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ORIGINAL ARTICLE

Continued use of virtual commissioning models: A novel approach toward digital twins for automated production systems

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Abstract
Virtual Commissioning (VC) is an increasingly integral practice in the engineering of production systems, evidenced by growing research and industrial adoption. Advancements in VC model fidelity, computational performance, and automated generation are improving the validation of complex production systems and point toward further applicability beyond conventional control software validation. In industrial practice, however, VC models are still confined to their original use. While emerging applications for VC models in the operational phase highlight the potential for model reuse, a structured method for transforming these valuable engineering assets into Digital Twins (DTs) is still absent. This paper addresses this gap through three main contributions: first, by clarifying the VC/DT boundary within production contexts and identifying open research questions; second, by introducing a novel six-phase transformation method; and third, by identifying industrially-derived use cases and their specific requirements. The proposed method adopts the Design Science Research (DSR) methodology to systematically structure the problem space, derive actionable objectives, and design the iterative development process. Initial results include a set of industrial use cases with their corresponding requirements, as well as the exemplary execution of one development cycle. Finally supplemented by a qualitative cost-benefit analysis, this work offers practical guidance for realizing VC-based DTs that support operational tasks in production environments.

Keywords Virtual commissioning · Digital factory · Production planning · Digital twin · Operational phase

1 Introduction

In recent years, Virtual Commissioning (VC) has emerged as a key method in engineering complex, highly automated production systems [1]. By leveraging simulation models and connecting them to the real control systems, manufacturers can validate and test production systems and their associated control programs before physical implementation, accelerating the commissioning process and significantly reducing control software errors [2]. Although VC is becoming established in industries with highly automated and complex production systems, its application is typically confined to the engineering phase. The broader concept of the Digital Twin (DT), promising capabilities like real-time decision-making, manufacturing optimization, operation control, and predictive maintenance throughout the entire operational phase [3], continues to shape academic and industrial discourse. Subsequently, this focus on DTs often overshadows the practical advantages of VC models, which are already highly capable, readily available, yet frequently underutilized beyond their initial purpose.

While DTs are often considered as potential solve-all targets in digitalization, this work proposes a shift in perspective toward VC and its models. Often dismissed as engineering by-products, VC models, thanks to their hardware connectivity

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and control level fidelity, hold untapped potential for operational support. In light of rising cost pressures and shrinking product life cycles, extending the utility of these valuable models offers clear economic and operational advantages. The reuse of VC models in operational contexts, such as for the validation of system changes [4], real-time collision prediction [5], predictive maintenance [6], quality monitoring [7], and training [8], is beginning to attract increasing attention.

Despite growing interest, a systematic approach for repurposing VC models from software validation into application-oriented DTs is still lacking. This specific gap also reflects a broader shortcoming: the lack of practical concepts for implementing concrete DT applications in industrial settings [3]. Our work addresses this methodical gap by exploring how existing VC models from engineering can be transformed into DTs that deliver tangible benefits in the operational phase of automated production systems.

This work advances a methodological approach that anchors open research questions in this area in concrete industrial needs and addresses them systematically. Drawing on Design Science Research (DSR) principles, we propose a structured transformation method to extend VC models from engineering into production-supportive DTs. The method is operationalized by deriving five relevant applications from a needs analysis with key stakeholders and translating them into achievable design goals and core requirements. Its applicability is further demonstrated through an exemplary execution of one development cycle for a selected use case.

This paper is structured as follows: First, we review the current state of the art, focusing on the definitions and distinctions between VC models and DTs. Next, we present our proposed six-phase transformation method, providing detailed results for the first two phases and conceptually addressing the subsequent phases through one selected use case. The paper concludes with an economic assessment and a discussion of broader implications and future research directions.

2 State of the art

The following section examines the definition and role of VC within the broader framework of DTs, highlighting their relevance for modern production systems. Furthermore, a literature review addresses existing approaches for extending the use of VC models beyond their original purpose of control software validation during engineering.

2.1 Definitions and delimitation

Virtual Commissioning is a simulation-based validation methodology for mechatronic systems in which the control system is connected to a simulation model of a component, machine, or production system to perform early, development-accompanying tests before physical realization [1]. In contrast to conventional approaches, where the mechanical, electrical, and software domains are typically integrated for the first time during physical commissioning, VC enables early synchronization and parallel engineering across all disciplines. This increases transparency in the development process, facilitates early detection and resolution of domain inconsistencies, reduces the risk of costly late-stage errors, and improves overall software quality [2]. In a typical VC setup, a geometrical plant model with kinematic capabilities is augmented by behavioral logic elements that accurately replicate the system's dynamic responses to real control signals. This enables the actual control system to interact with a digital counterpart in near real-time, allowing functional sequences, material flows, and operator interactions to be tested and visualized before deployment on the physical system.

Although DTs are an essential concept within the scope of production digitalization, the lack of a consistent understanding necessitates a clear definition and delimitation of the term before its use in this work. The basic concept of the DT, as introduced by Grieves [9], describes a virtual representation of a physical product in real space, connected through bidirectional data exchange. This foundational perspective has been expanded by Tao et al. [10] into a five-dimensional DT architecture. In addition to the physical and virtual entities and their interconnections, they highlight the essential roles of data integration and service capabilities, as illustrated in Fig. 1. These software services are vital for achieving the intended functionalities of the DT and enable a wide variety of applications. The informational backbone, which is the core driver of DT functionality, consists of diverse data streams derived from physical assets, virtual

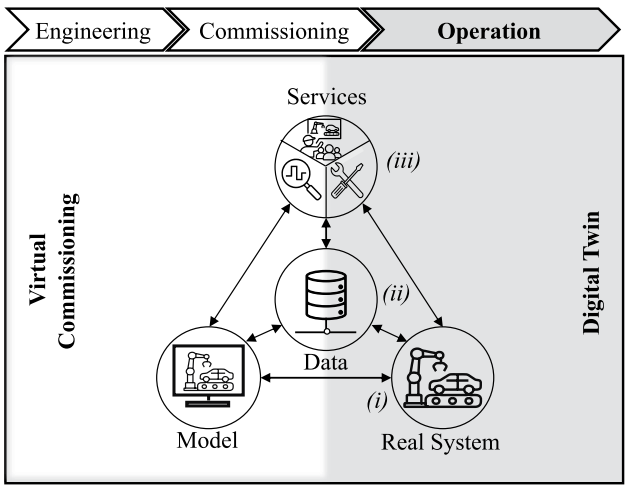


Fig. 1 Placement of VC in the concept of Tao's DT. Adapted from [10]

models, domain knowledge, and services. Complementing this, the German Mechanical Engineering Industry Association (VDMA) defines the DT in manufacturing as a practical digital representation of a real system that combines simulation models, historical data, and live data to enable evaluation, prediction, and optimization [1]. In this work, the definition of Tao et al. is adopted and aligned with the VDMA's practical manufacturing perspective, which positions VC models in the engineering phase and DTs in the operational phase.

While VC models provide realistic virtual representations that enable validation services and encapsulate relevant domain knowledge, they are, by design, not integrated into operational environments. As shown in Fig. 1, they lack three essential elements:

(i) **System-Model Alignment:** addresses the static validity of the model. This refers to the challenge of maintaining consistency across mechanical, electronic, and software domains between the virtual representation and the "as-operated" physical system. It requires a system-model coupling where changes in operational structure, hardware configurations, or control logic continuously drive model updates, ensuring the model's actuality is maintained in response to physical changes.
(ii) **Integration of Operational Data:** concerns the dynamic validity of the model's process state. The missing component is an operational data-acquisition and integration pipeline that captures heterogeneous shop-floor streams and injects them in a timely and aligned manner to achieve state synchronization. This step ensures the model's process state accurately reflects the real system's state, whether operating in parallel or based on recorded data.
(iii) **Provision of Operational Services:** represents the functional gap necessary to unlock the DT's added value. Whereas VC models typically deliver software validation services to experts during engineering, operational DTs require further functional extensions for ongoing services. By returning actionable insights or direct control commands to the shop floor, these services effectively close the bidirectional loop, generating tangible operational benefits on the shop floor.

2.2 Continued use of VC models

Recent studies have demonstrated substantial potential for extending the role of VC models beyond the engineering phase into operational use. The review first examines approaches originating directly from VC research before broadening the scope to related DT developments.

2.2.1 VC-specific approaches

In the following, we provide an overview of relevant developments categorized by the shortfalls identified for the continued use of VC models.

Integration of operational data Early research by Kain et al. [11] introduce an architecture for reusing Hardware-in-the-Loop (HiL) simulation models from engineering, for diagnostic and prognostic purposes. The methodology proposes a "Synchronous Simulation" mode, where the HiL model, utilizing its own controller, runs in parallel with the physical asset, enabling model-based diagnostics by comparing the simulated behavior with the measured real-world outputs. Additionally, a "Forward Simulation" mode is outlined for prognosis and controller optimization, which uses the model to predict future system behavior based on the current plant state. This reuse requires the models to be parameterizable and necessitates a synchronization mechanism to align the simulation with the real plant state, ensuring the model accurately reflects the physical system and allows for reliable conclusions.

Building on this concept of parallel execution, Zipper et al. [12] introduce a model architecture for passive process monitoring, leveraging a modular co-simulation framework to detect deviations between operation-parallel VC models and the physical asset. This framework integrates specialized sub-simulation models coupled to the running production cell via a shared PLC. Building on this, Zipper et al. [13] propose an active, real-time state synchronization method to compensate for the inherent 'Reality Gap'. This extension reformulates synchronization as a dynamic optimization problem, continuously adapting simulation inputs to minimize the error between simulated and measured physical outputs. While this achieves a highly synchronized state, the optimization-based approach is computationally intensive, demanding high-performance FMI implementations for effective scaling to complex production plants.

Seeking a real-time-capable alternative to computationally intensive state synchronization methods, Heller et al. (2024) develop a dynamic prescheduling method to enable operation-parallel monitoring and predictive collision avoidance. A high-fidelity VC model, assuming its geometric accuracy as a baseline, is permanently coupled to the running production cell via a shared PLC, with the simulation intentionally executing each actuator movement slightly faster than the physical system. This predictive lead enables continuous, on-the-fly adjustment of motion parameters, particularly for event-discrete actuators, providing a lightweight solution for simultaneous synchronization. The approach requires an initial state alignment and, as the authors note, encounters limitations in scenarios with high stochastic process

variability or in close-proximity movements, where the predictive lead may cause false-positive collision reports.

System-model alignment While the aforementioned approaches focus on synchronizing dynamic process behavior, Talkhestani et al. [14] develop the "Anchor-Point-Method" to maintain long-term structural alignment between VC models and the physical manufacturing system, primarily to support plant reconfiguration. The method links mechatronic components to stable "anchor points," which serve as references across the mechanical, electrical, and software domain models. Changes are identified by comparing the current PLC control software, exported via a neutral XML format, against a stored reference baseline. A rule-based analysis then detects the affected anchor points and their inter-domain dependencies. This process automatically generates a "Change-Request-Model", which assists engineers in updating the relevant domain models to keep them synchronized with the physical asset. However, the method's effectiveness is limited to detecting only those modifications that are reflected in the control software, meaning purely physical changes without a corresponding software update remain unrecognized.

Provision of operational services A key strategy for enabling operational use of VC models is to advance model fidelity beyond traditional VC levels. This is often achieved through co-simulation, which orchestrates domain-specific simulators via standards such as the Functional Mock-up Interface (FMI) [15]. Addressing the resulting computational load, Littfinski et al. [16] propose methods for intelligent, autonomous partitioning of these models to ensure real-time co-simulation performance. This fidelity can also be enhanced by embedding operational knowledge, such as the failure modes and error models proposed by Kuhn et al. [17]. Chen et al. [18] and Klingel et al. [5] extend the trajectory of operational-parallel simulation frameworks that maintain VC model execution alongside the physical system. Chen et al. [18] employ a real-time co-simulation between CNC controllers and high-fidelity VC models to continuously assess the workpiece quality. Klingel et al. [5] develop a predictive collision avoidance system by embedding VC-based simulations directly into the control loop or coupling them via a fieldbus, utilizing CNC lookahead for sub-millisecond trajectory forecasting and hybrid bounding-volume collision detection. Also, an increasingly popular alternative application for VC models is operator training, where immersive environments enhance situational understanding and practical capabilities of plant operators [8].

These VC-specific works collectively address concepts for the continued operation of VC models by keeping the model up to date, acquiring and integrating real-world data, as well as providing extended operational services.

2.2.2 Digital twin research

A wider range of relevant research explores developments in simulation-based DTs for mechatronic systems. In the following, we provide an overview of relevant developments related to the key shortfalls identified for the continued use of VC models.

Integration of operational data Effective DT implementation relies on high-fidelity, low-latency data-acquisition and integration pipelines. Current research emphasizes robust, time-aware data exchange to enable real-time interaction and time-critical processing, relying on standardized protocols such as the Open Platform Communications Unified Architecture (OPC UA) for semantic interoperability and lightweight messaging frameworks like the Message Queuing Telemetry Transport (MQTT) as the technical basis for efficient data transfer [19, 20]. To minimize latency, edge computing places filtering, compression, feature extraction, and preliminary inference close to the asset before forwarding curated streams to the DT [21]. In operational production environments, open questions remain about how to effectively collect, process, and integrate operational data. This must be done without compromising the integrity of delicate production processes, while also ensuring a favorable cost-benefit ratio for the integration effort. In particular, there is a lack of methods that can be scaled to entire production systems and ensure state synchronization with application-driven accuracy.

System-model alignment To ensure model actuality, methods are proposed to continuously detect and compensate for discrepancies arising from wear or changes in configuration. This ranges from algorithmic parameter tuning to automated adaptation, such as reinforcement-learning-based approaches that minimize deviations between observed and simulated behavior [22]. For structural accuracy, common pipelines reconstruct as-built geometry from laser scanning or photogrammetry [23, 24]. However, these existing methods are often heavyweight and primarily address the initial "as-built" state. A clear gap remains for practical and scalable methods that can detect and incorporate deviations occurring during production. Furthermore, approaches that focus on leveraging existing data sources, while also considering the adaptation of operational work processes, have not yet been fully exploited.

Provision of operational services DT research already offers a rich portfolio of operational applications. These

include real-time monitoring and diagnostics, logistics support, quality prediction, prognostics, and health management [3, 25]. Human-centered applications are increasingly coming into focus, especially for operator training and operational support, as exemplified by concepts such as augmented reality for maintenance tasks and training scenarios based on DTs [26, 27]. This development reflects the paradigm shift towards Industry 5.0, which strives for symbiotic human-machine collaboration [28]. To unlock the full value of simulation models beyond complex engineering tools, their simulative capabilities must be packaged for non-expert use, emphasizing lightweight deployment, explainable feedback, and human-in-the-loop workflows. Realizing this routine use requires functionally extensible architectures capable of translating complex models into accessible, practice-focused tools that emphasize lightweight deployment, explainable feedback, and human-in-the-loop workflows with clear operational benefits.

2.3 Need for action

The continued use of VC models in the operational phase of production systems presents a significant opportunity, yet its realization is hindered. Current research in this field often addresses isolated technical problems, while an overarching development methodology for practical, highly effective operational applications is not sufficiently considered. This gap is particularly evident in the lack of scalable approaches for transferring existing VC models of complex, real-world production systems—the very environments where VC promises the greatest benefits.

Although applicable architectures and procedures for realizing production system DTs exist, they predominantly assume a "top-down" implementation [3, 29, 30]. This focus creates a practical barrier, as implementing complex, general-purpose architectures from scratch is less feasible than the "bottom-up" transformation of existing, high-value engineering artifacts, such as VC models.

While technical challenges persist, this work focuses on addressing the identified methodological gap first. We posit that a bottom-up approach, deriving operational DTs from simulation models originating in VC, offers a more pragmatic pathway for industrial adoption. Rather than aiming for monolithic, top-down architectures, our approach focuses on the fundamental challenges of transforming VC models into accessible, practice-focused tools. This requires a systematic methodology that aligns application-specific requirements with scientific principles to overcome key implementation barriers.

3 Transformation method

Building on the identified need for action, we propose a VC-based DT as a logical extension of VC models towards production-supportive DTs. The core idea of the concept is to reuse validated VC models, including geometry, kinematics, behavioral logic, and control interfaces, and augment them with VC's three missing capabilities required for operational DTs: system-model alignment, integration of real system data, and provision of operational services. To systematically develop the necessary methodological and technical solutions in these areas while ensuring both scientific rigor and industrial applicability, we propose a novel transformation method. It integrates industrial requirements with state-of-the-art research insights, enabling the development of practically deployable DT solutions. This approach accelerates the implementation of DT solutions by reducing modeling effort and leveraging existing software solutions.

Our transformation method is grounded in the DSR paradigm, which provides a framework for developing scientifically founded artifacts that address real-world problems. DSR integrates innovation-oriented design with the evaluative rigor of behavioral science, yielding artifacts, such as concepts, methods, and implementations, that are both practically relevant and scientifically robust [31]. Building on Hevner's framework and the methodological phases proposed by Peffers [32], we adapt these foundations to develop methods and tools for creating VC-based DTs that leverage existing VC models.

As depicted in Fig. 2, the approach links the production environment with the knowledge base through an iterative cycle of problem identification, artifact development, evaluation, and refinement, explicitly tailored to operationalize VC models as DTs in industrial production contexts. The subsequent section details this process in six phases.

I. Problem Identification and Motivation The first phase of the transformation method focuses on identifying research problems and justifying the need for action by analyzing the practical environment. Starting from the overarching need for a methodological approach to develop practical DTs, the problem is further delineated into three deficiency areas: missing system-model alignment, insufficient integration of real system data, and the limited provision of operational services during plant operation. To motivate addressing the gaps, there follows an examination of industry practices to understand stakeholder responsibilities and to locate groups likely to benefit from a VC-based DT application. Their needs are then elicited through a qualitative protocol that combines role-focused, semi-structured interviews with cross-functional focus groups oriented

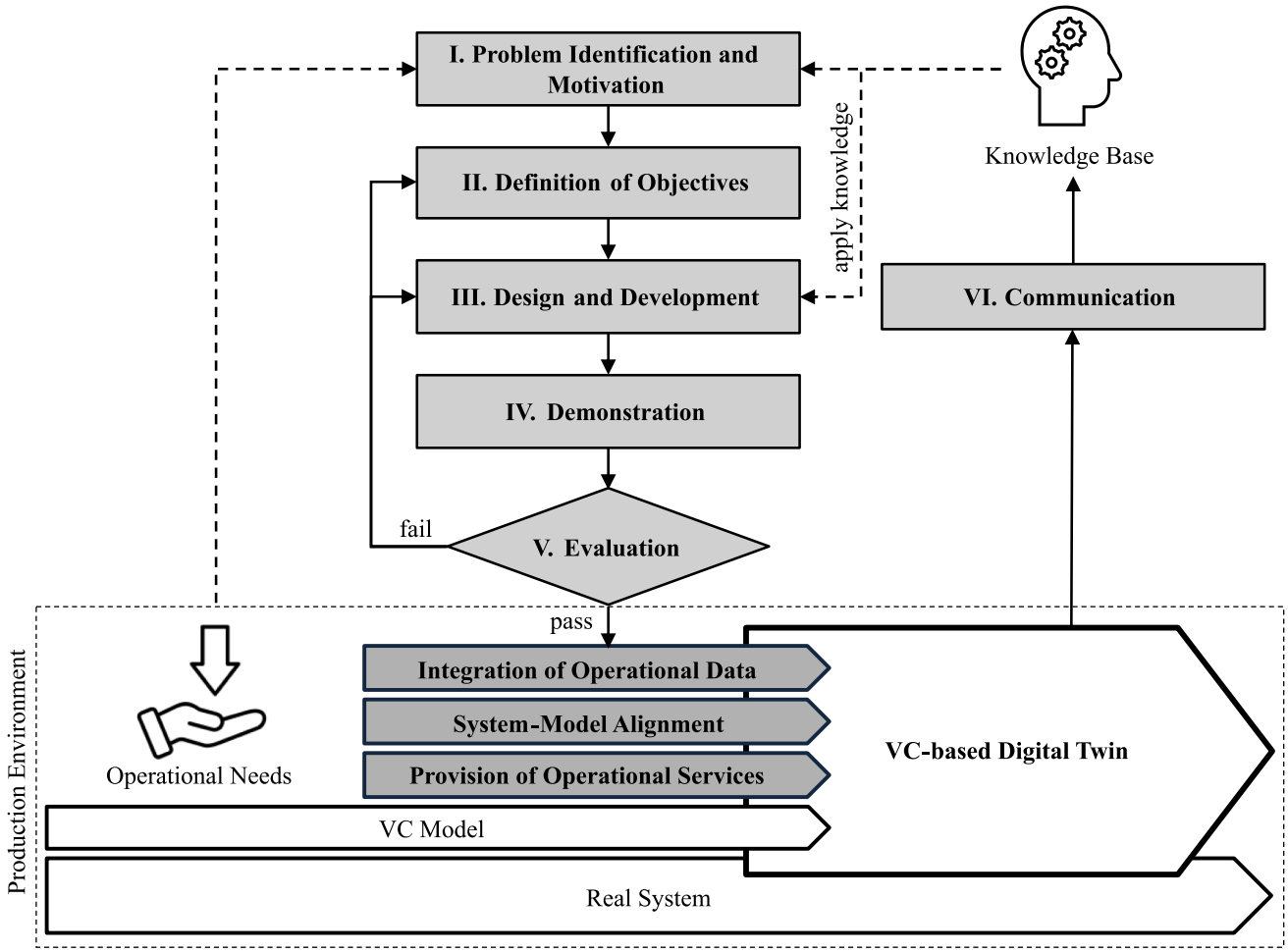


Fig. 2 Transformation method for VC-based DTs

toward open, explorative discussion. The interviews probe task-specific challenges and information flows, while the focus groups surface shared pain points, desired simulation capabilities, and candidate service scenarios across disciplinary boundaries. The phase concludes with a practice-validated needs statement.

II. Solution Objectives Based on the identified scientific challenges and industrial needs, the second phase formulates solution objectives that guide the development of VC-based DTs and derive the corresponding requirements. While the objectives articulate the intended application of the DTs, the requirements translate this vision into concrete specifications that guide artifact development. Together, they ensure that the resulting VC-based DTs are relevant and implementable in real-world production contexts. Following Hevner's DSR framework [31], the resulting requirements are categorized into the three interrelated design domains of Human, Organization, and Technology, which jointly define the socio-technical environment of artifact development:

- **Human**-centric requirements are mainly derived from discussions with stakeholders who are expected to interact directly with VC-based DTs. These requirements focus on aspects such as training relevance, ease of use, and the comprehensibility of virtual representations.
- **Organizational** requirements stem from planning, development, and management stakeholders and reflect structural and procedural factors relevant to deployment. These include role clarity, alignment with existing workflows, and process ownership.
- **Technology** requirements are developed in collaboration with domain experts in modeling and control systems. They relate to technical feasibility, including integration into system landscapes, infrastructure readiness, and the accuracy and connectivity of simulation models with the real system.

III. Design and Development In the third phase, artifacts are designed and developed to meet the previously defined objectives and requirements, drawing on applicable scientific knowledge to inform and support the design process, as illustrated in Fig. 2. In the context of VC-based DTs, this is achieved through methods, functional extensions, or other technical solutions that address the missing capabilities required for operational DTs. Each artifact is conceived and developed to satisfy a distinct subset of requirements while remaining interoperable within the VC-based DT. This modular structure enables incremental build–evaluate cycles in line with DSR principles, while also ensuring scalability across diverse industrial applications. This translates into artifacts such as model plug-ins for operation-parallel data acquisition, methods for geometrical change detection, and functional extensions for operational services.

IV. Demonstration In this phase, the developed artifacts are instantiated and applied within a representative industrial context to demonstrate their utility in solving the identified problem. For VC-based DTs, this entails deploying the prototypical system in a production-near setting that reflects real operational constraints. By showing how these artifacts interact within the socio-technical environment, the demonstration provides evidence of practical applicability and establishes a foundation for the subsequent evaluation phase.

V. Evaluation The evaluation phase builds upon the demonstration by systematically assessing whether the developed artifacts satisfy the objectives and requirements. To ensure both formal compliance and practical relevance, the implemented services are verified against the specified requirements and validated with respect to their objective and operational utility in the production environment. Evaluation combines quantitative performance indicators with qualitative expert feedback to determine applicability, robustness, and user acceptance of the VC-based DT. Insights from this phase feed directly into iterative refinement cycles, allowing continuous improvement of the artifacts, adjustment of design choices, or adaptation of solution objectives where necessary, as illustrated in Fig. 2.

VI. Communication The final phase ensures effective communication of research outcomes to academic and industrial audiences. This includes disseminating the developed artifacts and evaluation results to support understanding, applicability, and broader adoption. As illustrated in Fig. 2, this addition to the knowledge completes the cycle between the production environment and the knowledge base.

4 Results

This chapter presents the results obtained by applying the proposed transformation method, with a focus on the practical realization of VC-based DTs that provide direct support during the operational phase of automated production systems. It begins with the outcomes of Phase I, Problem Identification, highlighting in Section 4.1 the key stakeholder roles and their associated operational tasks. Based on the identified support needs, Section 4.2 derives objectives and requirements in accordance with Phase II, resulting in five representative use cases of VC-based DTs. To demonstrate the method's applicability further, Section 4.3 examines the exemplary execution of one design cycle for a selected use case in greater detail, covering the transformation steps from design to evaluation (Phases III-V).

4.1 Problem identification

To address Phase I of the proposed transformation method, this section presents the results of implementing a structured approach to identify key stakeholders and their needs. The problem identification process began with an analysis of industry practices and expert insights, spanning management, development, planning, and shop floor levels. This top-down perspective helped determine where support potential exists and which stakeholders are most likely to benefit from a VC-based DT. Based on this screening, we conducted role-focused interviews and subsequently prioritized shop floor stakeholders, as they hold direct operational responsibility, face time-critical decisions, and experience the immediate consequences of tool limitations.

As a result, four central roles emerged as particularly relevant for the practical deployment of VC-based DTs:

- **Production Operator:** Responsible for ensuring the continuous operation of the production system, reporting any anomalies or faults, and performing basic maintenance and troubleshooting tasks.
- **Maintenance Technician:** Tasked with the upkeep of equipment, performing maintenance, and resolving mechanical or electrical issues to minimize downtime.
- **Control Engineer:** Focuses on diagnosing control software problems, implementing updates, and optimizing system behavior to enhance performance.
- **Quality Engineer:** Ensures product quality by monitoring production processes, analyzing quality data, and initiating corrective actions when necessary.

Building on this foundation, interdisciplinary workshops were held with the identified stakeholder groups at multiple international production sites to capture a broad spectrum of operational procedures. To establish a common basis for discussion, VC and DT concepts were first introduced through demonstrations of site-specific VC models and detailed walkthroughs accompanied by modeling experts. The workshops followed a semi-structured format that combined guided discussions, open exploration, and role-specific reflection. Stakeholder needs were elicited by systematically analyzing task-related challenges, decision-making processes, and recurrent tool limitations. This approach enabled the identification of both routine operational requirements and exceptional scenarios where existing practices exhibit significant shortcomings. The collected insights were iteratively consolidated and validated across stakeholder groups, resulting in distinct areas of need. These areas were subsequently positioned within the commissioning and operational phases of the production system life cycle, thereby highlighting when and under which conditions simulation-based support can create the greatest value.

Table 1 provides an overview of these needs by mapping them to the corresponding stakeholder roles and life cycle phases. In the following section, these needs are examined in detail, forming the basis for the definition of objectives and the derivation of targeted use cases.

4.2 Use case definition

In this section, the previously identified needs are examined in greater detail to ensure a clear understanding of the underlying challenges. Based on this analysis, objectives are derived that translate stakeholder needs into application-oriented and practical use cases. Executing Phase II of the proposed method objectives, core requirements are formulated that guide the development of methods and technical solutions. The requirements specifically address the shortcomings of VC models and define the conditions under which they can be transformed into operational DTs.

To achieve this, a structured use-case analysis was applied. A goal concept was derived jointly with stakeholders by translating the identified needs into application-oriented objectives. Based on this foundation, functional requirements were elicited through user stories and supported by mock-up representations. These mock-ups served as boundary objects to capture requirements from the user perspective and to structure them across three dimensions: human, organizational, and technical. This procedure ensured that the problem definition not only reflects industrial practice but also specifies how a future system is expected to be used and which functionalities are required to enable this use.

Table 1 Stakeholders and Associated Support Needs

Stakeholder	Support needs	Phase
Production Operator	•Shop Floor Training	Commissioning
Maintenance Technician	•Shop Floor Training •Fault Reconstruction	
Control Engineer	•Fault Reconstruction •Software Optimization •Collision Avoidance	Operation
Quality Engineer	•Quality Monitoring	

4.2.1 Shop floor training

In highly automated and complex production environments, there is a consistent need for effective training opportunities, particularly for production operators and maintenance technicians who must operate and support the systems reliably under dynamic and fault-prone conditions. This demand is particularly critical in greenfield projects, where entire operating teams must be prepared within tight timelines before production starts. During these phases, production systems are often unavailable for training because of assembly and commissioning activities, and they may not yet include all final functionalities. Once production begins, the use of real systems for training becomes severely constrained. Operational equipment cannot be paused without disrupting productivity, and safety-critical scenarios, such as malfunctions or emergency procedures, must not be intentionally triggered. This is particularly limiting for maintenance technicians, who depend on realistic fault conditions to build diagnostic expertise. Moreover, training workpieces are often unavailable in the variety needed for comprehensive training. Even during scheduled production downtimes, the time available for training remains very limited. As a result, traditional training methods often remain theoretical or rely mainly on learning through practical experience during actual operations. Neither approach is satisfactory, nor do they contribute to an attractive and safe working environment for new operators.

Objectives The objective of the VC-based DT for shop floor training is to establish a flexible, production-independent simulation environment that facilitates skills development for production operators and maintenance technicians. It is intended to enable effective hands-on training by visualizing machine structures, simulating system behavior, and supporting realistic interaction with the control system. Leveraging the high control level fidelity of VC models, the DT aims to create a virtual environment where operational tasks, such as system operation, fault handling, and maintenance, can be practiced. This approach is intended to allow shop floor employees to acquire the necessary competencies

safely, efficiently, and independently of system or hardware availability, starting immediately after software validation and before actual commissioning. In addition, the VC-based DT is envisioned not only as a training platform but also as a long-term knowledge carrier bridging the transition from engineering to operation.

For production operators, the VC-based DT aims to support early familiarization with system layout, workflows, and process behavior. It should enable the practice of key operational tasks, such as interacting with control interfaces, performing manual changeovers, and responding to component faults, within a realistic virtual environment.

For maintenance technicians, the VC-based DT aims to provide a realistic environment to train the handling of machine errors, including rare or safety-critical faults that cannot be recreated on physical systems. This enables the development of diagnostic and troubleshooting skills by using established diagnostic tools and procedures. In addition, the early provision of training environments allows early access to control logic as well as mechanical and electrical planning data, which promotes an in-depth understanding of the system even before the actual commissioning.

Requirements To realize the outlined training objectives, the following requirements must be met across the human-centric, organizational, and technical design dimensions.

From a human-centric perspective, the VC-based DT must feature intuitive interfaces, immersive visualization, and easy-to-configure simulation environments, enabling users to focus on mastering the complexity of the production system. To maximize acceptance and support self-directed learning, the DT should offer scalable training scenarios that accommodate different skill levels. Guided exercises, repeatable checkpoints, and feedback mechanisms help users build confidence and learn from mistakes.

On an organizational level, using a VC-based DT for training requires seamless integration into existing operational workflows and defined processes for knowledge transfer from engineering to operation. Simulation-based training should be systematically scheduled and supported by proper infrastructure, necessary training equipment, and qualified trainers. To ensure consistent and scalable qualification across sites, the reuse of standardized training setups should be enabled. In addition, clear responsibilities for maintaining the DT, updating training content, and managing user access are essential to ensure long-term operability.

The technical requirements of the VC-based DT focus on replicating realistic operating conditions. This includes integrating actual control elements, support for various operating modes, and the simulation of complex fault scenarios. The DT must accurately represent the system's current functions and incorporate the latest control software to enable effective training. Also, to ensure long-term applicability, mechanisms for deviation detection and tools for efficient model updating are required to maintain alignment with the real system. In addition, the VC-based DT for training should incorporate real production situations to keep training content relevant throughout the system's life cycle.

The setup shown in Fig. 3 exemplifies a training environment tailored to meet both human-centered and technical design criteria.

4.2.2 Fault reconstruction

In fast-paced and highly automated production environments, maintenance technicians and control engineers often face constraints when analyzing system faults. Technicians are typically under pressure to restore system availability as quickly as possible, leaving little room for thorough fault diagnosis. As a result, errors, particularly those caused by incorrect operations, higher-level control logic, or flaws in automation sequences, are often addressed by quick fixing and resetting the system, while the root causes remain unidentified. This limits the ability of control engineers to adapt or improve control software and prevent recurrence. This issue is particularly significant for rare, sequence-dependent faults that only arise under specific boundary conditions during live production, which are distinct from issues typically caught during pre-production VC tests. Conventional methods in the operational phase, such as signal tracing or manual inspection of control sequences, are time-consuming and often result in overwhelming data in complex systems. Also, inaccessible system areas or secondary control systems usually hinder fault diagnosis. Consequently, essential diagnostic information, such as the precise sequence of material flow, sensor activation, and actuator states, is often unavailable in a comprehensive and easily digestible format.

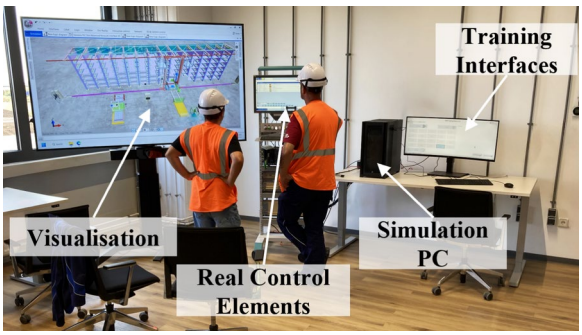


Fig. 3 VC-based DT Setup for Shop Floor Training

Objectives The goal of the VC-based DT for fault reconstruction is to provide a dedicated environment for retrospective analysis of recorded operational events, including logic-related faults and process deviations, decoupled from live production. It aims to enable systematic, time-resolved investigation of specific occurrences by virtually recreating the system conditions based on captured operational data. This allows the DT to serve as a practical diagnostic tool for maintenance technicians and control engineers, enhancing understanding of complex behaviors, supporting targeted maintenance, and enabling robust control logic modifications. Beyond pure fault diagnosis, this detailed virtual replay facilitates the identification of performance bottlenecks or suboptimal sequences by enabling visual exploration and comparison against nominal behavior derived from the model or previous recordings, thus supporting continuous process improvement efforts. To enable production-independent and reliable fault analysis, relevant operational data such as signal values, control states, and higher-level process information must be recorded continuously in a synchronized manner. The VC-based DT must then accurately reproduce these recorded sequences, allowing the tracing of system progression, material flow, and complementary information states within the virtual environment. Discrepancies between the model and the real system must be accounted for to reconstruct reliable system states. Verified system states, such as a confirmed workpiece position within a sensor's detection range, should be distinguishable from inferred states, such as workpiece position outside the sensor's observable area.

Requirements Achieving effective fault reconstruction with a VC-based DT requires the fulfillment of essential requirements:

From a human-centric perspective, the VC-based DT must offer intuitive mechanisms for transforming heterogeneous data from multiple sources into a coherent and structured representation. This requires a form of data processing and visualization that enables control engineers and maintenance technicians to explore system behavior without the need for in-depth simulation or data analysis expertise. At the same time, the platform must support sufficient analytical depth to allow focused inspection of specific system areas when required.

On an organizational level, data management and model maintenance responsibilities must be clearly assigned. To enable efficient data recording and effective integration of the DT into diagnostic workflows, efforts should focus on critical bottleneck systems, well-defined data scopes, and structured data storage and retrieval mechanisms. In addition, maintaining the model's actuality further requires dedicated training measures and standardized processes.

From a technical standpoint, the VC-based DT must provide a temporally precise and logically consistent reconstruction of system states based on recorded operational data. This requires the synchronized recording of selected control signals across relevant subsystems, with data being buffered cyclically and selectively persisted upon fault detection to reduce storage overhead. To facilitate accurate post-event analysis, reintegration of recorded data into the VC model must allow for temporal alignment and support interactive control features such as pausing and stepping through sequences. Minor deviations between the virtual and physical systems must be tolerated without compromising analytical validity, while larger discrepancies necessitate dedicated tools for model adaptation.

4.2.3 Collision avoidance

The increasing demand for individualized products requires more adaptable and flexible production systems. To achieve this, control systems must also exhibit a high degree of adaptability, enabling the rapid or even automated generation or adaptation of control software and parameters. However, this increased flexibility introduces potential risks, particularly system faults that may not be detected before the operational phase. One of the most critical challenges for control engineers in this context is collision detection and avoidance, which involves identifying and mitigating potential collisions before they occur to ensure safe and efficient operations.

Objectives The VC-based DT for collision avoidance aims to establish a predictive, simulation-based solution for real-time collision detection and prevention in the operational phase for automated production systems. By integrating a VC-based DT into the production system, a VC model that is directly linked to the real control system can be used to monitor and predict potential collisions. Through this real-time coupling, the DT can accurately predict and visualize impending collisions, enabling preemptive interventions to avoid operational disruptions or safety hazards.

Control engineers can leverage this technology to optimize system performance while simultaneously ensuring safety. The ability to simulate and visualize potential collision scenarios in real-time allows technicians to make adjustments to the system's parameters without the need for physical trials, reducing downtime and minimizing risks. Furthermore, the use of predictive algorithms within

the VC-based DT enhances its capability to detect collisions with high accuracy, even in dynamically changing environments.

Requirements Realizing the potential of VC-based DT solutions for collision avoidance necessitates addressing specific requirements.

From a human-centric perspective, providing an intuitive and interactive visualization of collision scenarios is vital for effective decision-making. Such visualizations improve situational awareness, enabling faster and more accurate decisions, and ultimately enhancing safety and efficiency in the manufacturing process.

On an organizational level, integrating VC-based DT solutions into existing safety concepts is crucial to ensure seamless integration while maintaining compliance with established industry standards. Safety regulations such as ISO 13849, which governs the safety-related parts of control systems, must be adhered to in order to guarantee that automated collision avoidance mechanisms do not introduce unforeseen risks.

From a technical level, real-time communication between the VC-based DT and the physical system is essential to ensure immediate response to potential threats. High-resolution simulation models must be developed to provide an accurate geometric representation of the production system, allowing for precise collision detection and predictive collision avoidance. Motion prediction is necessary to recognize imminent collisions before they occur and, therefore, realize the predictive collision avoidance. Depending on the application focus, especially stringent model accuracy and synchronization between virtual and real environments may be required.

4.2.4 Quality monitoring

Ensuring high product quality is a critical objective in manufacturing, particularly in flexible and automated production environments. Traditional quality assurance methods often rely on periodic inspections and post-production testing, which may fail to detect defects during production. This reactive approach can lead to increased rework, production inefficiencies, and higher costs. Quality engineers need a transformative solution for continuous quality monitoring by synchronizing real-time production data with high-fidelity simulation and process models.

Objectives The VC-based DT for quality monitoring aims to provide a proactive, real-time quality assurance solution by integrating high-fidelity VC models directly into the production process. By integrating VC-based DTs into manufacturing systems, companies can transition from traditional quality control methods to an online and proactive framework. A DT acts as a real-time virtual replica of the production process, continuously updated with real-time control data. This enables manufacturers to compare actual production conditions with expected outcomes, detect deviations early, and take corrective actions before defects impact product quality. The ability to predict and mitigate quality issues before they escalate enhances overall process reliability and efficiency.

The implementation of VC-based DTs for quality monitoring benefits multiple stakeholders within a manufacturing environment. Quality engineers, for instance, can utilize DTs to monitor system performance in real-time, ensuring compliance with industry quality standards while also enabling in-depth root cause analysis of detected issues. Meanwhile, production operators can leverage insights provided by the DT to make immediate adjustments to production parameters, preventing defects before they occur and optimizing overall process stability. By offering these advantages, VC-based DTs foster a more adaptive and data-driven approach to quality assurance.

Requirements For successful deployment, several technical, organizational, and human-centric requirements must be met.

From a human-centric level, the successful implementation of VC-based DTs for quality monitoring requires intuitive and actionable data visualization. Customizable dashboards should be developed to present real-time insights tailored to different stakeholders, ensuring that the information is accessible and easy to interpret. Furthermore, optimization strategies based on predictive analytics can help manufacturers enhance product consistency and reduce material waste. Additionally, fault transparency mechanisms should be incorporated, enabling quick identification and resolution of quality issues, thereby minimizing downtime and improving production efficiency.

At an organizational level, it is crucial to integrate VC-based DT solutions into existing quality assurance workflows to ensure that predictive insights are effectively utilized. Compliance with industry standards, such as ISO 9001 for quality management and traceability, must also be maintained to guarantee that DT-driven quality monitoring aligns with established best practices. Ensuring smooth adoption within an organization requires clear guidelines and training programs for employees to fully leverage the technology.

From a technical perspective, real-time state synchronization between DTs and physical production systems is

essential to ensure accurate and timely quality assessment. High-precision simulation models must be developed to enable detailed comparisons between expected and actual production outcomes. Additionally, advanced online quality comparison methods, powered by artificial intelligence and machine learning, can be integrated to enhance defect detection and classification.

4.2.5 Software optimization

In the operational phase of automated production systems, control software must undergo continuous refinement to accommodate evolving process requirements, system modifications, and productivity goals. These modifications are typically carried out during scheduled downtimes, where control engineers operate under significant time constraints and with limited opportunities for system-level testing. Existing software testing methods often depend on test benches requiring substantial software changes to work with a few hardware components. Conventional testing approaches usually rely on simplified test benches that require intrusive software adjustments and only represent partial system functionality. Such environments fail to capture the complexity and variability of real-world production processes, limiting their ability to accurately predict the effects of software changes. Furthermore, systematic methods for validating the effectiveness of control logic modifications before deployment are largely lacking. Existing tools focus mainly on syntactic or semantic code comparisons and provide little insight into process-relevant performance indicators such as cycle times, throughput, or buffer utilization. Consequently, engineers are often forced to rely on live system testing to evaluate improvements, introducing the risk of costly faults, unintended behavior, or productivity losses.

Objectives The VC-based DT for software optimization aims to provide a high-fidelity, production-parallel simulation environment that enables both the identification of optimization potential and the validation of control software modifications. Unlike traditional VC approaches focused primarily on functional verification, this DT integrates process-oriented performance analysis as a core element of the optimization workflow. Parallel to live production, control engineers can simulate realistic production scenarios to systematically detect performance bottlenecks, inefficiencies, or undesired system behaviors. These insights allow alternative control strategies or parameter configurations to be implemented and tested in a risk-free environment. The DT must continuously capture and visualize key performance indicators, such as cycle times, buffer utilization, energy consumption, and bottleneck frequencies, to facilitate direct comparisons between different software versions. These metrics serve not only as a basis for performance analysis but also to verify that implemented changes lead to measurable performance improvements. By tightly coupling simulation, analysis, and software adaptation, the VC-based DT enables data-driven decision-making and significantly reduces the risk of adverse effects during live deployment.

Requirements The practical realization of a VC-based DT for software optimization entails addressing several essential requirements:

From a human-centric perspective, the DT must offer intuitive interaction and visualization tools that make complex performance relationships accessible and actionable. The system should automatically capture, aggregate, and present key performance indicators in a clear, goal-oriented format. These visualizations must highlight deviations across different software versions and support comparative evaluations, enabling control engineers to trace optimization effects without requiring in-depth data analysis expertise.

Organizational requirements include clearly defined responsibilities and dedicated resources for model maintenance, updating, and continuous alignment with the real system throughout its life cycle. A dedicated organizational unit should oversee VC model versioning, accuracy, and ensure adequate personnel and infrastructure resources for ongoing simulation-based testing and analysis.

From a technical standpoint, the DT must align strictly with the physical system to allow valid and reproducible validation of software optimizations. The control code must be executed within the VC-based DT without modification while reproducing the same system behavior and process performance as in the real environment. To achieve this, the model must be continuously updated based on systematically acquired plant data, including geometric layouts, control structures, and parametric configurations. Depending on the optimization objective, deeper parameterization of process models may be required to adequately reflect relevant system dynamics. Furthermore, the simulation must replicate all relevant external influences, including supervisory and interconnected control systems, to provide a realistic and representative test environment.

4.3 Exemplary design cycle

Building on the objectives and requirements for practical use cases defined in the previous section, this section details a practical case study for a representative scenario: online collision avoidance. This use case was deliberately selected for its advanced state of development. While the technical concepts underpinning this scenario, such as perception, risk assessment, and real-time decision-making, have

been published in detail [5, 33, 34], this section provides a methodological overview. This case study serves to illustrate how one complete design cycle, comprising Phases III (Design and Development), IV (Demonstration), and V (Evaluation), is applied to convert a VC model into a VC-based DT. This implementation represents the first development cycle within our transformation method, focusing primarily on establishing technical feasibility.

Design and development Online collision avoidance is utilized during the operational phase to continuously monitor and prevent potential collisions in automated production systems. Such collisions may occur in flexible production environments, particularly when manual teaching is required due to changes in the production setup. Additionally, robot paths generated from CNC programs can result in different path strategies with varying motion ranges. These variations may result in potential collisions, which an online collision avoidance system can effectively mitigate. Existing solutions are complex to configure and do not seamlessly integrate into the life cycle of a production system. Therefore, the utilization of a VC-based DT can prove advantageous. To enable this, VC models must be transformed into a VC-based DT. This transition is realized by developing targeted socio-technical artifacts designed to address the identified gaps of the VC model, guided by the previously derived requirements.

The solution for Data Integration is realized via the architecture shown in Fig. 4. The VC-based DT remains connected to the real programmable logic controller (PLC) (2) and receives the same signal data as its physical counterpart over the fieldbus driver (1). This necessitates real-time integration on the control level, ensuring seamless interaction between the simulation model and the real-world system. As the VC-based DT can directly interface with the control system, it enables autonomous operation to stop in the event of a predicted collision (3). Thought co-execution state synchronization between the control system and the VC model is inherently ensured, as the simulation model is executed using the same solver as the machine control. This eliminates the need for any additional synchronization mechanisms, since both systems operate with a shared time base and identical motion calculation logic.

Online collision avoidance requires the VC-based DT to have a high model accuracy, especially in relation to the geometric representation. In order to achieve accurate System-Model Alignment, a manual approach had to be chosen to transfer real measurements into the model and check their accuracy. In the future, however, an approach similar to that of Braun et al. would be possible, based on sensor fusion of operating data and transponder-based workpiece localization [35].

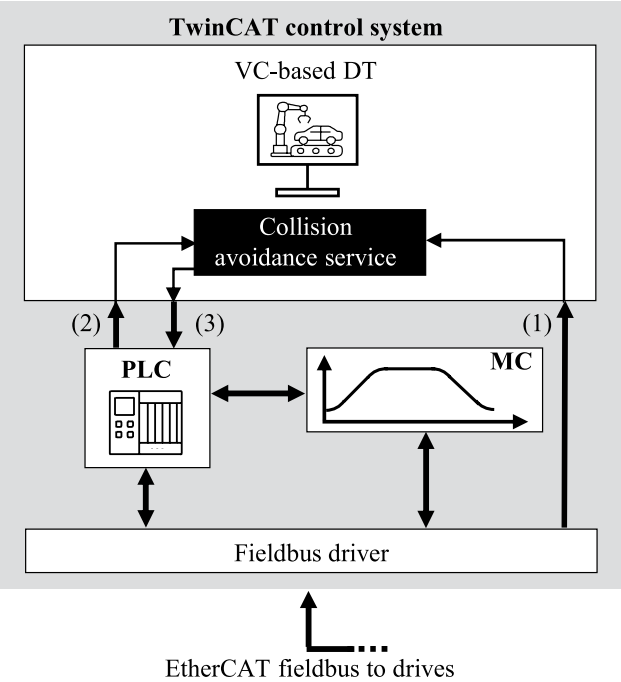


Fig. 4 Abstract representation of the architecture of the online collision avoidance service. Based on [5]

The service of prediction avoidance requires a movement prediction. This capability provides the basis for the solution to Service Provision, which extends beyond the VC model's original purpose. The ability to predict potential collisions is realized with the help of a feature of the open control system by TwinCAT from Beckhoff. By leveraging the lookahead of the motion control (MC), which calculates upcoming movement positions, the VC-based DT can anticipate future collisions in advance (see Fig. 5. This predictive capability is facilitated by the real-time connectivity of VC models.

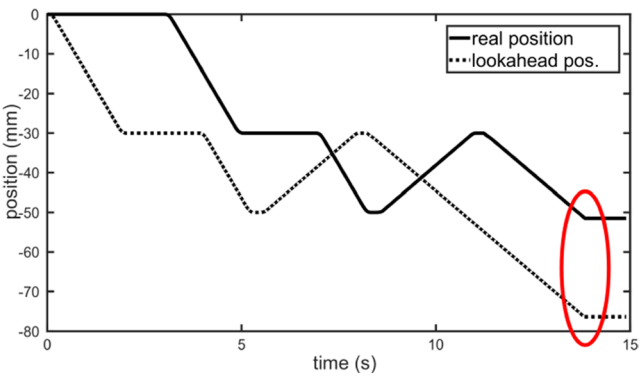


Fig. 5 Illustration of the lookahead feature in a MC

Demonstration The solution is implemented within the ARENA2036 research campus, utilizing three Stäubli robots. These robots are controlled with the mentioned open TwinCAT control system from Beckhoff. The control system is directly interfaced with the robots via the uniVAL interface, enabling real-time communication over EtherCAT. On the simulation side, ISG-virtuos is employed as VC software, facilitating real-time connectivity with the control systems. Within the VC-based DT, collision detection is integrated, utilizing various types of geometric bounding volumes for detection. The relative positions of each robot and its surrounding workspace are continuously evaluated by computing incremental positional changes (Δpos). When the accumulated positional deviation between two volumes converges toward zero, a potential collision is inferred (see Fig. 6). Upon detecting a collision between these volumes, the control system immediately stops the robot's movements.

The physical demonstrator is depicted in Fig. 7, with the simulation environment visualized in the background. Within the simulation, the predicted movements from the lookahead are visualized as translucent.

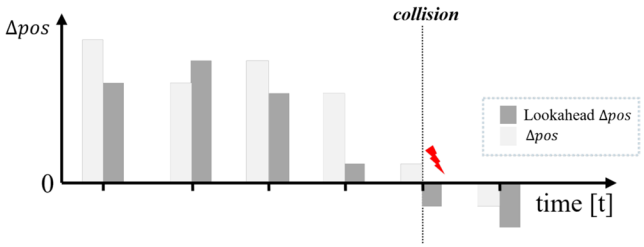


Fig. 6 Representation of the collision detection through distance calculation using the lookahead feature

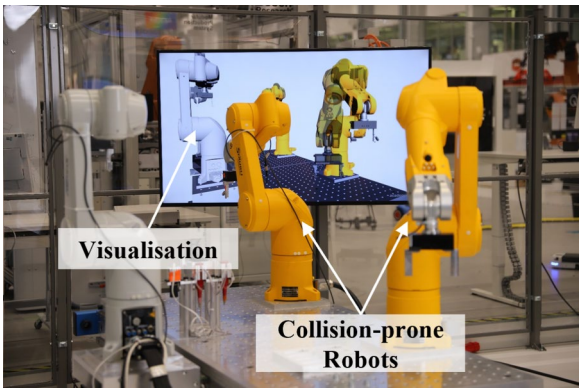


Fig. 7 Demonstrator of the online simulation for collision avoidance using a VC-based DT: simulation and predicted movements (translucent) on the TV in the background

Evaluation The evaluation of the VC-based DT was conducted by deliberately inducing potential collisions during the robot's motion sequences. The objective was to assess the system's effectiveness in predictive collision avoidance under realistic operational conditions.

From a technical perspective, the results are promising: collisions were detected before any physical contact occurred, allowing the robot to halt its motion preemptively. This confirms the system's capability for real-time communication with the real control system and its accuracy in motion prediction. For future work, using high-resolution simulation models would enable more precise geometric mapping, which would significantly contribute to successful online collision detection and prevention.

From a human-centered perspective, the system provides an interactive visualization of potential collisions, enhancing situational awareness. This feature supports production operators in making informed decisions, thereby improving both safety and efficiency within the production environment. For future situational awareness, it is essential to evaluate whether operators trust and rely on the system. Users must feel confident that the system provides accurate, timely, and actionable warnings. Assessing this aspect of human–machine interaction requires clarifying the transparency of the system's underlying processes, ensuring that operators understand why and how alerts are generated. Additionally, it is crucial to strike an appropriate balance between necessary intervention and over-automation, as excessive automated control can lead to disengagement or complacency, thereby reducing the operator's situational awareness and overall effectiveness. Evaluating these factors allows designers to optimize the system's support for human decision-making while maintaining safety and engagement in the production environment.

On the organizational level, the system is designed for seamless integration into existing safety protocols. Compliance with relevant standards, particularly ISO 13849 for safety-related control systems, must be considered in future work to ensure that no additional risks are introduced. Beyond technical compliance, organizational factors such as staff training, clear operating procedures, and defined responsibilities for monitoring and responding to system alerts are essential. Embedding the system within the broader safety culture of the organization not only ensures regulatory adherence but also promotes consistent usage, trust among operators, and continuous improvement of safety practices. Evaluating these factors in real-world operational settings will be critical to understanding how organizational structures, policies, and human factors interact with the technological capabilities of the collision detection system.

Overall, the evaluation of this first development cycle shows that the defined requirements across the technical, human-centered, and organizational dimensions are partly met. The VC-based DT thus fulfills the key goal of enabling predictive, real-time collision avoidance during operation. These non-fulfilled requirements, particularly in the human and organizational domains, must be explicitly addressed in a subsequent development cycle. A thorough evaluation of human and organizational perspectives is essential to validate and enable the effective deployment of this use case in an industrial production system. This includes assessing operator trust, cognitive workload, and interaction efficiency, as well as examining how the system can be integrated into existing safety protocols, workflows, and organizational structures.

5 Discussion and outlook

This section discusses the proposed six-phase transformation method based on the results presented in Section 4. The applicability of the transformation method is demonstrated by its successful execution for a complex, industrially relevant use case. As detailed in 4.3, a complete design cycle (Phases III-V) was performed to develop and evaluate the first viable artifact for a VC-based DT for online collision avoidance. This demonstrates the method's capability to guide the development of a technically feasible artifact that addresses a specific operational need.

5.1 Cost-benefit analysis

In the production industry, cost is the most important factor in deciding whether a method or use case is implemented or not. For this reason, we use a qualitative cost-benefit analysis as an additional instrument to discuss the pragmatic value and economic viability of the method, particularly its strength in leveraging existing VC models for operational use. The evaluation of VC-based DTs requires a balanced consideration of costs and benefits. While costs can be qualitatively estimated with reasonable accuracy, the benefits are far more context-dependent and vary strongly with the specific implementation and operational environment. The primary cost drivers for VC-based DTs are personnel effort and the necessary technical resources, whose magnitude varies depending on the specific application. Their influence within a given scenario significantly affects the overall utility of the use case, depending on the extent to which the associated costs constrain its feasibility. To enhance comparability, we categorize costs into three distinct groups that collectively capture both human and technical factors, considering the absolute magnitude and duration of the required resources.

- Low costs: only minor model adjustments are required; operation remains offline and time-limited; no permanent data integration is necessary; model actuality is optional; personnel effort is minimal and time-limited.
- Moderate costs: the model is used offline with periodic data updates; moderate actuality is required; limited interface or visualization extensions are added; user training and preparation are necessary but limited.
- High costs: the model runs online and continuously; permanent data acquisition and synchronization are required; systematic alignment with the real system and increased geometric and behavioral fidelity must be maintained.

The benefits of VC-based DTs, in contrast, are more difficult to categorize, as they depend heavily on the specific production environment, operational constraints, and organizational context and targets. The previous section provides a detailed account of the relative advantages our use cases offer in terms of gains in efficiency, output, or quality. Building on this foundation, the following analysis qualitatively evaluates these benefits in relation to their associated costs.

Figure 8 provides a qualitative overview of the five use cases, considering two variants: one based on VC models and another involving the creation of use cases from scratch. The use cases are enumerated and color-coded: blue indicates instances in which VC was integrated into the process and a corresponding VC model is available, whereas black denotes cases in which the required models were generated exclusively for the respective use case. The figure shows that

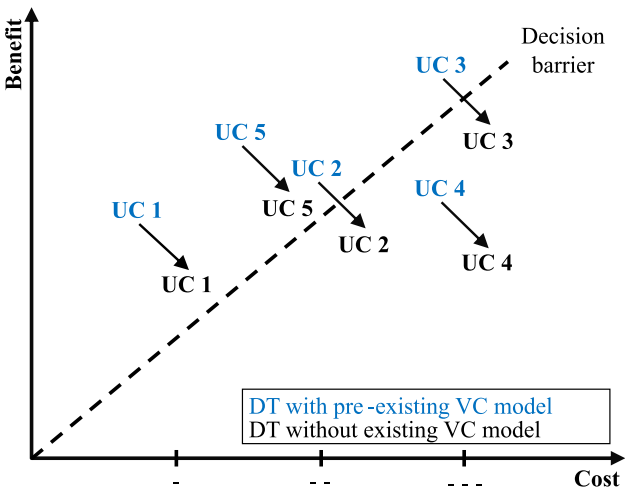


Fig. 8 Qualitative cost benefit analysis for the identified use cases with (blue) and without (black) existing VC models

without a VC to build on, the benefits are diminished and the costs are increased. We argue this is because models created 'from scratch' (black) incur significant reverse-engineering costs, are available much later in the lifecycle, and often lack the validated behavioral fidelity of their VC counterparts, which are based on original, validated engineering data.

Looking at the use cases one by one, shop floor training (UC 1) is the cheapest in comparison. It is restricted to a limited time and as such requires limited resources. Collision avoidance (UC 3) and quality monitoring (UC 4) are most likely going to be the most expensive ones in any scenario, seeing as they are not limited to a small time window, but are constantly requiring hardware and people. With UC 3 being the most expensive and most beneficial one, it was presented in greater detail in Section 4.3. Software optimization (UC 5) can be fairly inexpensive, depending on how frequently and how intensively it is being done. In general, this represents one of the less cost-intensive options, as the model is already available and can be operated offline, requiring only limited personnel effort and certainly not continuous, around-the-clock operation. Finally, fault reconstruction (UC 2) occupies an intermediate position. It necessitates a model that operates for the majority of the time, if not continuously, while the demand for human resources is restricted to the instances in which faults actually occur.

This cost reduction is a critical factor that moves the use case across the "decision barrier", making it economically viable. This shows that the transformation method is not only applicable but also valuable, as it provides a pathway for realizing high-impact operational DTs that might otherwise be cost-prohibitive to develop from scratch.

5.2 Summary

We present Table 2 for a comprehensive use case overview with their objectives, requirements, and associated costs and benefits. It serves as a decision-making reference for prioritizing future development by summarizing the identified use cases, their objectives, and their essential requirements.

5.3 Outlook

The applicability and value of the transformation method have been successfully demonstrated. All five use cases were systematically processed through the problem identification and objective-setting phases (I-II), while the full design cycle (Phases III-V) was exemplarily applied to one use case. By communicating these findings, this paper fulfills the final step of the method (Phase VI). This initial validation provides a robust foundation and defines the scope for future work. The agenda for future research is thus clearly informed. A primary goal is to apply the methods design cycle to the other four identified use cases, moving both deeper into the specific human and organizational factors of each, and broader across the application portfolio. Furthermore, the qualitative cost-benefit analysis, which provided the strategic rationale for this work, can be extended through quantitative case studies to precisely measure the economic impact of this transformation. Wherever future work decides to go, it can start here and then either go deeper or broader with the proposed use cases.

Table 2 Use Cases, Objectives, and Key Requirements (human, organizational, technical) for VC-based DTs with their qualitative costs and benefits ranging from small (−/+) to large (−−−/+++)

Use Case	Objectives	Key Requirements (h/o/t)	Cost&Benefit
Shop Floor Training	Realistic, flexible training decoupled from live systems	Intuitive interfaces, scalable scenarios, guided tasks/ Structured knowledge transfer, standardized training setup/ Integration of realistic controls, fault simulation	human cost: - technical cost: - benefit: ++
Fault Reconstruction	Retrospective diagnosis and root-cause analysis	Clear visualization, intuitive timeline replay/ Defined recording procedures, structured data access/ Time-consistent playback, moderate model actuality	human cost:−− technical cost:− − benefit: ++
Collision Avoidance	Predict and prevent collisions during runtime	Real-time feedback, minimal interaction/ Safety integration into the control/ Motion prediction, real-time sync, geometry fidelity	human cost:− − − technical cost:− − − benefit: +++
Quality Monitoring	Detect deviations during runtime, prevent scrap	Dashboards, alerts, process transparency/ QA integration, ISO 9001 compliance/ Real-time comparison, high-precision simulation	human cost:− − − technical cost:− − − benefit: ++
Software Optimization	Evaluation and validation of control software changes	KPI-oriented analysis, comparative visualization/ Dedicated resources, model lifecycle management/ High model actuality, accurate representation of influences	human cost: - technical cost:− − benefit: ++

6 Conclusion

This paper set out to answer the question of how existing VC models can be transformed into operational DTs that deliver direct shop floor support. Rather than pursuing greenfield DT development, we propose a bottom-up transformation that addresses the fundamental shortcomings of VC models by developing solutions for three DT-enabling capabilities: model alignment, integration of real system data, and provision of operational services. We contributed a DSR-inspired transformation method to systematically develop the necessary methodological and technical solutions in these areas. The method establishes actionable objectives, verifiable requirements, and structures an iterative development process, providing a pathway for the practical implementation of VC-based DTs. As initial validation, we identified five practical use cases grounded in industrial needs: shop floor training, fault reconstruction, quality monitoring, collision avoidance, and software optimization. For each use case, we specify targeted objectives and derive key requirements. Applicability of our method is further demonstrated through an elaboration of VC-based online collision avoidance, outlining key development steps. Finally, a qualitative cost-benefit analysis emphasizes how much of a positive difference it makes to reuse existing VC models compared to shoehorning digitalization into later phases. By demonstrating its applicability, the proposed transformation method paves the way for unlocking the full potential of VC models and establishing their role as practical enablers of digital production.

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Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

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