

Bridging Extended Reality and Digital Twins: Mapping Standards for the Industrial Metaverse

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Abstract

Extended reality (XR) is increasingly used to support training, assistance, inspection, and collaboration in industrial work, while digital twins (DTs) provide standardised representations of physical assets, processes and operational data. Their convergence is increasingly associated with the industrial metaverse. Each has been standardised within its own community, so that XR applications can be deployed across devices and industrial assets can be described consistently across suppliers. In challenging environments, however, the value of XR is constrained by the boundary between XR and DT standards, which neither set of standards reaches. Information must move across industrial systems, digital twins, XR interfaces, and arrive in a form the people doing the work can act on. This position paper presents a preliminary cross-domain mapping of that boundary. Concepts from the ISO 23247 series on digital twins for manufacturing and the Asset Administration Shell (IEC 63278) are examined alongside XR standards. These standards cover runtime APIs, such as OpenXR and WebXR, and content information models, such as ISO/IEC 3721. The concepts are then mapped to four integration concerns: semantic and spatial alignment; worker and task context; bidirectional interaction and operational feedback; and provenance and multi-system composition. Each is addressed in part by the XR or the DT standards, and left open at that boundary. The paper raises these concerns for discussion and closes with an initial agenda for standards-enabled XR in industrial work. The paper is intended to support discussion of how standards can better connect industrial systems, DTs, XR applications, and human work practices.

Keywords

extended reality, digital twin, standardisation, ISO 23247, OpenXR, interoperability, industrial work

1. Introduction

Industrial work increasingly relies on digital representations of the assets and processes involved. Extended reality (XR), encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR), makes this information available to workers in context, supporting situated guidance, remote expertise, and hands-free access during maintenance, inspection, assembly, and training [1, 2, 3]. Digital twins (DTs) provide the underlying structure for these representations, and an established body of research examines how twins are described, hosted, and kept consistent with the systems they represent [4, 5, 6, 7]. The convergence of DTs and XR is increasingly discussed in the industrial metaverse [8, 9].

DTs and XR have developed within largely separate standardisation communities. DT standards define physical entities, their properties, and the exchange of information about them [10]. XR standards, on the other hand, address applications, runtimes, devices, and interaction [11]. Industrial deployments often require both sets of standards because they must combine structured information about industrial assets with immersive, context-aware interfaces for workers. Information from a twin must therefore be linked to an XR representation, situated within the worker's environment, and made usable for a specific task. Conversely, observations and interactions generated through XR may need to be connected back to the industrial information system. These connections become particularly important when XR is used for challenging or mission-critical work. For instance, in a cobot-based assembly cell, the worker

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shares a workspace with a robot, operates under cycle-time pressure, and consults twin information via an XR interface while the cell is running. In that setting, an incorrect write-back is a safety event, and misplaced or out-of-date guidance carries more risk than no guidance at all. This scenario is used as an example in Section 3.

This raises a standardisation question across the two technology domains: *How can industrial digital twin information be connected to interoperable, contextualised, and actionable XR experiences for the workers?* To address this, the position paper maps relevant standardisation activities across industrial DTs and XR, including the ISO 23247 series, the Asset Administration Shell (AAS), OpenXR, and relevant ISO/IEC work. Furthermore, we identify four integration concerns at the boundary between industrial DT information and worker-facing XR experiences: semantic and spatial alignment, worker and task context, bidirectional interaction and operational feedback, and provenance and multi-system composition. Building on these concerns, we identify three directions for future research and standardisation, as well as governance considerations applicable to all of them.

2. A Cross-Domain Mapping of Industrial DT and XR Standardisation

2.1. DT Standardisation

The principal international framework for manufacturing DTs is the ISO 23247 series, *Automation systems and integration — Digital twin framework for manufacturing*. Parts 1 to 4 were published in 2021 [12, 13, 14, 15] and define the framework’s core: Part 1 establishes the vocabulary, centred on the notion of an *observable manufacturing element* (OME), the physical thing a twin represents; a reference architecture decomposing a twin system into a device communication entity, a DT entity, a user entity and a cross-system entity; the information attributes carried by each class of OME, including personnel; and requirements for information exchange between those entities. The entity model of Part 2 is what is usually invoked when a system claims ISO 23247 alignment. Two further parts published in 2026 extend the framework. Part 5 [16] introduces the digital thread, a ledger with metadata and a query interface linking twin information across the product life cycle. Part 6 [17] classifies the arrangements by which twins produced by different parties interoperate, which is directly relevant where components originate from organisations with no shared implementation.

A parallel effort, more prescriptive in form, is the AAS, standardised as IEC 63278 [18] and developed through Plattform Industrie 4.0 and the IDTA (Industrial Digital Twin Association). While ISO 23247 supplies a reference architecture, the AAS supplies an implementable information model: an asset is described through submodels, each a separately versioned package of properties, so that interoperability can be adopted incrementally. The AAS ecosystem has also begun to represent human-related information: *Workstation Worker Matching Data* [19] is published, while *Digital Worker Profile* [20] and *Human Worker Assignment Data* [21] are under development. Similarly, [22] demonstrate that human characterisation can be incorporated into the AAS without requiring structural modifications.

2.2. XR Standardisation

The XR standardisation landscape addresses several layers of an XR system, but these layers do not directly correspond to the information models used in industrial DTs. Interoperability on the XR side is governed principally by OpenXR [23], a Khronos Group specification that abstracts headsets, controllers, and basic tracking behind a common application interface, and is implemented by both proprietary and open runtimes. WebXR provides a browser-based alternative with weaker device access but substantially lower deployment cost. These standards primarily address *device and runtime interoperability*. OpenXR, for example, specifies mechanisms for applications to access display, pose, input, spatial tracking, and related runtime capabilities. It does not define the industrial meaning of objects represented in an XR scene, their relationship to production assets, or the operational information associated with them. Consequently, an application can be interoperable at the device level but still be dependent on a particular industrial information system. ISO/IEC JTC 1/SC 24 [24] addresses broader aspects

of computer graphics, VR/AR/MR, and information representation. ISO/IEC 3721 [25], for example, defines an information model for MR/AR content, including physical and virtual objects and their spatial relationships.

In summary, the resulting gap is primarily in semantic and contextual integration. DT standards specify how industrial entities are represented and how their information is exchanged, while XR standards primarily specify how digital content is rendered and interacted with across devices. The correspondence between an industrial entity, its DT information, and its XR representation is therefore not addressed as a unified interoperability layer and is often implemented at the application level [1, 26].

3. Four Integration Concerns between DT and XR

Integrating DT information with XR-mediated interaction requires several forms of correspondence between the two technology domains. Table 1 maps these four integration concerns to representative concepts already defined in DT and XR standards. Below we examine each concern and the resulting interoperability gap in more detail.

Integration concern	DT concept	XR concept
Semantic and spatial alignment	Identifier and location of an observable element (Part 3) [14]	Spatial anchors, persistence and reference spaces [23]; object relations [25]
Worker and task context	Personnel as an observable element (Part 3) [14]; AAS submodels [19]	Pose, gaze, hand and body tracking, user presence [23]
Bidirectional interaction and operational feedback	Device control sub-entity (Part 2) [13]; information exchange (Part 4) [15]	Action system, input only [23]
Provenance and multi-system composition	Digital thread (Part 5) [16]; twin composition (Part 6) [17]	Anchor sharing via vendor extensions [23]

Table 1

Representative DT and XR concepts addressing four integration concerns at the standards boundary. The mapping is illustrative rather than exhaustive.

Semantic and spatial alignment. Twin information is useful to a worker only when it is associated with the correct physical entity and presented at its location. This requires a correspondence between three identities: the industrial asset, its digital representation, and the spatial representation through which the worker encounters it. Both domains address location, but at different levels of granularity. ISO 23247-3 lists location among the attributes of an observable element, expressed as GPS coordinates, a postal address, an ISO 6709 reference, or a relative description such as a work unit within a room. These attributes identify where an element is situated in a plant; they do not provide the metric registration required to place content upon it. The OpenXR spatial entity framework provides the converse: anchors, planes and markers that persist and are tracked across sessions, typed by geometry rather than by the asset they represent. ISO/IEC 3721 [25] models physical and virtual objects and their spatial relationships, although this association remains internal to the scene and does not extend to asset identity. The correspondence between asset data and spatial anchor is therefore established in application code. A common mechanism is to encode twin identifiers in physical QR markers resolved through a document server [1, 26], an approach that remains susceptible to occlusion and dependent on whether the XR headset’s runtime supports the marker-tracking features. In the assembly cell, markers may be occluded by the robot, fixtures, or the worker during operation. Content formats do not fully resolve the issue: glTF’s KHR_xmp_json_ld extension describes provenance and rights for 3D content rather than the industrial asset represented [27], while identifiers stored in the free-form extras field lack a standardised type and may not survive format conversion.

Worker and task context. The *worker* is present in both domains. On the DT side, personnel appear in ISO 23247-3 as a class of observable element, and the AAS submodels describe workers through profile, qualification and workstation assignment [19, 20, 21]. On the XR side the human appears as

a pose, a gaze direction and a stream of input events. Neither describes the worker *during* the task. Workload, attention and engagement are not represented in the standards examined, and neither is the state of the task itself: which step is active, for how long, and any deviation from the expected sequence. This limits the extent to which guidance can be adapted to the individual receiving it, sequenced against the step in progress, or resumed by another worker after an interruption. In the assembly cell, for example, a worker taking over mid-cycle may have no standardised record of the last completed step.

Bidirectional interaction and operational feedback. XR-DT integrations commonly present twin information to workers, while feedback from workers is often handled through separate channels or remains on the XR device. ISO 23247-4 frames information exchange from observable elements, and ISO 23247-2 defines a device control sub-entity, but the standards examined do not specify how an action taken in XR should be linked to an industrial operation, authorised, and validated. Existing standards provide parts of the mechanism: OPC UA supports callable methods and role-based permissions [28], while the AAS API specifies write access to submodel elements [18]. However, these mechanisms do not establish the full context of an XR-initiated action, such as the target asset, its spatial identification, and the task step in which the action occurs. In the assembly cell, this leaves the link between the worker's action, the intended robot or asset, and the authority to execute it to application-specific implementation.

Provenance and multi-system composition. The 2026 additions to ISO 23247 provide mechanisms close to what XR-mediated work requires, aimed elsewhere. The digital thread of Part 5 [16] supplies a ledger, metadata and a query interface designed to link information across a product life cycle, not to carry the provenance of the worker-facing layer, what was shown, when, and on what basis. Part 6 [17] classifies compositions of twins produced by different parties, addressing heterogeneity among twin providers rather than composition across layers, i.e. sensing, twin and presentation, which is the arrangement an XR deployment actually has.

4. Discussion and Research Agenda

Three directions appear feasible using existing instruments. *First*, the relationship between asset identities and spatial anchors could be specified as a shared artefact rather than being defined solely at the application level. ISO/IEC JTC 1/SC 24 and ISO/TC 184/SC 4 already maintain a joint working group on visualisation formats derived from product data, and correspondence between twin identifiers and persistent spatial anchors is adjacent to this scope. *Second*, task-time worker context could be represented through an AAS submodel, complementing the published Workstation Worker Matching Data template [19] and related templates currently under development [20, 21]. These templates describe the worker characteristics for scheduling purposes but do not currently represent the worker's context within an ongoing task. *Third*, provenance for the human-facing layer could be incorporated into the digital thread specified in ISO 23247-5 [16], which already provides a ledger, metadata, and a query interface for asset life-cycle information. A further consideration applies across all three directions. The standards examined in this paper describe what is technically possible; they do not, in themselves, determine what should be permissible in a given deployment. Requirements arising from the GDPR and the AI Act, including legal basis, purpose limitation, retention, and the handling of inferences concerning workers [29, 30], are therefore directly relevant to worker and task context as well as provenance, while remaining outside the information models discussed above. Adjacent standardisation efforts exist: the IEEE 7000 series addresses ethical considerations in system design, while IEEE 7014 addresses systems that model human states [31, 32]. Whether such requirements can be encoded and enforced through system architecture and implementation, or must instead be addressed primarily through deployment and governance policies, remains an open question. Each of the three directions therefore needs to consider this issue alongside its technical specification. Together, these directions identify concrete opportunities for extending existing standardisation frameworks to better support the integration of digital twins and XR in human-centred industrial systems, while highlighting the governance questions that such extensions must address.

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