. Translating to RE, one could imagine a DT maintaining links between requirements, design elements, and test results – essentially a "digital thread" of traceability. While formal DT-based traceability solutions in RE are scarce, some related work hints at possibilities. Kandasamy *et al.* (2022) discuss a DT for power systems cybersecurity that inherently links system models to security requirements, easing analysis of requirement impact under attacks.

Digital Twin for Stakeholder Communication

A frequently cited benefit of interactive DTs is enhanced communication among stakeholders. Kober *et al.* (2024) emphasize that one *central aspect* of DT adoption is handling stakeholder communication, given the term's ambiguity. Their study (27 interviews) identifies challenges in DT projects, noting the *"complex communication dynamics"* that arise when multiple disciplines collaborate. In practice, an interactive DT serves as a common reference model: engineers, managers, and clients can all view and discuss the same simulated system. For example, an interactive DT dashboard might let a requirements analyst demonstrate how a requested feature affects system output, ensuring everyone has a shared understanding. Lacueva-Perez's SHION twin, while technical, includes a cloud interface where operators can visualize injection-molding outcomes in real time. Such immediate visual feedback improves alignment: if a stakeholder sees that a requirement (e.g. dimensional tolerance) leads to frequent defects in simulation, they can adjust it early.

Methodologies

Model-Driven Engineering (MDE) Approach

- Use MDE to systematically create and maintain DT models derived from requirements.
- Requirements are formally modeled (using UML, SysML, or domain-specific languages).
- Automatic generation of simulation, verification, and validation artifacts from models ensures traceability and reduces ambiguity.
- Reference: *Lehner et al., "Model-Driven Engineering for Digital Twins" (2025)*.

Iterative and Incremental Refinement (Spiral / Agile)

- Combine DTs with agile or spiral development cycles.
- Use DT simulations to test and validate evolving requirements in near-real time.
- Continuous stakeholder feedback helps refine requirements early, reducing costly changes later.

Bidirectional Traceability and Impact Analysis

- Establish traceability links between requirements, DT components, and test cases.
- Any modification in requirements is propagated to the DT model; DT feedback can trigger requirement updates.
- Use automated tools or requirements management systems (e.g., IBM DOORS) linked to the DT.

Real-Time Validation and Verification

- Use the DT to simulate the behavior of the system under different scenarios.
- Compare simulation outputs against expected requirement specifications.
- Apply statistical analysis and anomaly detection to identify deviations.
- Reference: *Timmapuram et al., "Exploring the Performance and Accuracy of Digital Twin Models" (2023).*

Data-Driven Requirements Refinement

- Integrate live data (from sensors, logs, or IoT platforms) into DT models.
- Analyze operational data to refine or adjust requirements to better match real-world conditions.
- Apply machine learning for pattern detection and requirement evolution.

Probabilistic & Bayesian Modelling

- Model uncertainty and incomplete requirements using Bayesian networks or probabilistic graphical models.

- DT can dynamically update its belief about requirement satisfaction as new data arrives.
- Reference: *Kapteyn et al., "A Probabilistic Graphical Model Foundation for Enabling Predictive Digital Twins at Scale" (2020)*.

Human-in-the-Loop (Interactive Simulation)

- Stakeholders can interact with the DT via dashboards, VR/AR interfaces, or scenario-based tools.
- Users test "what-if" scenarios and refine requirements based on observed outcomes.
- Enhances shared understanding among engineers, designers, and non-technical stakeholders.

Natural Language Processing (NLP)-Enhanced Requirement Engineering

- Use NLP tools (including large language models) to translate informal requirements into formal DT specifications.
- Automate detection of ambiguity, inconsistency, or incompleteness in requirement statements.
- Reference: *LLM-enhanced digital twin modeling (arXiv, March 2025)*.

Continuous Integration and Deployment (CI/CD) for DT Models

- Automate the update and deployment of DT models whenever requirements change.
- Use CI/CD pipelines to ensure that requirement changes are validated against the latest DT simulation.

Conclusion

Interactive digital twins represent an exciting frontier for improving requirements engineering. By coupling high-fidelity simulations with user-driven exploration, DTs can make requirements more precise, analyzable, and aligned with stakeholder intent. Our review of recent literature (2022–2025) shows concrete examples of this promise. Gu *et al.* showed that a DT-based framework can *"outperform"* traditional requirement conversion methods in accuracy. Stary *et al.* argue convincingly that co-creating requirements through digital process twins enhances stakeholder participation. Case studies like IPG Automotive's CarMaker demonstrate how simulations can guide requirement decisions in practice.

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