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A Multidimensional Activity Theory Framework for Human–Computer Interaction with Digital Twins

Aleeza Adeel and Mark Apperley

School of Computing and Mathematical Sciences, The University of Waikato, Hamilton, New Zealand

ABSTRACT
This article proposes a user-centered framework to address interaction and usability challenges in complex Digital Twin systems(DTs) through an adaptation of Activity Theory, termed Pyramidal Activity Theory (PAT).Despite the growing adoption of DTs across industries, designing effective user interactions remains challenging due to the diversity of application domains, where multiple models, stakeholders, phases, and operational scales are often distributed across heterogeneous software environments. These complexities can lead to fragmented workflows, communication barriers, and inconsistent interaction experiences. PAT adapts the framework to focus on interaction structures by explicitly incorporating users, tools (models), live Data, interfaces, and outcomes.The framework is demonstrated through two conceptual case studies.The first case study conceptually maps interactions in an advanced manufacturing environment, while the second demonstrates how PAT can inform the design of a prototype Digital Twin interface for industrial energy systems. PAT provides a structured mechanism for analyzing interaction pathways and translating socio-technical relationships into interface design considerations. Future work will include empirical evaluation and usability assessment.

KEYWORDS
Digital Twins; human–computer interaction; user-centered design; activity theory; interface design and industrial systems

1. Introduction

As industries advance toward digitization, Digital Twin systems (DTs) have emerged as powerful tools for simulating, monitoring, and optimizing real-world systems (Giberna et al., 2025). A DT continuously synchronizes with its physical counterpart using real-time data, enabling dynamic decision-making across various operational scales. DTs have been successfully implemented in sectors such as manufacturing, energy, healthcare, and smart cities, where they contribute to improved efficiency, automation, and operational reliability, by accurately mirroring real-world behavior (Adamenko et al., 2020).

As DT adoption expands into more complex and interdisciplinary industrial settings, the demand for a standardized, model-independent interface is increasing (Soman et al., 2025). User-centered DT interfaces (Barricelli et al., 2019) must be black-box, supporting multi-user collaboration across diverse domains, while remaining adaptable and scalable (Park & McKilligan, 2018). However, current DT interfaces are often case-specific (Sharma et al., 2022) and model-dependent (Juarez et al., 2021), limiting their usability across applications (Barricelli & Fogli, 2024). They frequently lack cross-domain interoperability, are designed for single-user interactions, and cater to narrowly defined industrial use-cases. This fragmentation poses significant challenges for engineers, operators, and decision-makers, who must interact within shared DT environments, as shown in Figure 1.

To address the challenges of the Digital Twin ecosystem and to better understand the human–computer interaction (HCI) issues within these complex systems, it is necessary to examine established HCI

CONTACT Aleeza Adeel aa2438@students.waikato.ac.nz School of Computing and Mathematical Sciences, The University of Waikato, Hamilton, New Zealand

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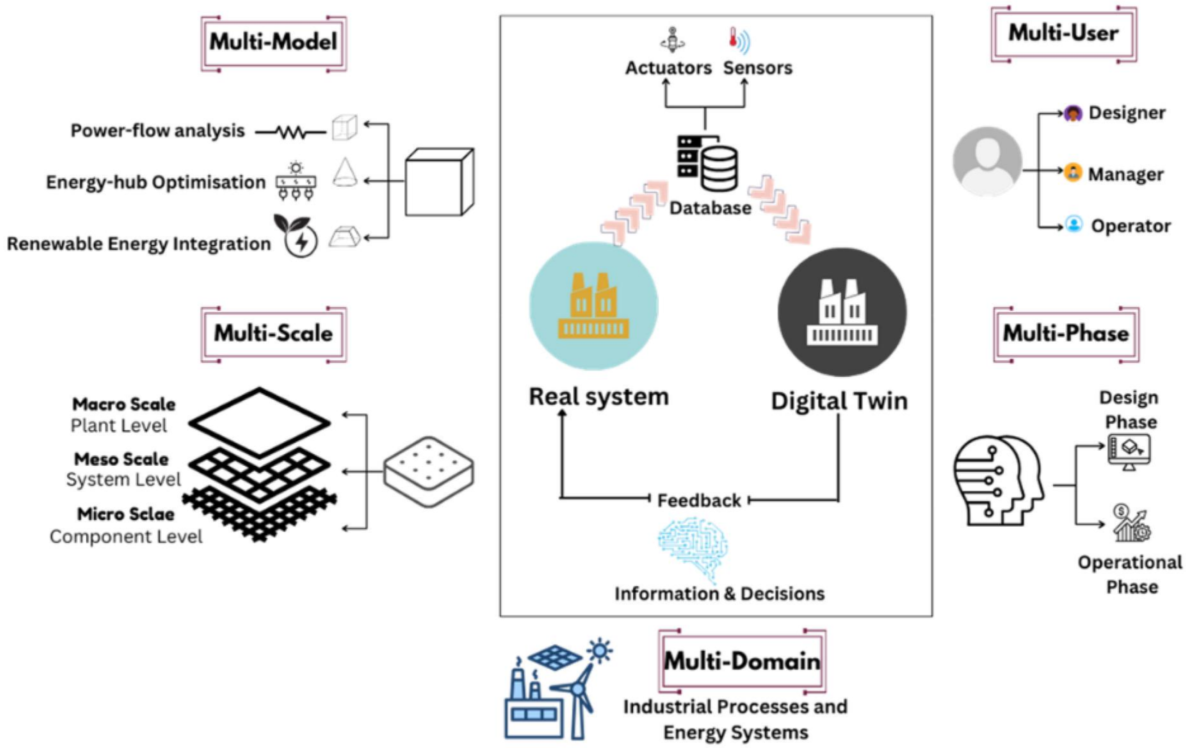

Figure 1. A generic Digital Twin illustrating its multiple perspectives, which lead to design and interaction challenges.

frameworks. Frameworks such as Distributed Cognition (Hollan et al., 2000), Situated Cognition (Suchman, 1987), User-Centered Design (Norman & Draper, 1986), Cognitive Dimensions of Notations (Green & Petre, 1996), and End-User Development (Lieberman et al., 2006) offer valuable insights into collaboration, context, usability, and user participation. However, each of these frameworks illuminates only part of the interaction landscape and lacks the socio-technical depth required for large-scale, data-intensive DT environments. For this reason, this article draws on traditional Activity Theory (AT) (Nardi, 1998) as its foundational framework. AT is a socio-cultural model (Vygotsky & Cole, 1978) that emphasizes the relationship between individuals (subjects), the tools they use, the goals they pursue (objects), and the broader social and organizational context in which activities occur. Over time, AT has evolved through several generations (Khayyat, 2016). Building on this foundation, this article introduces Pyramidal Activity Theory (PAT) as an adaptation of AT. PAT extends traditional AT by offering a three-dimensional view that captures the multi-directional interactions among core DT elements: Users (Subjects), Models (Tools), Live Data, User Interface, and Outcomes (Objects) (Wu et al., 2021). Unlike the fourth generation of AT (Khayyat, 2016), PAT excludes motivational and emotional factors in order to focus on the structural and operational relationships that directly inform interaction design within Digital Twin environments. As described later in Section 3.1, the dimensions are used to represent distinct interaction pathways, forming a structured framework for analyzing interactions and supporting the design of user-centered, scalable, and model-agnostic interfaces.

Section 3.2 presents two illustrative case studies that demonstrate the application of PAT in industrial contexts. The first case study conceptually applies PAT to an advanced manufacturing system, showing how the framework can be used to model collaborative human–machine interactions, dynamic workflows, and decision-support processes within DT environments. The second case study focuses on industrial energy optimization and illustrates how PAT can inform the design and implementation of a prototype DT interface that integrates multiple simulation models. Together, these examples illustrate how PAT structures complex interaction flows, clarifies stakeholder roles, and supports the translation of socio-technical relationships into interface design considerations.

This research contributes to the field of HCI by providing a structured and adaptable framework for analyzing and designing interactions within DT environments and other complex socio-technical systems. The contribution is primarily conceptual rather than empirical. Building on insights from the

Digital Twin and HCI literature, the article proposes PAT as a Digital Twin-oriented adaptation of Activity Theory for structuring interaction within complex DT environments. The framework is intended to support usability, system coherence, and informed decision-making while enabling user-centered workflows within increasingly complex industrial ecosystems. Rather than providing empirical validation of interaction outcomes, PAT offers a theoretically grounded structure that can support interaction analysis, interface design, and prototype development.

2. Background

2.1. Review strategy and framework selection

The literature reviewed in this study was identified through targeted searches conducted across major academic databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. The search process focused on publications related to Digital Twins, HCI, Activity Theory, human-centered Digital Twins, interactive DT systems, and socio-technical interaction frameworks. Search keywords included combinations of terms such as "Digital Twin," "Human–Computer Interaction," "Activity Theory," "Human-Centred Digital Twin," "Interactive Digital Twin," "DT interface design," "user-centred DT," "digital twin usability," and "DT interaction frameworks." The review primarily considered peer-reviewed journal articles and conference papers published between 2018 and 2025, while foundational works in Activity Theory and HCI were included where conceptually relevant.

Inclusion criteria focused on studies addressing DT interaction, interface design, usability, human-centered systems, socio-technical modeling, live-data integration, and operational decision-making within DT environments. Studies which focused exclusively on low-level simulation algorithms, hardware implementation, or purely technical optimization without relevance to HCI or user interaction were excluded. In addition to database searches, backward citation tracing was used to identify foundational and highly cited works relevant to Activity Theory, HCI, and Digital Twin interaction research.

2.2. Literature review

The reviewed literature reveals a growing recognition that Digital Twin environments require interaction frameworks capable of supporting collaboration, decision-making, and socio-technical complexity. To establish an appropriate theoretical foundation for addressing these challenges, this section examines existing HCI frameworks and evaluates their suitability for Digital Twin interaction design. Activity Theory (AT) was selected as the primary theoretical lens because it is one of the few established HCI frameworks capable of modeling mediated action, hierarchical goals, and the socio-technical dynamics central to Digital Twin environments.

Compared with AT, other HCI frameworks each illuminate only part of the interaction landscape. Distributed Cognition highlights how cognition is shared across people and tools but does not address motives, rules, or broader social structures (Hollan et al., 2000; Hutchins, 1995). Situated Cognition emphasizes real-world context, yet lacks a structured means of analyzing how tools, goals, and community interact (Suchman, 1987). User-Centered Design (Gulliksen et al., 2003; Norman & Draper, 1986) guides practical design processes but focuses mainly on usability and task refinement rather than deeper socio-technical relationships. Cognitive Dimensions of Notations (Green & Petre, 1996) examines the cognitive demands of representations but overlooks organizational and social layers. Design-oriented approaches such as End-User Development (EUD) (Lieberman et al., 2006; Paternò, 2013) and Concept Design (Carroll, 2000) emphasis user participation and early-stage interface ideation but lack the socio-technical analytical depth required for complex DT environments.

Nardi (1996) argue that Activity Theory stands apart because it integrates users, tools, mediating artifacts, rules, community, and outcomes into a single coherent system, making it a more promising framework for HCI design. This holistic and systems-oriented perspective aligns with the nature of Digital Twins, where interactions span multiple roles, tools, data streams, and operational scales. For these reasons, AT provides a stronger conceptual foundation for understanding user activity and forms the theoretical basis for the Pyramidal Activity Theory (PAT) advanced in this work.

2.3. Evolving Digital Twin design approaches: From technology-driven to human-centered systems

DT concept, introduced by Grieves and Vickers (2017), has evolved into a powerful paradigm for modeling, simulating, and analyzing real-world systems. Its applications now span a variety of domains including manufacturing, construction, aerospace, healthcare, and energy (Attaran & Celik, 2023; Singh et al., 2022). DTs have become central to Product Lifecycle Management, where they enhance product design, support informed decision-making, and enable virtual prototyping (Lo et al., 2021; Tao et al., 2019).

In recent years, there has been a growing focus on integrating HCI into DT systems. HCI enhances usability, efficiency, and adaptability by prioritizing the user's role in interacting with complex digital environments (Barricelli & Fogli, 2024). Building on this, DTs are increasingly viewed as platforms for collaborative design and co-creation, supporting broader stakeholder engagement across the product development lifecycle (Wagner et al., 2019). In this context, End-User Development approaches are becoming increasingly relevant, enabling non-technical users to contribute to DT customization and functionality (Batty, 2018).

Despite these advancements, significant challenges persist. These include the lack of interdisciplinary collaboration strategies (Barricelli et al., 2019), insufficient attention to user-centered design and customization (Singh et al., 2021), and the absence of standardized frameworks for integrating DTs with Product-Service Systems (Donoghue et al., 2018).

To overcome these barriers, researchers advocate for the development of standardized frameworks, deeper user involvement, and collaborative design methodologies that support scalable and user-friendly DT systems (Hananto et al., 2024). Notably, Park and McKilligan (2018) explored how HCI design principles intersect with DTs, while Vainionpää et al. (2022) highlighted the growing importance of HCI in shaping DT development and adoption. Reinforcing this perspective, Wu et al. (2021) proposed an integrated five-dimensional framework that systematically captures the relationships among physical and virtual entities, services, data, and their dynamic interconnections, laying the groundwork for comprehensive and adaptive DT ecosystems.

2.4. Human–computer interaction and Digital Twins

The integration of HCI with DT technology represents a transformative shift in how humans interact with digital representations of physical systems. Digital Twins are no longer confined to being static, data-driven models; they are evolving into interactive, adaptive, and human-centered platforms that support real-time decision-making. Research by Dingli and Haddod (2019) and Josifovska et al. (2019) highlights the development of intelligent interfaces and multimodal adaptation frameworks, enabling users to interact with DTs more intuitively. However, although these systems enhance accessibility, they often prioritize interface innovation over deeper modeling of user activity, which limits understanding of how users' goals, constraints, and interpretive processes shape their engagement with digital twins.

The human-centered perspective is further emphasized by Onan Demirel et al. (2021) and George et al. (2023), who underscore the role of ergonomics, user involvement, and sustainability objectives in DT design. Although these approaches contribute valuable usability principles, they mainly focus on surface-level qualities such as comfort, cognitive load, and visual clarity. They do not fully address how user interactions evolve across modeling, simulation, and operational decision-making phases, and they remain largely centered on individual users rather than collaborative or multi-user scenarios.

Advanced HCI technologies, as discussed by Lv et al. (2023) and Yigitbas et al. (2021), leverage AR/VR, adaptive systems, and immersive environments to enhance user engagement, creating interfaces that are both context-aware and responsive to human needs. Despite these advances, immersive environments rely heavily on technological affordances rather than conceptual clarity about user activity. They improve visualization but can obscure the complexity of decision-making within layered simulations or multi-scale data, and their strong dependence on specific hardware limits generalizability across systems.

Table 1. A comparison of digital twin frameworks showing their level of support for five key capabilities (● Full support ◐ Partial support ○ No support).

Framework	References	Multi-user	Multi-model	Multi-domain	Multi-scale	Multi-phase
Intelligent interfaces	Dingli and Haddod (2019)	○	◐	◐	○	○
Human-centric digital twins	Onan Demirel et al. (2021); George et al. (2023); Asad et al. (2023)	●	●	◐	◐	●
AR/VR & immersive DT	Lv et al. (2023); Yigitbas et al. (2021)	●	●	○	◐	◐
Interactive DT	Adamenko et al. (2020); Carlin et al. (2024); Kong et al. (2020)	◐	◐	◐	●	●
Domain-specific applications	Long et al. (2024); Su et al. (2023); Medina and Hernandez (2025)	◐	◐	○	◐	◐

Furthermore, emerging studies, including Soman et al. (2025), introduce the concept of human twin interfaces, where DTs integrate human attributes to improve system adaptability and performance. Applications in the construction industry (Long et al., 2024; Su et al., 2023) and product design (Medina & Hernandez, 2025) reveal that DTs, when coupled with robust HCI frameworks, enhance collaboration, visualization, and lifecycle management.

To clarify the evolving landscape of Digital Twin design, the frameworks introduced above are grouped into five categories: intelligent interfaces, human-centric digital twins, AR/VR and immersive digital twins, interactive digital twins, and domain-specific applications. Table 1 evaluates each category against five core capabilities—multi-user, multi-model, multi-domain, multi-scale, and multi-phase (design and operational). This categorization reflects the thematic focus of each work and helps position its contribution within the broader Digital Twin literature. For each capability, Table 1 indicates whether support is full, partial, or absent. The capability assessment presented in Table 1 is intended as a qualitative comparative analysis of the extent to which existing Digital Twin frameworks address key interaction and system characteristics relevant to complex DT environments. "Full support" indicates that the capability is explicitly addressed as a central feature of the framework, "partial support" indicates that the capability is addressed indirectly or within a limited scope, and "no support" indicates that the capability is not substantially considered within the framework. The assessment is based on the primary focus, scope, and interaction characteristics reported in the reviewed literature.

While recent advances in DT research indicate substantial progress in modeling, simulation, and domain-specific optimization, a critical synthesis of existing studies, viewed through an HCI framework, reveals several important trends and gaps. Intelligent interface approaches prioritize adaptive UIs and multimodal interaction but provide only superficial treatment of user intentions or the wider socio-technical landscape in which interactions occur. Human-centric digital twin studies introduce valuable ergonomic and participatory elements, yet they largely focus on individual usability rather than the collective, organizational, and multi-user dynamics typical of real DT deployments. Immersive DT work using AR/VR technologies improves visual engagement and spatial understanding, but these systems are frequently technology-driven, platform-specific, and limited in their ability to generalize human decision-making behaviors. Interactive Digital Twin frameworks strengthen links between real-time data, simulation, and user action, however, they rarely employ a robust theoretical foundation for representing user motives, contradictions, or social structures that influence interaction. Domain-specific implementations in construction and manufacturing illustrate the practical value of DT interfaces but remain tightly coupled to single application contexts, offering limited guidance for designing transferable or scalable interaction models across domains.

The overall comparative assessment as shown in Table 1 shows that although each category provides partial support for capabilities required in modern DT systems—such as multi-user, multi-model, multi-domain, multi-scale, and multi-phase interaction—no existing approach offers an integrated socio-technical lens capable of analyzing interaction across the full DT ecosystem. There remains a lack of a coherent model that links user activity, computational tools, live data flows, interface mechanisms, organizational rules, and community structures into a unified analytical framework. This fragmentation highlights the need for a holistic, theoretically grounded approach capable of linking users, tools, live data, interfaces, outcomes, organizational rules, and community structures within a single analytical framework. Although existing approaches provide valuable insights into specific aspects of Digital Twin interaction, none offers an integrated socio-technical perspective that spans the full DT ecosystem. It is

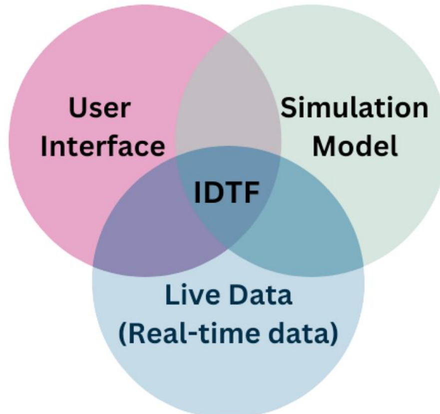

Figure 2. Components of the Interactive Digital Twin Framework.

this gap that motivates the development of Pyramidal Activity Theory (PAT), presented in the Section 3.1.

HCI plays a critical role in the development of DT interfaces by ensuring their usability, interactivity, and adaptability. Rather than functioning solely as real-time data replicas, DTs are increasingly conceptualized as interactive systems that actively enhance user engagement and support informed decision-making processes (Barricelli & Fogli, 2024). This shift highlights the necessity of embedding HCI principles into DT design.

Previous studies have introduced methodological frameworks that reinforce this approach, aiming to strengthen real-time user interaction and data integration within DT systems (Adamenko et al., 2020; Carlin et al., 2024; Kong et al., 2020). Similarly, the *Human-Centric Digital Twin (HCDT)* paradigm emphasizes embedding user-centric interactions to improve both usability and decision support (Asad et al., 2023). Collectively, these developments advocate a transition from passive data representations to systems that are actively engaging and responsive.

To clarify the structural composition of such systems, Figure 2 presents a Venn diagram that captures the three core components of the Interactive Digital Twin Framework under consideration here: a User Interface (conceived as a black-box abstraction for simplified interaction), Live Data (ensuring real-time consistency), and a Simulation Model (providing domain-flexible modeling capabilities).

2.5. Activity Theory (AT): Evolution and limitations

As established in Section 2.2, Activity Theory (AT) serves as the foundational framework for the proposed model. AT has its origins in psychology, particularly in the work of Soviet theorists (Leont'ev, 1978; Vygotsky & Cole, 1978), who conceptualized human cognition as a socially and culturally mediated process. Initially rooted in developmental and educational psychology, AT was later incorporated into HCI research (Nardi, 1998) as a robust framework for analyzing user interaction within broader social and organizational contexts. Over the decades, AT has evolved through several conceptual generations (Khayyat, 2016).

The first generation, led by Vygotsky and Cole (1978), emphasized mediated action through tools and signs but focused primarily on individual cognition, with limited attention to social or collective activity. The second generation, developed by Leont'ev (1978), broadened the scope to collective activity systems, but did not fully address the complexities of multi-user or digital interactions. Engeström (2014, 2001) added elements, for example rules, community, and division of labor, to reflect the collective nature of human activity, yet AT continued to struggle with scaling to complex, interdisciplinary digital systems. The fourth generation of AT incorporated motivational factors (Khayyat, 2016), but even these advances do not fully satisfy the requirements for modeling complex, simulation-based digital environments. Consequently, AT remains an emerging approach without a widely accepted or standardized framework for application to complex socio-technical systems.

According to Clemmensen et al. (2016), Activity Theory (AT) serves as a structured framework for analyzing and designing user interactions within digital environments. They also noted that "Traditional AT models have limitations when applied to large-scale, distributed, technology-mediated systems," citing frequent difficulties in analyzing environments involving multiple actors, tools, and continuous real-time feedback. Similarly, Spinuzzi and Guile (2019) conclude that "Even fourth-generation models struggle to incorporate the full complexity of modern digital systems, especially regarding real-time data, layered user roles, and dynamic interaction with computational models." This is also emphasized in a systematic review by Barricelli and Fogli (2024), who highlight the absence of a standardized, user-centered framework for digital twins in HCI and emphasize the need for scalable, adaptive models that can accommodate the increasing complexity of industrial ecosystems. Consequently, AT remains an emerging approach for complex systems such as digital twins. The following challenges remain unresolved:

- Digital twin ecosystems require seamless and structured integration of multiple models (Sharma et al., 2022).
- Many DT systems do not fully embrace user-centered design, which affects usability and system adoption (Barricelli et al., 2019).
- There is a need for consistent and standardized framework for designing digital twin interfaces (Soman et al., 2025).
- Real-time adaptation based on live sensor data and ongoing system changes is essential for digital twins (Bilberg & Malik, 2019).
- Existing approaches often lack robust strategies for mediating between users and systems, limiting usability and interactive decision-making (Barricelli & Fogli, 2024; Märtin et al., 2019; Spinuzzi & Guile, 2019).

These limitations highlight the need for an adaptation of Activity Theory that is better suited to modeling interaction within Digital Twin environments.

3. Methodological approach

3.1. Conceptual modeling: The proposed Pyramidal Activity Theory (PAT)

This research introduces Pyramidal Activity Theory (PAT) as a conceptual framework for understanding interactions within Digital Twin DT environments. Building upon the foundations of the fourth generation of Activity Theory (AT) (Khayyat, 2016) as shown in Figure 3(a), PAT extends the model into a third dimension and repositions the user at the apex of a square pyramid structure, emphasizing a user-centered design approach. Unlike earlier AT models, PAT moves beyond linear relationships by embedding real-time responsiveness, dynamic roles, and multi-layered system interaction, within a single unified structure. The model incorporates key elements from the Interactive Digital Twin Framework, which identifies the User Interface, Live Data, and Simulation Model as core components as illustrated in Figure 2 and discussed in Section 2.2. By incorporating these elements in a multidimensional framework, PAT facilitates multi-faceted interactions and supports both the design and operational phases of digital twin systems.

The PAT model as shown in Figure 3(b) consists of five key vertices—Subject (User), User Interface, Tools (Models), Live Data, and Object (Outcomes)—which form five faces as shown in Figure 4, each representing a distinct interaction pathway essential for DT functionality. As shown in Figure 4, these faces support both the design and operational phases of DT systems, enabling a seamless transition from conceptual planning to real-time deployment. The user remains central in this structure, positioned at the apex and influenced by rules, division of labor, and the broader stakeholder community. Motivational factors, level of awareness, and perceived barriers have been excluded in this model to maintain a focus on interaction mechanics rather than external influences. The User Interface functions as a mediation layer, simplifying system complexity and allowing intuitive engagement with the underlying computational models. Simultaneously, Live Data plays a pivotal role in continuously informing

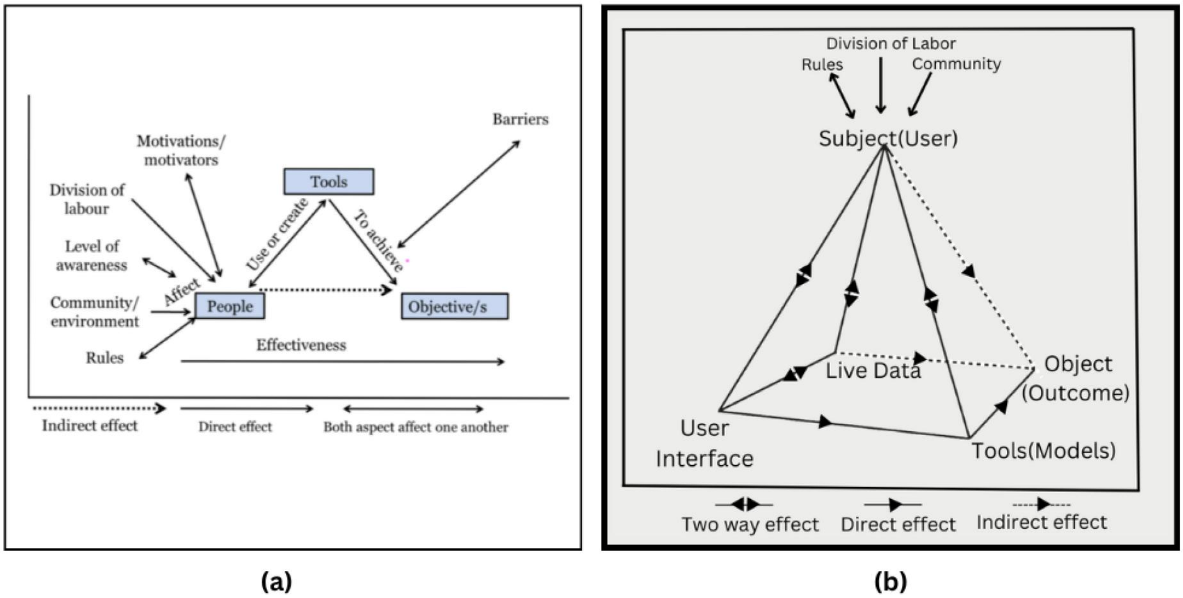

Figure 3. (a) Fourth generation of Activity Theory model (Khayyat, 2016); (b) Proposed Pyramidal Activity Theory (PAT) model.

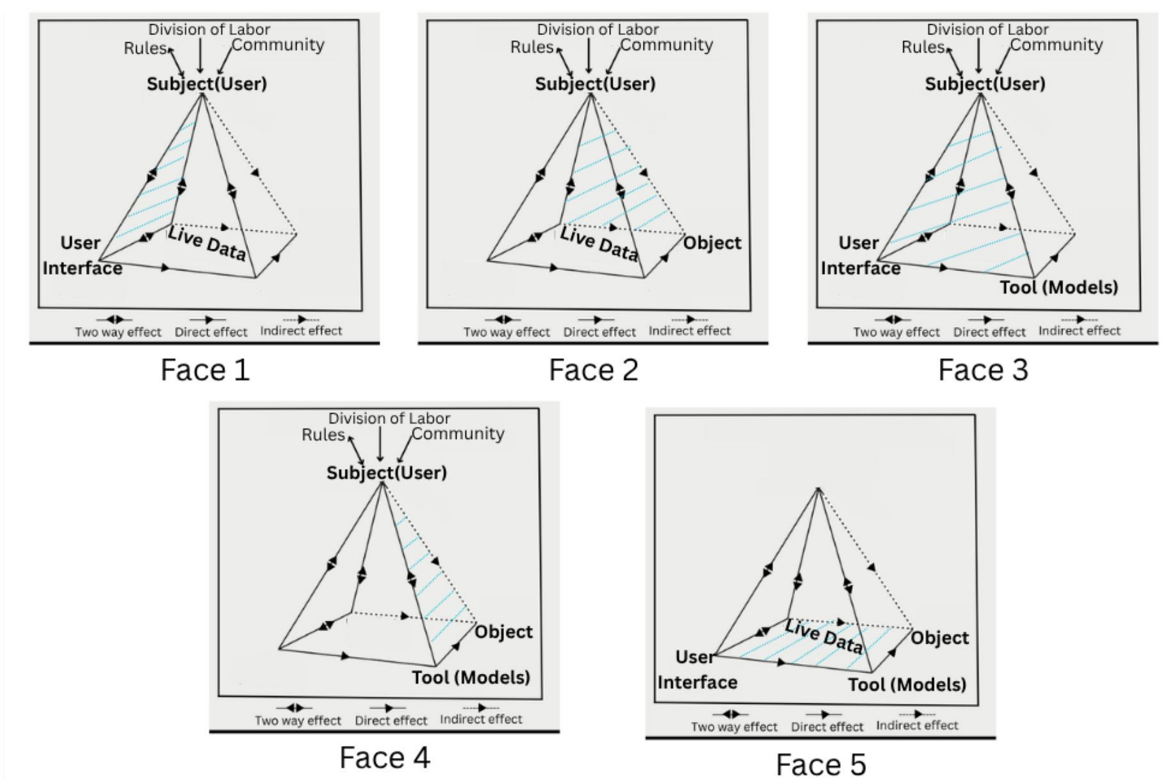

Figure 4. The five interaction faces derived from the PAT model (Figure 3b), with each blue-shaded face representing a distinct interaction within a Digital Twin environment.

both users and models, supporting real-time responsiveness and system adaptability. The Object signifies the intended outcomes resulting from this dynamic interaction.

Each of the five faces of the pyramid reveals a unique perspective within the activity system. As shown in Figure 4, Face 1 connects the User, Live Data, and User Interface, highlighting how users perceive and respond to real-time information. Face 2 illustrates the user's indirect influence on Outcomes through engagement with Live Data, emphasizing feedback loops and observational learning. Face 3

Table 2. Mapping of PAT interaction faces to interaction roles and interface implications.

PAT faces	Interaction focus	Design questions	Interface implications
Face 1	User interaction with live system feedback	How should real-time information be presented to support rapid interpretation and response?	Dashboards, alerts, live monitoring panels, responsive feedback mechanisms
Face 2	Observation of system outcomes through live data	How can users understand the effects of operational changes and system behavior?	Performance indicators, summaries, trend visualization, feedback displays
Face 3	Interaction with computational tools through the interface	How should complex models be configured and controlled without overwhelming users?	Model abstraction, modular configuration panels, guided interaction workflows
Face 4	Goal-oriented interaction and decision-making	How can system outcomes be linked clearly to user actions and operational objectives?	Simulation controls, optimization interfaces, decision-support visualization
Face 5	Autonomous model and data interaction	How should automated processes and adaptive system behaviors be represented to users?	Background analytics, automated optimization, adaptive feedback systems

captures the direct interaction between the User and Tools via the Interface, where system logic is configured and deployed. Face 4 preserves the classic AT triad—User, Tools, and Outcomes—representing mediated actions aimed at purposeful activity. Finally, Face 5 links Live Data, Tools, and Outcomes, showcasing the autonomous and computational functions that generate outputs. Together, these faces form a comprehensive, multidimensional representation of interaction flows within a Digital Twin, supporting continuous optimization and human-computer collaboration.

To further clarify their theoretical significance and practical application in Digital Twin design, Table 2 maps each face to its corresponding DT interaction focus, design questions, and interface implications.

3.2. Pyramidal Activity Theory (PAT) positioned within the landscape of HCI frameworks

PAT is proposed as a Digital Twin-oriented adaptation of Activity Theory that extends the framework to accommodate live operational data, computational tools, user interfaces, and system outcomes. Rather than replacing existing Activity Theory models, PAT seeks to address interaction challenges that emerge within contemporary Digital Twin environments.

The theoretical contribution of PAT lies in its ability to address gaps that established HCI frameworks have not resolved, particularly in environments characterized by real-time data flows, multi-scale modeling, and tightly interdependent human–machine decision processes, as found in Digital Twins (DTs). Although several well-known frameworks provide valuable analytical perspectives, as outlined in Section 2.2, each captures only part of the socio-technical complexity inherent to DT systems.

Activity Theory (AT) offers a strong foundation by modeling mediated action, hierarchical motives, and community dynamics. However, AT was developed for relatively stable work settings and does not account for simultaneous multi-level interactions, continuous data-driven feedback, or algorithmically mediated decisions—all central to DT operation, as discussed in Section 2.4. PAT builds on AT by introducing a structured, multi-layered representation of activity that links user goals, system abstraction levels, live data streams, and automated computational behaviors, adapting AT's socio-technical lens to the dynamic and data-intensive nature of DT ecosystems.

PAT is considered user-centered because design decisions originate from users, their activities, and their operational context rather than from technological capabilities alone. Interface requirements, data representations, and computational functionalities are derived from user goals and tasks, ensuring that DT functionality remains aligned with stakeholder needs. Consequently, PAT supports the translation of socio-technical relationships into interaction pathways, interface structures, and operational workflows.

PAT differs from existing approaches in three important respects. First, unlike traditional Activity Theory models, it explicitly incorporates Digital Twin-specific constructs such as live operational data, computational models, interfaces, and outcomes. Second, unlike Human-Centric Digital Twin frameworks, which primarily emphasize design principles and user needs, PAT provides a structured mechanism for linking socio-technical relationships to interaction pathways and interface design decisions.

Third, unlike five-dimensional Digital Twin models that focus on system architecture and information integration, PAT focuses on the analysis and design of user interaction within Digital Twin environments.

The exclusion of motivational and emotional factors in PAT was intentional and theoretically scoped to maintain focus on interaction mechanics within data-intensive DT systems. While traditional Activity Theory emphasizes motives, socio-cultural mediation, and human development, PAT narrows the analytical scope toward operational interaction structures involving interfaces, live data streams, and computational models. In highly dynamic DT ecosystems, interaction coordination, system responsiveness, and interface mediation represent the dominant analytical concerns. Consequently, PAT prioritizes structural and operational interaction dynamics rather than broader psychological or socio-cultural dimensions.

By integrating user roles, hierarchical activity structures, live data, computational models, interface mechanisms, and system outcomes into a single framework, PAT provides analytical coverage that existing approaches lack. Its contribution is threefold: it offers a conceptual model for framing DT interaction, an analytical tool for examining socio-technical activity across scales, and a design-oriented framework for supporting interface development. Together, these functions position PAT as a Digital Twin-oriented adaptation of Activity Theory that supports interaction analysis and interface design within complex, data-intensive environments.

3.3. Case study application

To illustrate the practical applicability of PAT, two case studies are presented. Case Study 1 uses a conceptual manufacturing scenario to show how PAT structures interaction flows and guides high-level design reasoning. Case Study 2 extends this by applying PAT in an operational energy-optimization context, where it shapes detailed interface decisions and supports the development of a functional prototype. Together, the case studies illustrate how PAT operates as a design-decision methodology across both conceptual and practical layers of Digital Twin development.

3.3.1. Case study 1: Applying PAT to advanced manufacturing systems for design decision-making

Consider an advanced manufacturing facility producing precision automotive components using robotic assembly lines, additive manufacturing (3D printing), and real-time quality inspection systems. DT in this environment synchronizes continuously with physical machines and sensors, allowing operators, process engineers, and maintenance staff to monitor equipment health, predict failures, and dynamically adjust production parameters.

While this scenario outlines a typical DT environment, the PAT framework shaped the underlying design logic for conceptualizing the interaction flows, as illustrated in Figure 5. PAT's clear separation of the Subject, Tools, Live Data, User Interface, and Outcomes required the interface to explicitly distinguish between:

1. What the user sees,
2. What the models compute,
3. What the live data drives.

This structured decomposition provided conceptual clarity before introducing any domain-specific functions. By mapping each component of the manufacturing system onto the PAT vertices and faces, the framework established a foundation for analyzing how users, data streams, computational tools, and system outcomes interact within the environment. This mapping step then informed the subsequent design process, with each interaction face of PAT guiding how information, controls, and system behaviors were represented in the interface.

The five interaction faces of PAT as defined in Figure 4 collectively provided direct guidance for the design decisions in the conceptual manufacturing environment. Each face highlighted a distinct interaction pathway that shaped the organization of data, tools, and system behaviors within the interface.

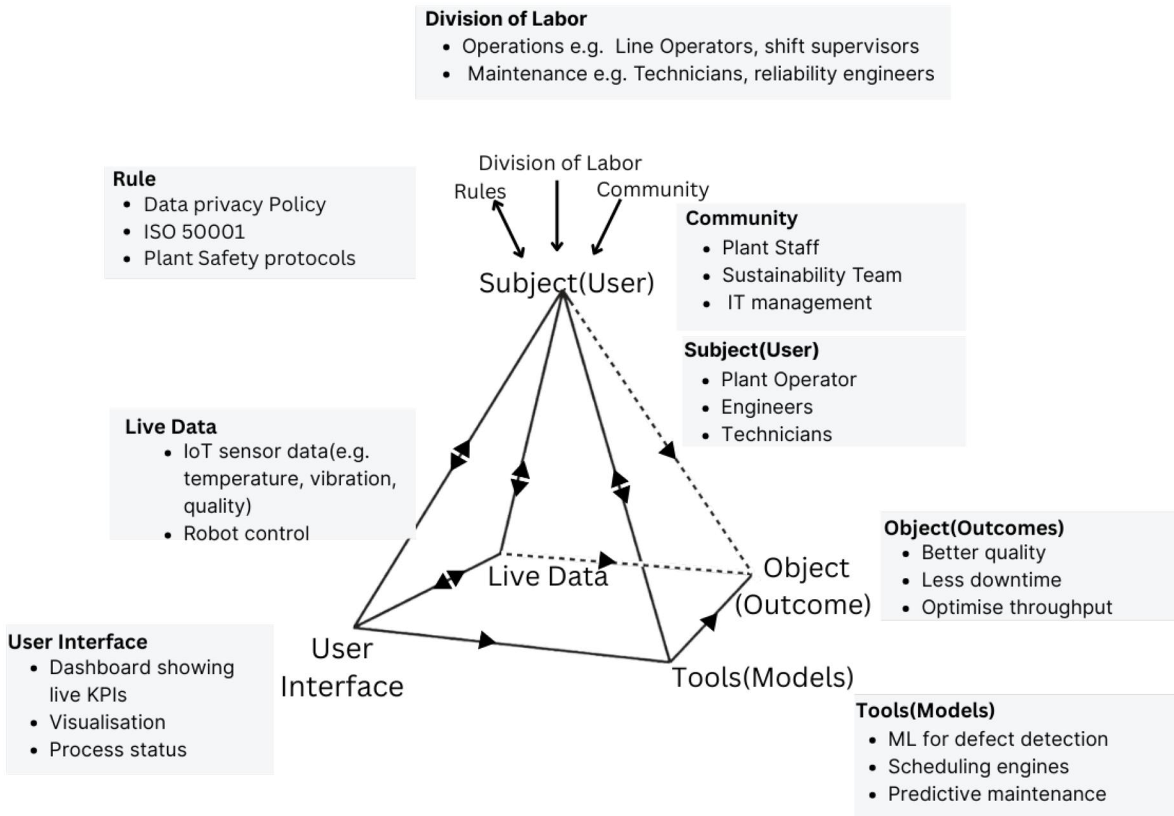

Figure 5. Mapping the key elements and interaction pathways of an advanced manufacturing system within the PAT framework.

- Face 1 (User–Live Data–User Interface): PAT requires real-time data to be presented in a way that enables immediate, meaningful user action. This principle informed the design of interface elements that deliver instant feedback on machine performance and allow operators to adjust process variables without exposing the internal logic of computational models.
- Face 2 (User–Live Data–Outcome): PAT emphasizes observational learning and feedback loops. Consequently, the interface includes high-level performance metrics and quality indicators so that engineers can evaluate the effects of workflow adjustments without directly interacting with or modifying the underlying models.
- Face 3 (User–User Interface–Tools): PAT identifies the user interface as the mediating layer through which all interactions with computational tools should occur. This principle guided the design of predictive-maintenance screens, allowing maintenance staff to schedule repairs based on model outputs while keeping the model's internal structure abstracted and manageable.
- Face 4 (User–Tools–Outcome): Drawing on PAT's classic activity triad, optimization and configuration features were designed to present clear and interpretable consequences—such as expected impacts on throughput, energy efficiency, or product quality—resulting from user-configured parameters.
- Face 5 (Live Data–Tools–Outcome): PAT highlights the importance of autonomous, system-driven interactions. This informed the inclusion of background analytics, such as automatic defect detection and adaptive parameter adjustments, which operate without direct user input but still produce interpretable and actionable results through the interface.

Through these design choices, PAT shaped the organization of interface components, data flows, and system behaviors, ensuring that interaction patterns remained coherent, intuitive, and aligned with the framework's multidimensional structure. This case study is intended as a conceptual and illustrative application of PAT rather than an empirically validated deployment. Its purpose is to demonstrate how the framework can be used to structure and analyze interaction relationships among users, interfaces, live data, computational models, and operational outcomes within a complex manufacturing-oriented DT environment. Accordingly, the example does not involve real-world user testing, operational deployment, or empirical performance evaluation.

3.3.2. Case study 2: PAT-driven design decisions and prototype implementation for industrial energy optimization

In this case study, the PAT framework is applied to guide the development of a Digital Twin (DT) prototype for energy optimization in a medium-scale manufacturing plant. The case study extends PAT from a conceptual interaction framework to an illustrative design methodology, with interface screens and workflows mapped to PAT's vertices and interaction faces. The objective is to demonstrate how PAT can be used to structure human–system interactions and inform interface design within an industrial energy-management context.

The DT monitors, simulates, and optimizes energy use across the manufacturing plant, integrating real-time sensor data, user inputs, predictive models, and external energy pricing to support informed decision-making and adaptive control. The Subject (User) is an energy systems engineer making decisions related to balancing demand, reducing peak loads, and integrating renewable sources. The User Interface consists of a real-time dashboard with interactive simulation controls, energy-consumption trends, and system alerts. The Tools (Models) include load-forecasting algorithms, optimization solvers, and machine-learning components for anomaly detection. Live Data streams continuously from IoT sensors capturing electricity usage, equipment runtime, and temperature. The Object (Outcome) is defined as optimal energy use, cost reduction, and meeting emission targets.

Before designing any interface components, PAT required the development team to articulate how Users, Models, Live Data, Interfaces, and Outcomes interact as a system. This ensured that design decisions were derived from the framework's interaction structure rather than domain intuition alone. PAT clarified what information should be visible to users, which actions should be mediated through the interface, and which processes could operate autonomously. Consequently, PAT served as the design blueprint for organizing workflows, interface navigation, and system functionality.

- Face 1 (User–Live Data–User Interface): The engineer interacts with real-time IoT sensor data through the interface (Supplementary Figure A1). They can adjust setpoints or activate load-shifting routines when peak alerts occur. PAT required real-time panels to be prominent and immediately interpretable.
- Face 2 (User–Live Data–Outcome): Engineers monitor model effects through flow-level feedback summaries (Supplementary Figure A2). PAT's emphasis on feedback loops informed the design of summary widgets and aggregated KPIs.
- Face 3 (User–User Interface–Tools): Users configure unit models by adjusting operational parameters (Supplementary Figure A3). PAT guided the creation of modular configuration panels that hide computational complexity while supporting flexible parameter manipulation. Because PAT positions the user at the apex of interaction, the interface provides guided feedback—for example, highlighting unspecified parameters in red (Supplementary Figure A7).
- Face 4 (User–Tools–Outcome): Users engage with optimization and forecasting tools to achieve defined outcomes (Supplementary Figure A4). PAT required the interface to clearly show cause–effect relationships and display impacts on cost, emissions, and performance.
- Face 5 (Live Data–User Interface–Tools–Outcome): Live sensor data feeds into the models, which compute derived variables (Supplementary Figure A5). PAT highlighted the need for autonomous behaviors, supporting the inclusion of background analytics and automated optimization routines. Multiple models can be incorporated, including machine-learning components (Supplementary Figure A6).

Table 3 demonstrates how PAT informed prototype development by linking each interaction face to specific design questions, interface decisions, and implemented system features.

Table 3. Translation of PAT interaction faces into interface design decisions and prototype features.

PAT faces	Design question	Design decision	Prototype implementation	Screen
Face 1	How should real-time information be presented?	Provide immediate and actionable feedback.	Live-data configuration and monitoring screens.	Supplementary Figure A1
Face 2	How can users observe system consequences?	Link outcomes directly to operational data.	Process dashboards and outcome summaries.	Supplementary Figure A2
Face 3	How should users interact with computational tools?	Hide complexity through guided workflows.	Flowsheet editor and configuration panels.	Supplementary Figures A3 and A7
Face 4	How can models support decisions?	Show consequences of model execution.	Simulation and optimization views.	Supplementary Figure A4
Face 5	How should autonomous behavior be represented?	Expose automated analytics and optimization.	Integrated models and machine-learning modules.	Supplementary Figures A5 and A6

Table 4. Multiscale structure of PAT framework.

Scale	Activity	Subject	UI	Live data	Model	Object
Regional level	Long-term energy planning and scenario evaluation.	Energy Managers Policy Makers	–	Smart meters Regional demand sensors Weather data	Regional energy planning models Scenario analysis tools	Regional energy balance and policy outcomes
Industry level	Policy enforcement and performance optimization.	Plant Managers Energy Analysts	–	Emission sensors Process-level energy meters	Industrial process optimization models Load forecasting	Reduce costs and improve energy efficiency of industrial processes
Unit level	Real-time control and fault diagnosis.	Machine Operators Process Supervisors	–	Sensor data (temperature, pressure, flow) Machine status Control system feedback	Process control models Fault detection systems	Energy efficient unit operations

Collectively, the five interaction faces translated the theoretical PAT constructs into concrete design requirements and prototype features. Beyond individual interactions, PAT also support interaction design across multiple operational scales. At the regional level, the framework informed scenario-based planning and long-term energy-management activities (Supplementary Figure A9). At the industry level, PAT supported the integration of optimization tools, emissions monitoring, and performance evaluation functions (Supplementary Figure A8). At the unit level, it guided the design of real-time monitoring, diagnostic interfaces, and operational control views (Supplementary Figure A5). This multi-scale structure ensured that interaction logic remained consistent despite changes in abstraction level and operational scope. Table 4 summarizes the application of PAT across regional, industry, and unit levels, illustrating how activities, users, data sources, computational models, and outcomes vary across scales while remaining connected through a common interaction framework.

The case study illustrates how PAT can support the transition from conceptual interaction modeling to guiding designs for prototype development while maintaining consistency across multiple operational scales within Digital Twin environments.

3.3.3. Evaluation of PAT against DT-HCI challenges

Table 5 summarizes how PAT conceptually addresses the key DT-HCI interaction challenges identified in the literature, namely multi-user, multi-model, multi-domain, multi-scale, and multi-phase interaction. The assessment indicates that these requirements are explicitly supported through the structural components of PAT, including Community, Division of Labor, Live Data, Tools (Models), User Interface, Outcomes, and the five interaction faces.

In addition to these Digital Twin-specific requirements, PAT also supports broader HCI considerations such as real-time awareness, model abstraction, decision support, and user-centered interaction through the integration of live data, computational models, and role-based interaction pathways.

Although this assessment does not constitute empirical validation, it demonstrates how PAT conceptually addresses key DT-HCI challenges and provides a structured basis for analyzing and designing interactions within complex Digital Twin environments.

Table 5. Analytical evaluation of PAT against the key DT-HCI interaction challenges identified in Figure 1 where ● donates full support.

Interaction challenge	Support level	How PAT addresses it
Multi-user	●	PAT explicitly supports multi-user interaction through the Community and Division of Labor components, which represent stakeholder groups, responsibilities, and role-specific interaction pathways.
Multi-model	●	PAT supports multi-model environments through the Tools (Models) component. Face 3 supports model configuration and interaction, while Face 4 supports model-driven analysis, simulation, and decision-making.
Multi-domain	●	PAT supports the integration of models and data originating from different application domains through the Tools (Models) and Live Data components. Because PAT focuses on interaction structures rather than domain-specific functionality, domain-specific models and data sources can be incorporated within the same interaction framework.
Multi-scale	●	PAT maintains the same interaction structure across regional, industry, and unit levels. Faces 1–5 remain applicable across abstraction levels, enabling consistent interaction logic while supporting different operational scopes.
Multi-phase	●	PAT supports both conceptual planning and real-time operational activities. Face 3 and Face 4 support planning, simulation, and optimization, whereas Face 1 and Face 2 support monitoring, feedback, and operational decision-making through Live Data.

4. Discussion

This study examined how PAT can support the analysis and design of user interactions within complex DT environments. Across the two illustrative case studies, PAT was applied to structure relationships among users, live data, computational models, interfaces, and outcomes within a unified socio-technical framework. The findings indicate that PAT can function both as a conceptual framework for analyzing DT interactions and as a design-oriented framework for informing interface development.

The first contribution of the study is the demonstration of PAT as an analytical framework for understanding interaction within data-intensive DT environments. By extending Activity Theory to explicitly incorporate live data, computational models, interfaces, and outcomes, PAT captures interaction pathways that are not directly represented in traditional Activity Theory or many existing DT frameworks. In the manufacturing case study, the framework provided a structured representation of collaborative human–system interactions and highlighted the role of feedback loops, information flows, and stakeholder responsibilities in shaping operational activities. These observations suggest that PAT offers a useful lens for examining the socio-technical complexity of DT ecosystems.

The second contribution is the demonstration of PAT as a design-oriented framework. In the energy optimization case study, PAT informed the organization of interface components, the grouping of system functionalities, and the presentation of information across multiple levels of abstraction. By linking stakeholder roles, activities, live data, and computational models, the framework provided a structured rationale for design decisions and enabled traceability between user requirements and prototype features. This illustrates how PAT can support the transition from interaction analysis to interface design and prototype development.

A further contribution relates to the framework's user-centered orientation. Unlike technology-driven approaches that begin with system capabilities, PAT begins with users, their activities, and the organizational contexts in which interaction occurs. Consequently, interface requirements and system functionality are derived from user goals and operational needs rather than technological affordances alone. This aligns closely with established HCI principles and provides a mechanism for incorporating user-centered design considerations into DT development processes.

The comparative review of existing frameworks further contextualizes PAT's contribution. While previous approaches typically focus on specific aspects of DT interaction, such as intelligent interfaces, immersive technologies, or domain-specific applications, PAT provides an integrated perspective that connects users, live data, computational models, interfaces, organizational structures, and outcomes within a single framework. This multidimensional perspective is also consistent with recent developments in knowledge graph–enabled Digital Twin architectures (Carbonaro et al., 2023), which similarly emphasize interconnected relationships among users, processes, data, and organizational entities. However, whereas such architectures provide technical mechanisms for representing these relationships, PAT contributes a complementary human-centered framework for analyzing them and translating them into interaction and interface requirements.

Taken together, these findings suggest that PAT provides a promising conceptual foundation for supporting user-centered Digital Twin interaction analysis and design. Nevertheless, the framework should be considered within the scope of several limitations. PAT deliberately excludes the motivational constructs introduced in fourth-generation Activity Theory (Khayyat, 2016) in order to focus on the structural and operational relationships that directly inform interaction design. Consequently, the framework is particularly suited to digital, data-centric environments where interaction structures can be explicitly modeled, but may be less appropriate in contexts where behavior is predominantly shaped by motivational, cultural, or socio-political influences. In addition, PAT has not yet been evaluated through empirical user testing, expert review, usability assessment, or deployment within operational Digital Twin environments. The case studies are illustrative in nature and are limited primarily to industrial and energy-related contexts, which may restrict the generalizability of the framework to other domains.

5. Conclusion and future outlook

The contribution of this work lies primarily in the development of a review-informed conceptual framework that integrates insights from Activity Theory, HCI, and Digital Twin research into a unified structure for interaction analysis and design.

This article introduced PAT as a Digital Twin-oriented adaptation of Activity Theory for analyzing and structuring user interactions within complex DT environments. By extending Activity Theory into a multidimensional framework, PAT incorporates live data, computational models, user interfaces, and system outcomes within a single socio-technical structure. Its pyramidal configuration is intended to support user-centered interaction design by clarifying relationships among stakeholders, data, models, interfaces, and outcomes, while maintaining coherence across multiple operational scales. The case studies presented in this article are intended to illustrate the theoretical applicability of PAT rather than provide empirical validation. Although developed in the context of Digital Twins, the conceptual principles underpinning PAT may also be applicable to other complex socio-technical systems characterized by dynamic interactions among people, technologies, and data.

The two illustrative case studies demonstrated how PAT can be applied across different industrial contexts. In the manufacturing scenario, PAT functioned as a conceptual model for analyzing collaborative human–system interactions and identifying key interaction pathways. In the energy optimization scenario, the framework informed interface organization, model abstraction, and prototype design decisions, illustrating how PAT can support the translation of socio-technical requirements into interface structures. Together, the case studies highlight the capacity of PAT to structure interaction flows, clarify stakeholder roles, and support interaction design across multiple levels of operation.

The comparative review of existing frameworks further contextualized the contributions of PAT. While previous approaches typically focus on specific aspects of DT interaction, such as intelligent interfaces, immersive technologies, or domain-specific applications, PAT provides an integrated perspective that connects users, live data, computational models, interfaces, organizational structures, and outcomes within a single analytical framework. In doing so, it offers a conceptual foundation for supporting interaction analysis and interface design in increasingly complex DT ecosystems.

Future research will focus on operationalizing and evaluating PAT within real-world Digital Twin environments. Initial work will involve expert evaluation workshops with HCI researchers, Digital Twin specialists, and industry practitioners to assess the framework's conceptual clarity, scalability, and applicability across diverse operational contexts. Building on these findings, structured usability studies with engineers, operators, and designers will examine how PAT-informed interfaces support user understanding, interaction effectiveness, and decision-making processes. Subsequently, deployment studies within industrial DT environments will investigate how the framework supports multi-scale interaction, collaborative decision-making, and live-data responsiveness under operational conditions.

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Author contributions

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ORCID

Aleeza Adeel http://orcid.org/0009-0009-3180-2640
Mark Apperley http://orcid.org/0000-0003-1588-1595

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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About the authors

Aleeza Adeel is a PhD. Researcher in Computer Science at the University of Waikato, New Zealand. Her research focuses on human–computer interaction, digital twins, and the design of model-independent user interfaces for industrial digital twin systems, with an emphasis on improving usability, interoperability, and decision-making support.

Mark Apperley is Professor of Software Engineering at the University of Waikato, Hamilton, New Zealand. His research covers human-computer interaction and information visualization, and most recently, energy informatics, specifically the application of ICT in renewable and efficient energy utilization, covering vehicle-to-grid technologies, smart community micro-grids, and industrial digital twins.