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A Web-Based Multi-User Virtual Reality Platform for Collaborative Product Development in Additive Manufacturing

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Abstract:

Laser-based powder bed fusion of metals (PBF-LB/M) couples geometric design tightly with manufacturing and post-processing constraints. In small and medium-sized enterprise (SME) supply chains, fragmented software ecosystems, bilateral communication channels, and file-based data exchange frequently delay the detection of manufacturability issues until late in the product development phase, when design modifications become cost-prohibitive. To address these bottlenecks, this study presents a browser-based, multi-user virtual reality (VR) platform engineered for collaborative product development across distributed SME networks. Requirements were derived from a work-process analysis conducted across four German manufacturing SMEs. Built on open web standards, the platform supports real-time, true-to-scale CAD inspection, cross-sectioning, spatial audio, and persistent 3D annotations on both desktop workstations and head-mounted displays.

The platform was evaluated in two stages. In a formative study, engineering student teams used the system to conduct collaborative design reviews of additively manufactured vehicle axles. Usability on a custom five-point questionnaire was moderate, and perceived workload was low to moderate. Teams that fully integrated VR achieved higher specific rolling performance than teams that did not, although the sample does not permit causal conclusions. In an expert evaluation, six industrial project participants reviewed an additively manufactured metal demonstrator using the developed VR platform. They reported that shared immersive reviews brought manufacturing and post-processing constraints into early design stages, moving verification earlier in the VDI 2206 V-model. These findings are synthesised into a socio-technical model outlining the technical, organisational, and communicative competencies needed to deploy collaborative VR in SME manufacturing networks.

Keywords: Additive manufacturing (AM), virtual reality (VR), laser powder bed fusion - metal (PBF-LB/M), small and medium-sized enterprises (SMEs), V-model, socio-technical competence

1. Introduction

Additive manufacturing (AM) has evolved from a rapid prototyping technique into an industrial production method for geometrically complex, high-performance components. Among the available AM processes, laser-based powder bed fusion of metals (PBF-LB/M) makes it possible to produce lattice structures, internal cooling channels and consolidated assemblies, which offer substantial advantages in aerospace, energy and medical engineering [1, 2]. For small and medium-sized enterprises (SMEs), metal AM is a way to compete in high-value markets by leveraging design freedom, minimal tooling and short lead times for low-volume, customised production [3]. Realising these benefits requires coordinating interdisciplinary knowledge across the product development value chain. Large enterprises increasingly support this coordination through digital threads and integrated product lifecycle management systems [4]. SMEs form the backbone of the manufacturing sector and are recognised for their agility, specialised expertise and responsiveness to market demands [5, 6]. They typically operate in heterogeneous digital environments, however, with standalone tools, file-based data exchange and informal communication. This situation is critical because PBF-LB/M couples design and process in a way that has no direct equivalent in conventional subtractive manufacturing, where production adapts within known tolerances to an upstream CAD model. In PBF-LB/M, geometric decisions directly affect process behaviour [7, 8]. Part orientation governs support placement, surface quality and mechanical anisotropy. Features that become inaccessible after printing must be resolved at the design stage, since correcting them after fabrication is often impractical [9, 10]. A successful build job therefore depends on design optimisation, process simulation, fabrication planning and customer requirements, all of which must be integrated earlier and more continuously than a sequential, bilateral workflow permits [11].

In a typical SME, the AM value chain spans a distributed network of internal departments and external service providers. Information passes bilaterally, from customer to project manager, from design engineer to simulation specialist, and from manufacturing service provider to post-processing partner (Fig. 1). Fragmented software infrastructure and the high licensing costs of advanced collaboration tools further constrain communication across this network [12, 13].

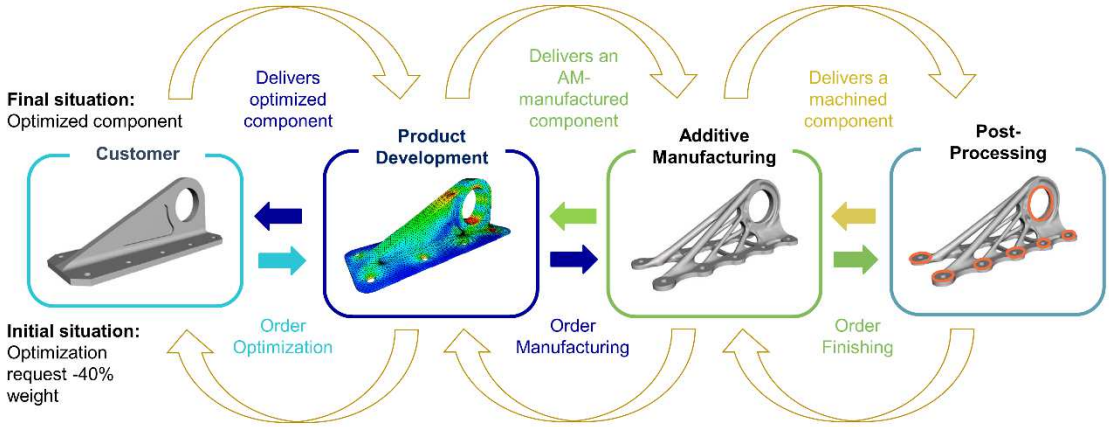


Fig. 1 Information and communication flow between stakeholders in the AM value chain.

Organisational characteristics compound these constraints. In SMEs, process knowledge is typically held by individuals rather than captured in formal organisational systems [14]. Small teams and flat hierarchies mean that engineers often work across several functional domains [5, 15]. While this keeps decision paths short, the reasoning behind design changes, implicit customer requirements and supplier limitations frequently goes undocumented. Requirements tracking and version control are also seldom digitised in a consistent way.

The V-model defined in VDI 2206 [16] is an established systems engineering framework for managing traceability and verification in complex product development. Its descending branch decomposes system-level requirements into subsystem specifications and component-level design parameters. Its ascending branch mirrors this breakdown by linking verification and validation activities explicitly to each corresponding phase. The V-model is well proven for projects with stable requirements and clearly separable phases. It assumes, however, that requirements stay stable while they are being broken down, and AM development routinely violates this assumption.

As the design and process are tightly coupled, significant findings often emerge only during manufacturing. Examples include thermal distortion that deviates from simulation, as-built surface quality that falls short of specification, and support structures that interfere with functional features. Under a sequential approach, the resulting design changes require re-entering completed phases at considerable cost [17].

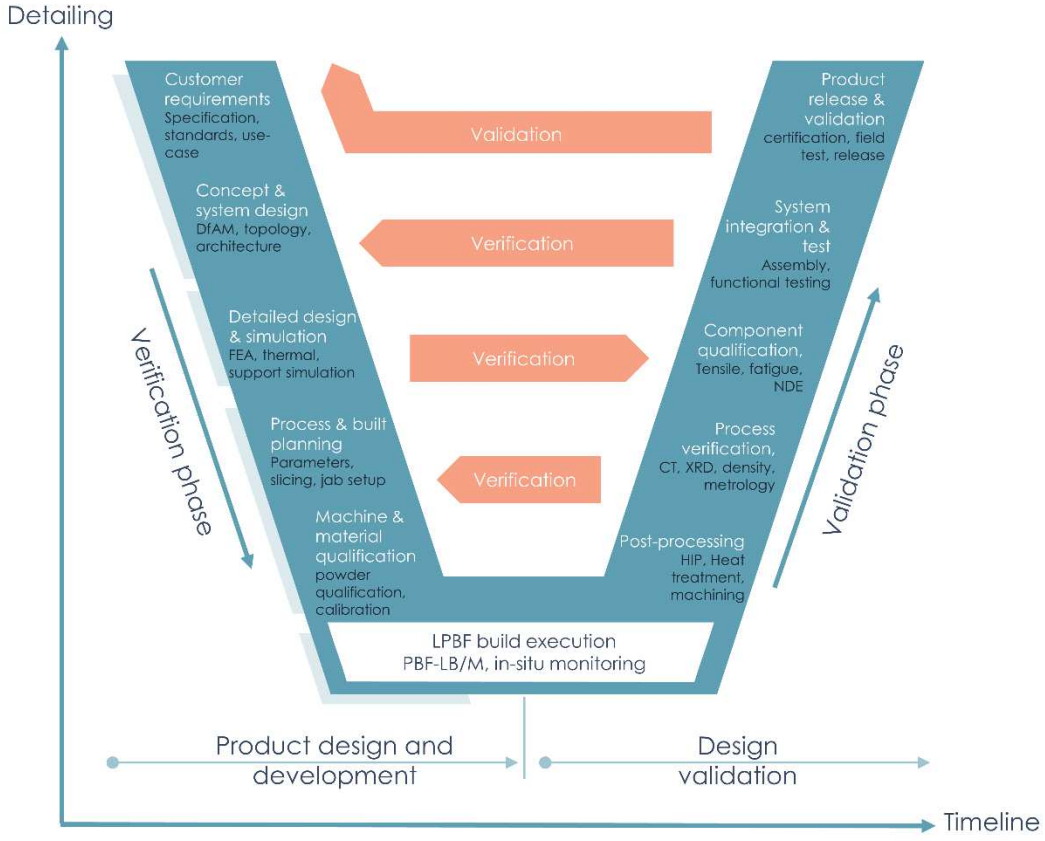


Fig. 2 Modified V-model for the PBF-LB/M product development workflow derived from VDI 2206 [16].

Fig. 2 shows a V-model adapted to PBF-LB/M product development. The V-model does not formally prohibit iteration, but its phase-gate structure makes iteration expensive in practice. Its documentation conventions are also not designed for the concurrent, cross-disciplinary exchange that effective AM product development requires. In SME practice, formal change management is therefore often bypassed in favour of direct, informal communication. This preserves development speed but sacrifices the traceability the V-model is meant to guarantee. These limitations reveal a methodological gap. Customers often mandate the traceability and assurance that the V-model provides. Yet suppressing the iterative feedback inherent to AM means accepting avoidable build failures and longer development times. SMEs therefore need a collaborative, centralised framework to replace fragmented bilateral exchange. Such a framework must ensure verification and regulatory compliance while remaining flexible enough to absorb design revisions that arise from manufacturing experience. This paper addresses this gap by developing VR, a web-accessible, multi-user virtual reality environment tailored

for additive manufacturing product development within SMEs. The platform was assessed with domain experts to identify the influencing factors and socio-technical competencies required to integrate VR into SME workflows.

This study addresses three research questions. RQ1: Which requirements must a collaborative VR platform meet to support AM product development in distributed SME value chains? RQ2: How usable and demanding is such a platform for first-time users in a collaborative design task? RQ3: Which technical, organisational and competence-related prerequisites determine its successful integration into SME workflows? The contributions of this paper are (i) a set of platform requirements derived from a work-process analysis in German SMEs, (ii) the web-based platform VR, (iii) a two-tier evaluation with engineering students and industrial domain experts and (iv) a socio-technical model of the success factors for collaborative VR in SME manufacturing networks.

2. State of the Art

2.1. New product development

New product development (NPD) for AM follows a multi-stage approach. It begins with identifying suitable candidate parts based on geometric complexity, potential for functional integration and economic viability. Once a component is selected, the design phase applies AM-specific principles, including design for additive manufacturing (DfAM) guidelines. These guidelines help designers exploit the geometric freedom of the process while respecting its constraints. Build process simulation follows the design phase. It predicts thermal deformation during the build to identify potential distortion, residual stresses and overhang regions [18]. Build preparation then defines part orientation, generates support structures, slices the part into layers and assigns scan strategies. These decisions directly influence build success, surface quality and post-processing effort [19]. A defining feature of the PBF-LB/M process chain is the strong interdependence between upstream design decisions and downstream manufacturing outcomes (see Fig. 3). Part orientation, for example, affects support volume, the distribution of surface roughness, mechanical anisotropy, and access for post-processing operations [20].

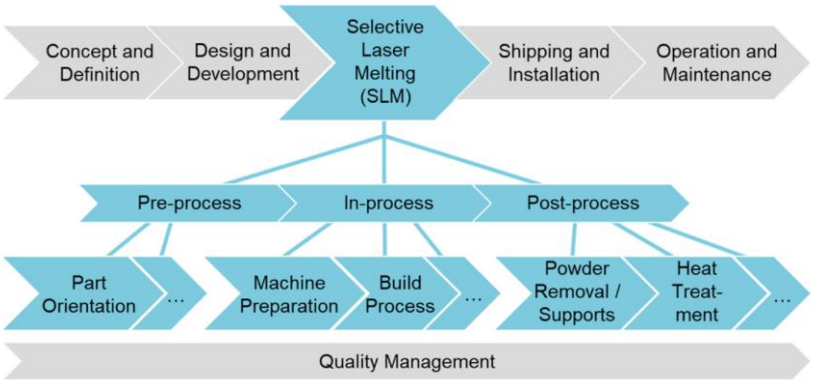


Fig. 3 PBF-LB/M process chain (adapted from [18]).

Effective NPD in PBF-LB/M requires continuous feedback between concurrent phases, which sequential, phase-gated development models accommodate only with difficulty. Several authors have proposed iterative or concurrent approaches. Gibson et al. [19] have outlined a generalised AM design process with feedback loops between functional specification, material selection and process planning. Kumke et al. [11] have introduced a structured DfAM methodology that distinguishes restrictive design rules from design strategies, and Sjarov et al. [21] have emphasised integrated digital workflows that maintain data continuity across the AM process chain. Most of these frameworks, however, presuppos a single organisation or a well-resourced development environment, as assumption that rarely holds in the distributed, resource-constrained settings typical of SMEs.

Implications: The AM-specific NPD literature establishes that cross-phase feedback must be continuous rather than phase-gated. It does not, however, provide tools that let distributed teams conduct this feedback around a shared three-dimensional model. A collaborative platform must therefore support concurrent review of design and manufacturability by multiple stakeholders at every stage of the process chain, not only at formal milestones.

2.2. Collaboration models in SME value networks

The AM ecosystem for SMEs differs structurally from that of large enterprises. SMEs typically operate within distributed value networks of specialised service providers, and each provider contributes expertise at a specific stage of the process chain. Several collaboration models address the resulting coordination challenges. Service-oriented AM business models allow SMEs to access manufacturing capacity through platform-based intermediaries, while design and quality assurance remain in-house. The AM service bureau, in which a single provider handles build preparation, manufacturing, and post-processing for multiple clients, is a common model in industrial practice [22]. Digitally integrated process chains emphasise standardised data exchange and defined handover points between process partners [21]. These models mainly capture the transactional dimension of collaboration, the exchange of information and deliverables. They give far less attention to its communicative dimension. File-based exchange and sequential feedback loops do not adequately support the transfer of tacit knowledge, spatial reasoning about complex geometries or real-time negotiation of design trade-offs [23]. SMEs in AM instead rely heavily on bilateral channels such as email, telephone, and annotated documents. These channels lack the spatial context necessary to convey three-dimensional manufacturing constraints. From a systems perspective, the SME process chain in AM can be described as a loosely coupled system [24]. As geometry becomes more complex, more stakeholders must contribute at each development stage. Without a shared spatial reference, each additional interface adds latency and ambiguity and increases the risk of information loss.

Implications: Existing SME collaboration frameworks solve the logistics of exchange but not the communication of spatial constraints. A platform that closes this gap must provide a persistent, shared spatial reference that every role in the process chain can access. Its cost and complexity must also suit SME resources.

2.3. VR in industrial contexts

Virtual reality has proven valuable for industrial design review, assembly planning, and training. Since the early 2000s, the automotive and aerospace industries have used immersive visualisation to evaluate ergonomics, spatial packaging and assembly sequences on full-scale digital prototypes [25]. These applications have typically relied on capital-intensive CAVE (Cave Automatic Virtual Environment) systems. The release of the HTC Vive and Oculus Rift in 2016 made comparable immersion available at a fraction of the cost [23] and renewed engineering interest in VR. Studies on immersive review sessions have revealed spatial conflicts missed in screen-based CAD review [23], fewer physical prototyping iterations [26], and improved spatial comprehension and faster decisions in factory layout planning [27]. Within AM, VR applications remain limited. Chheang et al. [28] have demonstrated collaborative VR inspection of CT-scanned AM parts via digital twins, including cross-sectioning of internal structures that are difficult to evaluate on screen. Such work, however, focuses on post-build quality inspection rather than on design-stage negotiation between the stakeholders of a distributed value chain. Anthes et al. [29] identify synchronous interaction, a shared spatial reference and low latency as critical requirements for multi-user engineering sessions. Silva et al. [30] propose a collaborative NPD model using VR and augmented reality (AR). Commercial platforms such as Autodesk VRED offer enterprise-grade collaborative VR. Their licensing costs, hardware requirements and integration complexity place them beyond the reach of most SMEs. Browser-based VR removes several of these barriers. WebXR and remote rendering deliver VR through standard web browsers, which reduces hardware dependency and eliminates the need for local installation [31]. Platforms such as Mozilla

Hubs, which Mozilla discontinued in 2024 and which continues only as an open-source community edition [32], have demonstrated multi-user, browser-based environments with shared spatial interaction [33]. These platforms target general-purpose social interaction and lack the engineering functions that AM design review requires, such as CAD import, measurement, structured annotation and integration with the process chain. The VR hardware landscape has changed substantially, and each change has lowered the barrier to industrial adoption [34]. The key shift has been from tethered, PC-dependent systems to standalone HMDs with onboard processing and inside-out tracking, such as the Meta Quest series. These devices need neither base stations nor dedicated computing infrastructure. Mobile processors initially limited the visual fidelity of standalone devices [23]. Hybrid modes have therefore emerged, in which a standalone HMD connects to workstations via USB or wireless streaming so that a high-performance GPU handles rendering [35]. This adds latency and network complexity. In return, it enables cable-free, high-fidelity use in any location, which matters in SMEs where dedicated VR laboratories are rarely available [34]. Complex CAD assemblies can now be rendered at frame rates comfortable for VR without the model simplification that earlier hardware required. Emerging ultra-lightweight headsets point towards devices that can be worn all day. For SMEs, these developments allow domain experts to inspect build geometries, support structures and access for post-processing directly in immersive space. Multiple stakeholders can view and annotate shared models at the same time, regardless of location [28].

Implications: The VR literature demonstrates the value of immersive review but also reveals two persistent barriers to adoption in SMEs. The first is the cost and integration complexity of commercial engineering VR. The second is the lack of engineering functions in accessible web-based platforms. A browser-first architecture with optional HMD immersion and engineering-specific collaboration tools addresses both barriers directly.

2.4. Research gap and objective

A synthesis of the existing literature highlights three primary unresolved challenges. First, the PBF-LB/M process chain requires continuous cross-disciplinary feedback that sequential, phase-gate development frameworks such as the V-model accommodate only with difficulty (Sections 1 and 2.1). Second, existing SME collaboration frameworks support the transactional exchange of data and deliverables, but leave the communicative and spatial aspects of design review largely unsupported (Section 2.2). Third, VR has proven valuable for immersive design review, but existing solutions are either expensive for SMEs to integrate or lack the collaborative and engineering-specific functions that AM product development needs (Section 2.3).

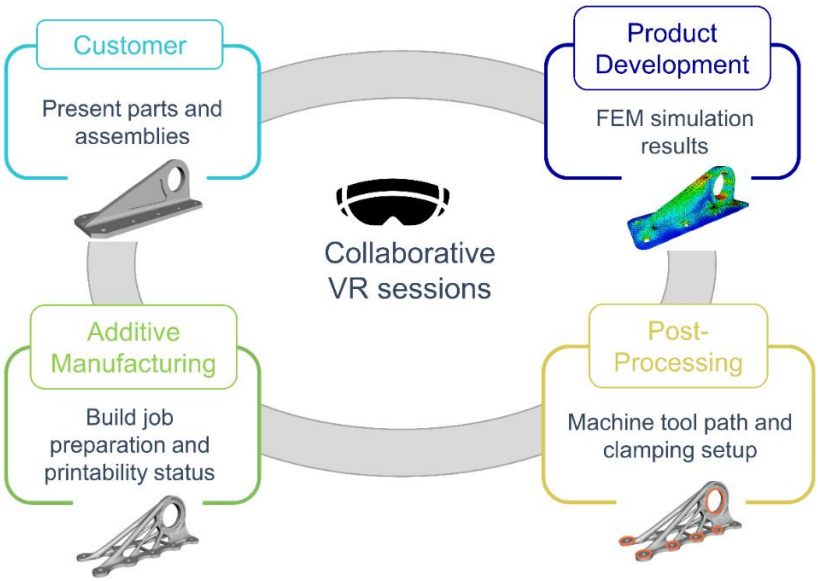


Fig. 4 Solution concept of the virtual, interactive collaboration environment VR

Consequently, current industry practice lacks an accessible, collaborative platform that seamlessly integrates into established workflows while enabling stakeholders to simultaneously examine and discuss 3D AM models. This deficiency is both methodological and technological. While existing literature heavily emphasises the technical optimisation of AM, the socio-technical dynamics of how cross-functional teams visually assess and negotiate manufacturing constraints remain under-researched. Fig. 4 illustrates the proposed solution concept for addressing this gap within the SME value chain. As a first step towards validated, collaborative AM workflows for SME networks, a formative evaluation assesses baseline usability, task workload, and user experience.

3. Methodology

To bridge the gap between fragmented SME product development practices and immersive digital collaboration, a three-phase methodological framework was implemented (Fig. 5):

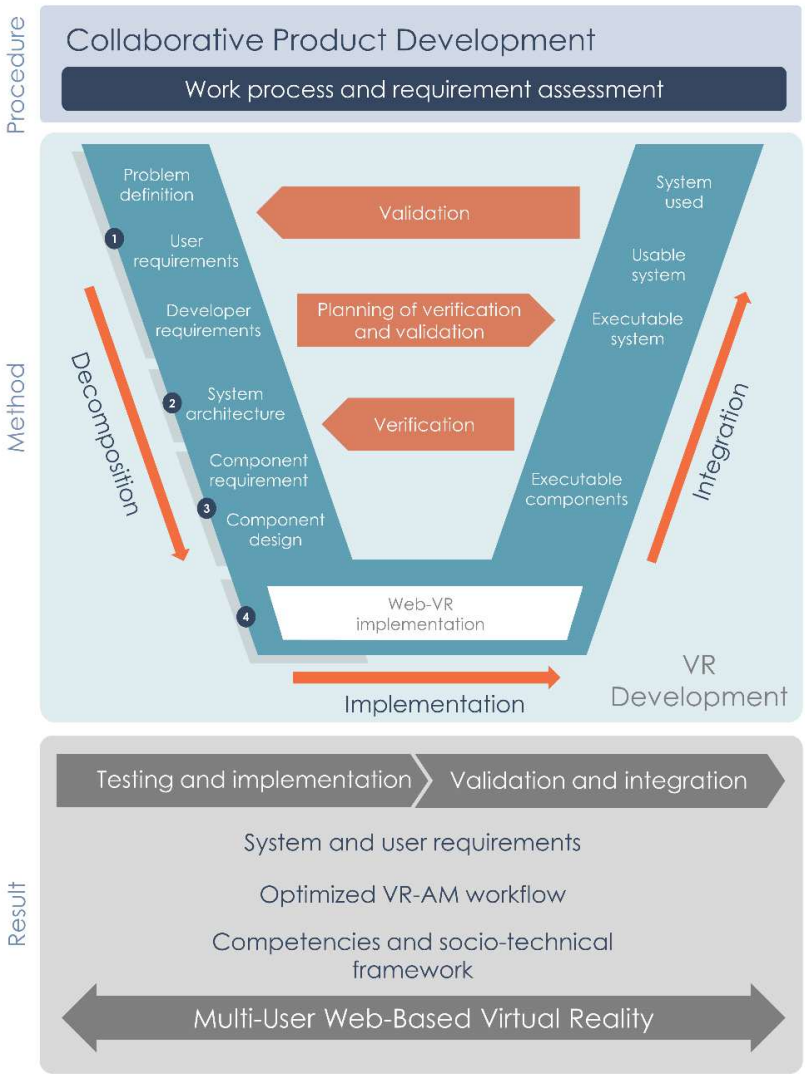


Fig. 5 Methodological framework for the development of the web-based VR platform.

- Phase 1: Work-Process and Requirements Analysis: An empirical investigation of workflow structures, communication bottlenecks, and digital toolchains across SME value chains, mapping the product lifecycle from initial order inquiry to component delivery (Appendix).

- Phase 2: Requirements-Driven Platform Engineering: The iterative specification, architectural design, and prototype implementation of the web-based collaborative VR platform (VR), guided by the systems engineering principles of the VDI 2206 V-model.
- Phase 3: Two-Tier Evaluation: A formative usability and workload study with engineering students, and a socio-technical expert evaluation with industrial domain experts.

3.1. Work process and requirements assessment

The operational context of product development within business organisations was evaluated using a work-process matrix analysis methodology grounded in vocational science (Howe and Knutzen [36]). Primary qualitative data were gathered through semi-structured interviews with domain experts representing four German SMEs. These organisations occupy complementary positions along the AM value chain in this study. The standardised interview protocol was structured around five themes to understand the competencies and current workflow for successful order execution within an SME manufacturing service provider:

- Roles and responsibilities
- Software tools and data workflow management
- Communication and coordination digital applications (internal and external)
- Skills and digital competencies of the workforce
- Limitations of integrating digital collaboration tools

Within the organisational context, the order execution process was divided into four sequential phases: order confirmation, planning, execution, and completion. The tasks in each phase of the AM workflow, and the personnel responsible for them, were analysed and mapped into a work-process analysis matrix. This matrix served as an operational reference framework. It captured how responsibilities and levels of expert involvement vary along the AM value chain, and it showed how experts take part in decisions at critical stages of AM product development. It has also exposed the need for better collaboration and decision-making between these stakeholders. On this basis, user-specific requirements were identified, and system requirements for the collaborative VR platform were derived. The development and deployment of VR are described in Section 4.2.

3.2. Testing and validation

VR was evaluated using a two-tier, mixed-methods framework that addressed two questions: how usable the interface is in operation, and how well the platform applies to socio-technical work across the product development phase. Measuring productivity or economic benefits at enterprise level would require long-term comparative baseline data, so this study used a formative, exploratory evaluation approach instead.

The first tier was a formative usability study with a cohort of engineering students during an AM design competition. The second tier was a socio-technical evaluation with industrial domain experts, built around a functional metal AM demonstrator. None of the students had prior experience in AM, so the first tier could capture baseline user experience, cognitive workload, navigation ergonomics and team collaboration patterns without the influence of domain expertise.

The second tier examined three aspects: how accurately information is communicated across trades, how far design verification can be moved earlier in the development cycle, and what organisational prerequisites are needed to deploy collaborative virtual environments in distributed SME networks. The data from both tiers form the basis for the findings, workflow models and socio-technical framework presented in Sections 5 and 6.

3.2.1. Usability and workload study

A dedicated virtual AM workshop was built to assess accessibility, collaborative dynamics and task load. It included the full set of VR collaboration features: import of CAD models in multiple formats, interactive spatial manipulation, dynamic cross-sectioning planes and persistent 3D annotations.

Student volunteers took part in a VR-based AM seminar and were organised into eight teams (G1–G8) of two to five members. Each team has designed a car axle following DfAM guidelines and imported its model into a shared VR session for inspection. In these sessions, team members held synchronous design reviews to assess printability and choose suitable build orientations. All axle designs were fabricated by powder bed fusion of polymers (PBF-P). The design performance of each physical axle was then quantified as its specific rolling performance, defined as the distance it travelled down an inclined ramp (m) divided by its mass (g).

At the end of the seminar, participants filled in a voluntary online questionnaire with two parts (Appendix). The first part assessed the usability of the VR interface with a custom ten-item questionnaire informed by the System Usability Scale (SUS) [37]. The items were positively worded and rated on a five-point Likert scale, so results are reported as item means rather than as standard 0–100 SUS scores. The second part assessed perceived task load on six dimensions adapted from the NASA Task Load Index (NASA-TLX) as unweighted (raw) ratings on a five-point scale [38, 39]. All responses were anonymised in line with applicable research ethics protocols.

3.2.2. VR-integrated AM product development workflow

To evaluate VR in a representative industrial setting, a metal AM demonstrator was designed and then fabricated by PBF-LB/M, together with the participating industrial SME partners. Throughout development, VR served as the shared environment for synchronous design reviews and manufacturability assessments.

Separate VR review sessions using head-mounted displays (HMDs) were held at the key decision points along the AM value chain, as shown in Fig. 6. These covered topology optimisation, internal structure design, build job preparation, computer-aided manufacturing (CAM) planning and quality inspection. Domain experts from the partner SMEs in design engineering, AM process engineering and quality assurance reviewed true-to-scale CAD models imported directly into the virtual environment. In these sessions, the interdisciplinary team focused on three manufacturing concerns:

- How accessible the support structures were for removal.
- Whether clamping and toolpath clearances allowed CNC post-machining.
- How clearly complex geometric constraints could be communicated in space.

After the review milestones and the fabrication of the demonstrator, participants gave feedback through post-session questionnaires with two parts: quantitative usability ratings and open-ended qualitative responses. The evaluation focused on three aspects:

- How the experts valued immersive, true-to-scale visualisation in VR.
- How well synchronous multi-user interaction features support product development.
- How practical it would be to integrate VR into existing SME engineering workflows.



Fig. 6 VR review sessions integrated into the AM product development value chain.

4. Requirements and system design

4.1. Work process analysis

Four main bottlenecks in the AM value chain of SMEs were identified from semi-structured expert interviews. Fig. 15-16 in the Appendix show the detailed work-process matrix and the roles and responsibilities in the order-execution phase of an AM design service company.

a) Bilateral (Linear) coordination: In a typical product development workflow, a design engineer sends the CAD model to a manufacturing specialist. The specialist replies by email, in annotated PDF reports or with two-dimensional screenshots. None of these formats gives the spatial context needed to convey the geometric complexity of AM parts. Information therefore passes step by step between neighbouring trades, and aligning requirements at order intake can take several days or even weeks. As a result, manufacturability problems are often found only after design freeze or after a failed build job. The part then needs several major design iterations, and each one adds to the time to market.
b) Information loss: Poor documentation, miscommunication and the lack of standard communication protocols often lead to serious misunderstandings, and in some cases to cancelled orders.
c) Data fragmentation: Manufacturing data are scattered across separate departments and software systems. This fragmentation also creates serious data security concerns.
d) Qualification gap: SMEs often lack in-house DfAM expertise and experience with digital collaboration tools.

Design requirements (R1–R4) shown in Table 1 were derived from the expert interviews of the work-process assessment. The requirements cover communication, accessibility, functional and spatial aspects. The platform has been developed iteratively following the V-model of the VDI 2206 guideline for systems engineering [16]. System-level user requirements was broken down into separate client, server and networking modules. These modules were built through rapid prototyping and then verified in structured integration tests before deployment. Although the sequential V-model is incompatible to

AM part development (Section 1), it was appropriate for developing the software platform, because the requirements R1–R4 remained stable once derived.

Table 1 Design requirements for the VR platform, derived from the expert interviews.

ID	Requirement	Description
R1	Synchronous multi-user collaboration	Real-time sessions in which distributed stakeholders share a common spatial reference, supported by spatial audio, shared viewpoints, and synchronised object states
R2	Low entry barrier and universal access	Operation in a standard web browser without local installation or dedicated infrastructure, with functionally equivalent participation for desktop users without an HMD
R3	Engineering-specific review functionality	Import of CAD models in common tessellated formats, true-to-scale visualisation, cross-sectioning, and persistent, attributable annotations
R4	Traceable decision capture	Recording of annotations and session artefacts so that design decisions remain documented

4.2. VR development

4.2.1. System architecture and network topology

VR is implemented as a web-based, multi-user platform using a hybrid client–server and peer-to-peer (P2P) network architecture to balance data persistence with real-time responsiveness (see Fig. 7). A collaboration session represents an isolated virtual workspace containing the 3D environment, connected participant instances, uploaded CAD models, and synchronised interaction states. Network responsibilities are partitioned according to data volatility:

- Centralised Server Infrastructure: An Express.js application server coordinates client connections, WebRTC signalling, session initialisation, and database persistence. The server remains agnostic to real-time spatial calculations, it maintains formal session descriptions, records persistent project data, and synchronises the global workspace manifest to newly joined clients without managing frame-by-frame transformation updates.

- Decentralised Peer-to-Peer Data Channels: High-frequency, latency-critical data streams are exchanged directly between connected clients via WebRTC peer-to-peer channels. This includes spatial transformation vectors (6-DoF avatar head and hand poses), directional audio/video streams, and dynamic manipulation matrices of active CAD objects.

This division of responsibilities minimises computational and bandwidth bottlenecks at the server, allowing interaction latency to be governed primarily by direct inter-client network performance. Consequently, deployment constraints are determined by local client GPU throughput, available network bandwidth for media streaming, and browser WebXR compliance.

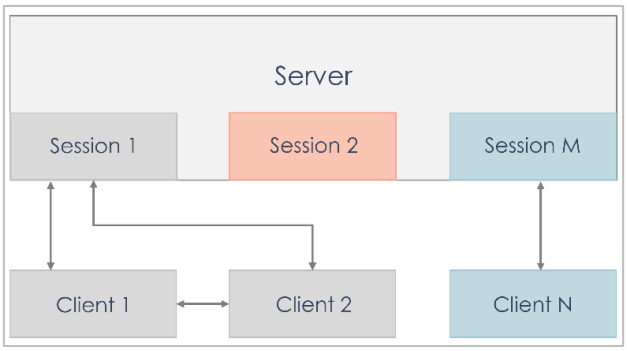


Fig. 7 System architecture and network topology of the web-based VR platform.

4.2.2. Modular client architecture

The client application is structured as an event-driven, multithreaded system implemented across background Web Workers (Fig. 8). This asynchronous separation ensures that computationally intensive operations such as parsing high-density polygon buffers or computing cross-sectional slicing planes do not block the main rendering thread, preserving smooth frame rates across both desktop monitors and immersive displays. Each functional module encapsulates its internal operational state and communicates across the application via an event-driven publish–subscribe pipeline. The modules map directly to the system requirements (R1–R4):

- Session and Synchronisation Modules: Manage peer handshakes, room state reconciliation, and network events, fulfilling requirement R1 (Synchronous multi-user collaboration).
- Rendering and Viewport Modules: Execute WebGL scene composition, camera frustum calculations, and user interface overlays directly in the browser, fulfilling requirement R2 (Low entry barrier).
- CAD Manipulation and Sectioning Modules: Provide interactive transformation handling, raycast collision, and dynamic mesh-clipping shaders, fulfilling requirement R3 (Engineering-specific review functionality).
- Annotation and Decision-Capture Modules: Handle surface-normal snapping, speech-to-text conversion, and persistent spatial mark-ups, fulfilling requirement R4 (Traceable decision capture).

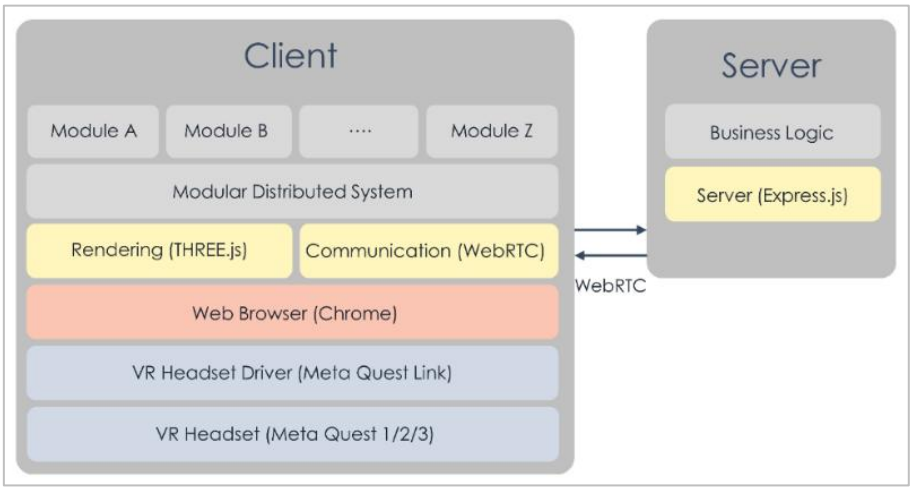


Fig. 8 Modular client architecture and functional mapping to system requirements R1-R4.

4.2.3. Execution environment and hardware abstraction

VR executes natively within standard web browsers, ensuring cross-platform portability without requiring local software installations or administrative access privileges. The software stack integrates three core web standards:

- Three.js: Provides accelerated 3D graphics rendering, material shaders, and real-time scene lighting within a WebGL browser canvas.
- WebRTC: Enables real-time, low-latency peer-to-peer audio, video, and bidirectional data communication.
- WebXR Device API: Interfaces directly with connected extended reality (XR) hardware, providing standardised controller mapping, spatial tracking, and stereoscopic projection across vendor ecosystems.

To support complex engineering CAD models without triggering thermal throttling or frame degradation on standalone mobile headsets, the platform employs a host-assisted rendering configuration. The client application runs in a web browser on a GPU-equipped host workstation, streaming stereoscopic frames to the HMD, (e.g., Meta Quest headset) via a high-speed USB-C link or local Wi-Fi. The HMD transmits 6-DoF tracking coordinates and controller input states back to the host runtime. The platform automatically detects connected XR hardware at start-up, while providing a functionally equivalent keyboard-and-mouse navigation mode for desktop users. Desktop participation therefore requires only a standard web browser, whereas immersive participation with complex models requires a GPU-equipped workstation and the HMD vendor's streaming software; requirement R2 is thus fully met for desktop users and only partly met for immersive use.

4.2.4. CAD-to-WebXR data pipeline

A central technical challenge in engineering VR is reconciling analytical boundary-representation (B-Rep) CAD files with real-time graphics engines that require discrete polygon meshes. To support SME workflows without proprietary middleware, VR integrates an open data pipeline accommodating four standardised tessellated file formats: .gltf/.glb, .stl, .obj, and .3mf. Tessellating CAD geometry presents an inherent trade-off between geometric accuracy and real-time graphics performance. Meshes must retain sufficient polygonal resolution to inspect fine geometric details, such as thin wall features, internal fluid channels, and support overhangs, while avoiding excessive triangle counts that degrade viewport interactivity. Because native CAD assemblies often contain non-essential modelling details, the platform provides a server-side API coupled with a Blender export plugin. This enables users to optimise polygon counts, remove unneeded auxiliary geometry, align component coordinate systems, and upload pre-configured virtual review spaces directly into the platform repository. Fig. 9 shows the graphical user interface of the VR environment.

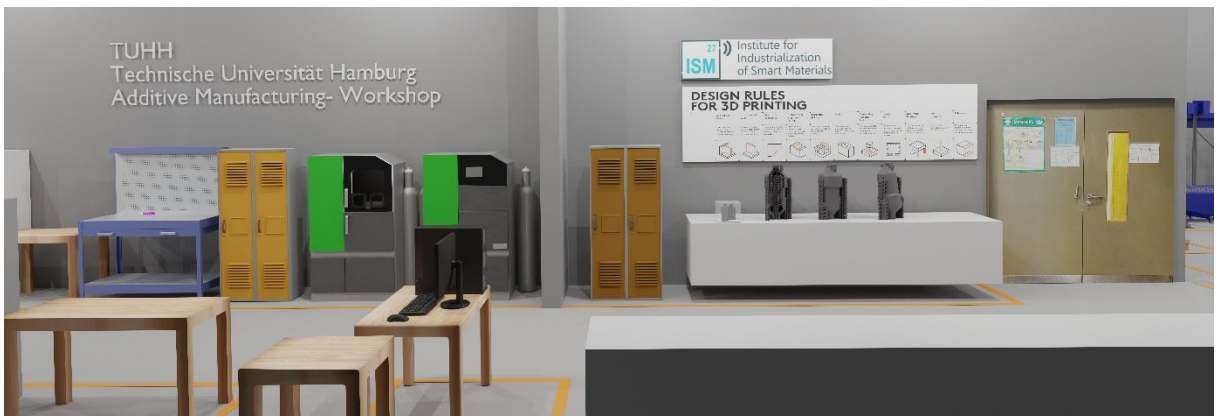


Fig. 9 Collaborative VR environment - additive manufacturing scenario.

4.3. VR environment and functional features

The platform provides a comprehensive suite of synchronous communication and model review tools across both desktop and immersive (HMD) operating modes:

- *Spatialised Audio and Visual Co-Presence*: Audio communication is spatialised dynamically according to participant distance and orientation, reinforcing spatial co-presence and conversational structure. Each participant is represented by an avatar whose head and hand orientations mirror physical user motion, accompanied by a directional ray pointer for referencing specific geometric features during group discussions.
- *Interactive CAD Manipulation and Cross-Sectioning:* Users can import tessellated CAD models (.3MF, .STL) directly into an active session. To avoid conflicting transformation inputs, model manipulations (translation, rotation, and scaling) use a single-user token-lock mechanism: one participant manipulates the component while the transformation coordinates synchronise across all client viewports in real time. Arbitrary cross-sectioning planes can be activated dynamically, allowing teams to expose and inspect internal cavities, trapped powder passages, and critical wall thicknesses. Multiple CAD components can be loaded and evaluated by side.
- *Virtual Camera Tool:* A handheld camera utility allows immersed and desktop participants to capture viewport snapshots of design issues, posting them directly into a session-wide chat stream accessible to all team members.
- *Persistent 3D Annotation Tool:* To meet requirement R4, the tool lets participants anchor spatial mark-up pins directly onto model surfaces or virtual boards (Fig. 10). Immersed users input textual descriptions using speech-to-text voice recognition, while desktop participants enter notes via standard keyboard typing. An interactive placement preview indicates the surface-normal orientation before the pin confirmed. Every annotation captures the author's username and creation timestamp, persisting throughout the session lifecycle to establish an attributable audit trail of engineering change requests.

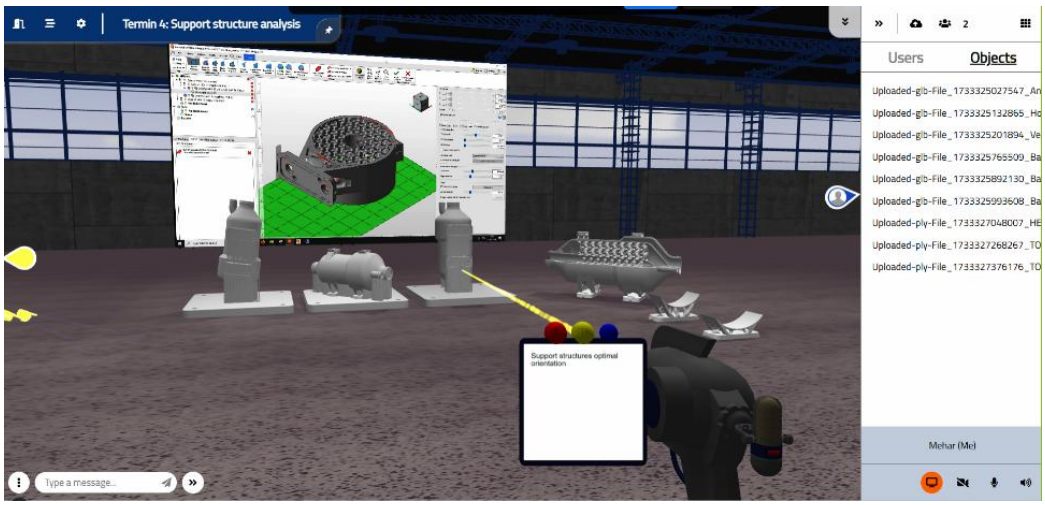


Fig. 10 In-session spatial annotation and model inspection features applied to an imported virtual object.

5. Evaluation results

5.1. Usability study

Each group designed an axle, and the axles were ranked by the performance metric defined in Section 3.2.1. Fig. 11 shows the final axle models that each group presented during the seminar. Survey responses were anonymous at the individual level but were recorded by group.

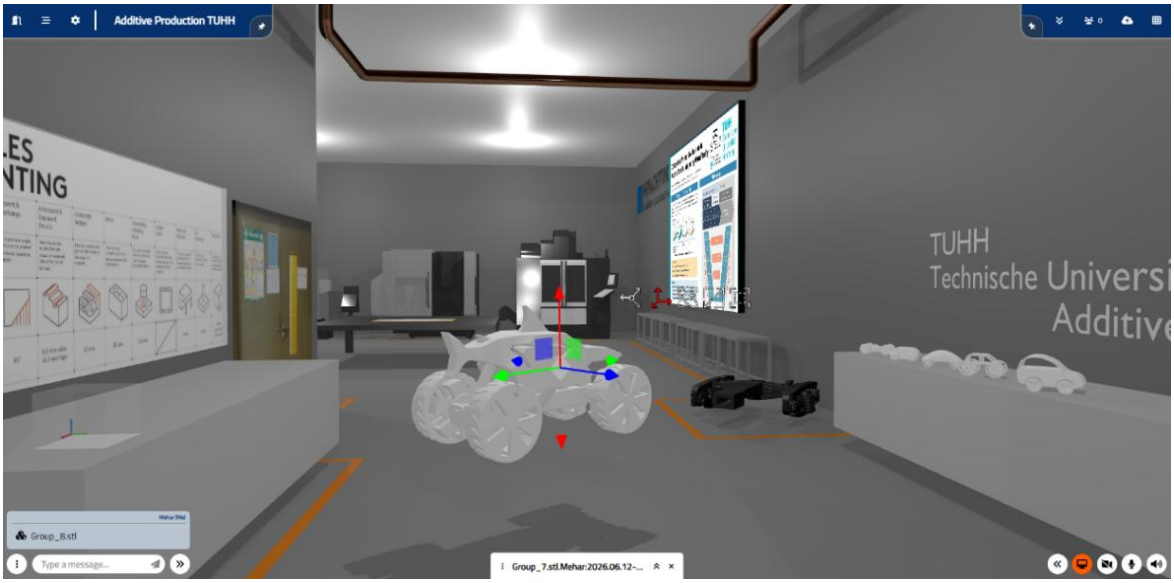


Fig. 11 Axle designs of the individual groups in VR.

5.1.1. Usability assessment

Participants rated the ten items of the custom usability questionnaire on a five-point Likert scale (Table 2).

Table 2 Item-level descriptive statistics for the custom usability questionnaire [1 = strongly disagree, 5 = strongly agree].

Item	Construct	Statement	M	SD
Q1	Suitability	Appropriate for virtual collaborative meetings	3.56	0.70
Q2	Engagement CAD GUI vs VR	More engaging than traditional CAD software for 3D model review	3.35	1.22
Q3	3D manipulation	Easy to manipulate and scale 3D models in the VR environment	3.47	0.72
Q4	DfAM understanding	Enhanced understanding of AM design features and DfAM guidelines	3.41	1.00
Q5	Screen-sharing within VR	The screen-sharing feature facilitates effective group discussions	3.41	1.23
Q6	Learning improvement	Improved understanding of 3D modelling and design analysis compared to traditional learning methods	3.38	0.99
Q7	CAD data import into VR	Successfully imported CAD models into VR (.stl / .ply / .glb / .3mf)	3.65	0.86
Q8	Collaboration	Supported effective collaboration and knowledge sharing	3.47	0.94
Q9	Physical comfort (HMD)	Minimal or no physical discomfort (motion sickness, eye strain)	3.94	0.97
Q10	Satisfaction	Satisfied with the overall VR experience	3.59	0.80

Note. M = mean; SD = standard deviation.

Physical comfort (Q9) received the highest mean (M = 3.94±0.97), indicating that the predominantly HMD-based interaction mode was well tolerated by first-time users. CAD import (Q7) ranked second (M = 3.65±0.86). The widest dispersion occurred for engagement relative to CAD software (Q2) and screen sharing (Q5). This suggests that the advanced collaboration features were the main source of inconsistent experience. The composite usability score (mean of Q1–Q10) was M = 3.52±0.66.

Three levels of VR engagement were identified in the session records:

- Full integration, with iterative CAD uploads and collaborative review (G2, G5, G8)
- Partial integration, with VR used for an intermediate review only (G4)
- Minimal or no VR integration, covering non-adoption (G3), individual-only use (G6), and technical failure (G7).

Group-level results (Table 3) show substantial heterogeneity. Group 1 did not participate in the survey. Group 8 scored M = 2.35±0.78, approximately 1.8 standard deviations below the cohort mean, with negative ratings concentrated on the advanced collaboration items (Q2, Q4, Q5, Q6, Q8) that the group used most intensively. Both respondents nevertheless rated CAD import positively, indicating that core model handling remained reliable. As a sensitivity check, excluding Group 8 raises the cohort mean to M = 3.68±0.48.

Table 3 Group-level composite usability score, overall satisfaction, and design performance.

Group	Usability M (SD)	Satisfaction M (SD)	Design score (m/g)
G2	3.80 ±0.14	4.00	7.23
G4	3.48 ±0.59	3.50 ±1.29	5.12
G5	3.50 ±0.56	4.00 ±1.00	13.63
G6	4.00 ±0.10	5.00	1.79
G7	4.20	5.00	4.25
G8	2.35 ±0.78	1.50 ±0.71	11.20

Note: G1 did not participate in the survey; G3 was excluded (no VR use); G7 contributed a single respondent.

5.1.2. Workload assessment

Six dimensions adapted from the NASA-TLX [38] were rated on a five-point ordinal scale (Table 4). The composite demand score, the mean of the five cost dimensions was M = 2.75±0.74, indicating a low-to-moderate workload. Physical demand and time pressure were rated low (M = 2.47 each), suggesting that HMD use was well tolerated and that the 1.5-hour session provided sufficient time for the review tasks. Mental demand and effort have been moderate (M = 3.00), and frustration was slightly lower (M = 2.82). In post-session feedback, participants have attributed these moderate values mainly to file-format errors and failed CAD exports. Self-assessed performance was the highest-rated dimension (M = 3.29), with more than half of the participants reporting successful task completion.

Table 4 NASA-TLX adapted workload dimensions [1 = Very Low, 5 = Very High].

Dimension	Operationalisation	M	SD
Mental demand	Cognitive effort: VR navigation, model viewing, annotation	3.00	0.71
Physical demand	Physical effort: headset or desktop controller use	2.47	0.87
Time pressure	Perceived urgency during the VR session	2.47	0.94
Performance[a]	Self-assessed success in completing inspection and assessment tasks	3.29	0.92
Effort	Overall effort required to complete designated VR tasks	3.00	0.87
Frustration	Level of frustration during VR interaction	2.82	0.73

Note. M = mean; SD = standard deviation. [a]Positively worded (higher = better); excluded from the composite workload score.

5.2. VR-integrated AM workflow

5.2.1. Collaborative design reviews on the demonstrator

The VR platform consolidates the design and evaluation phases within a shared virtual environment. Fig. 12 shows the VR sessions at different stages of product development as described in Section 3.2.2, which allow stakeholders to review design iterations and manufacturability at true scale and in their intended spatial context, irrespective of CAD proficiency.

Engineers, designers, and manufacturing specialists not only hold different information but also work with distinct problem-solving approaches and technical vocabularies, which shows up as communication friction in conventional reviews. A shared virtual model restructures this interaction, because participants reference and manipulate a common spatial representation instead of mediating between abstract descriptions. The expert sessions indicated that effective VR collaboration depends on clearly defined roles specifying who moderates, who contributes technical expertise, and who observes, with the option to shift these roles during a session.

A further structural shift has concerned the point at which manufacturing expertise enters the process. Conventionally, manufacturing specialists are engaged only after design decisions have been finalised, which restricts them to downstream problem identification. In the VR-supported workflow, they participated as co-developers from the earliest design stages, so that manufacturing issues could be raised while design flexibility remained (Fig. 13).

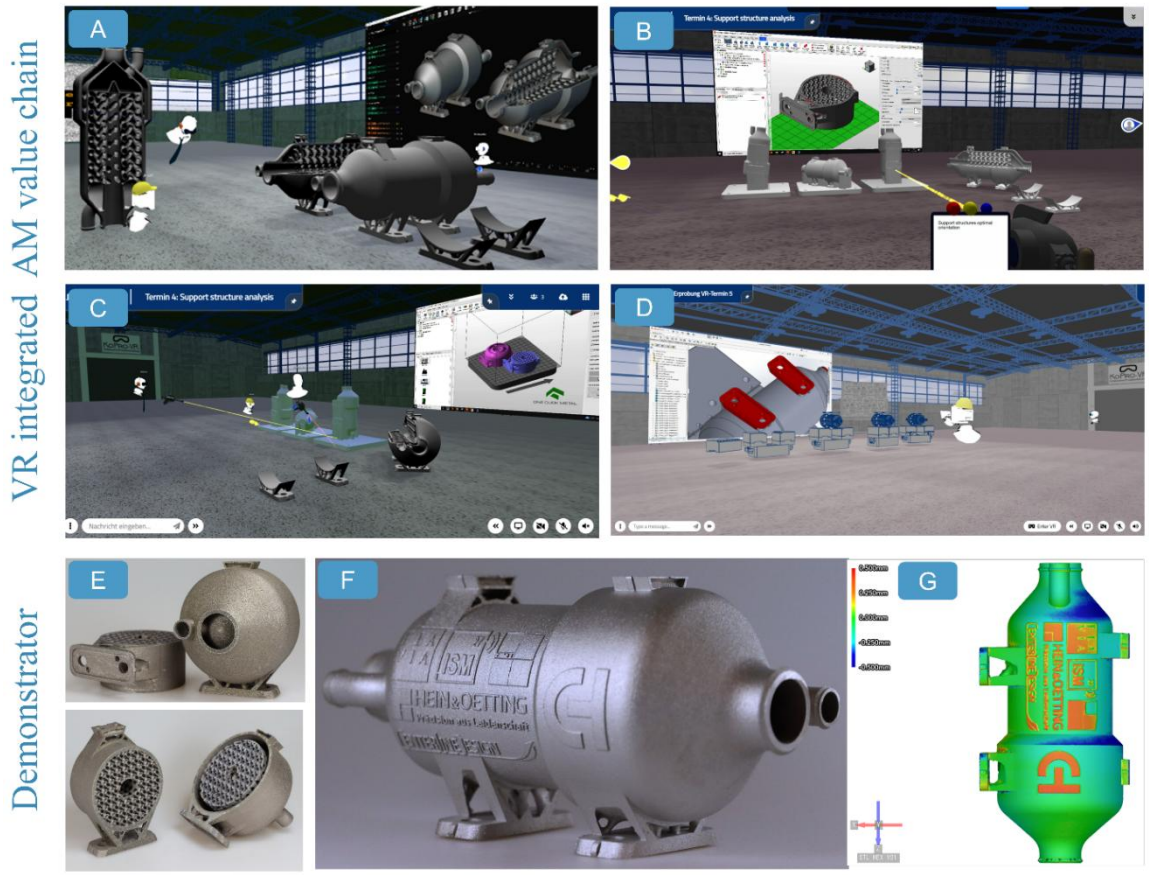


Fig. 12 VR-based collaborative design review of AM demonstrator: A-D) Evaluation of internal structures, build orientation of section and full-scale components, and post-machining setups for PBF-LB/M process; E-G) Fabricated section and full-scale components, and 3D scan comparison for quality assurance.

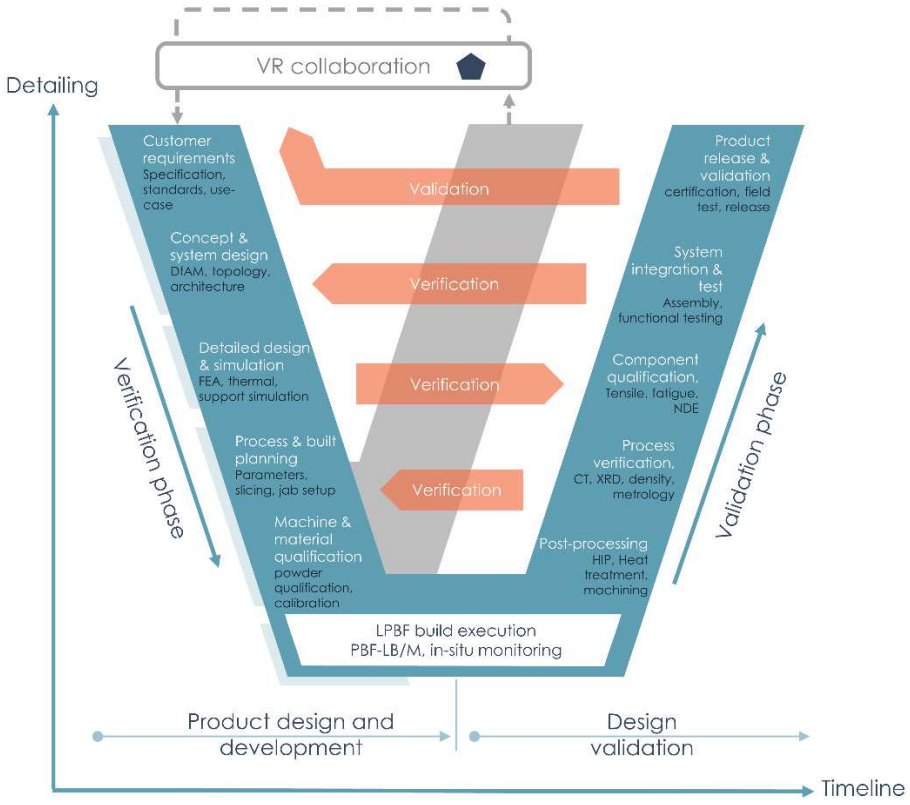


Fig. 13 Optimised VR-integrated AM workflow for product development (VR).

These observations are based on the reports of the participating partners. A quantitative comparison with conventional development (e.g., number of design iterations or build failures) was beyond the scope of this study.

5.2.2. Skills and qualifications required to integrate VR into SMEs

Observations from the demonstrator development and review sessions indicate that the main qualification bottleneck does not lie in operating the headset. Basic interaction competence (navigating the environment, scaling and orienting imported objects, and participating in a session) was acquired within a short familiarisation phase. Four other competence areas have proved decisive:

Data translation competence addresses the incompatibility between CAD formats and the mesh-based representations the environment requires, which has been the principal operational hurdle in the process chain examined here, namely subsequent machining of laser powder bed fusion components. The trial phase resolved it through a standardised routine, exporting via Blender to the Wavefront format and inserting models through a scaling and orientation tool, with mesh-based models used for additive and volume models for subtractive work preparation. Operating this routine reliably demands a competence between CAD work and IT administration that no existing occupational profile in the participating trades covers.

Multilateral communication competence follows from the shift from bilateral coordination to synchronous exchange across all trades. Specialists must externalise restriction knowledge (post-processing constraints, tooling-point requirements and AM design restrictions) intelligibly to partners without that background, and at the design stage rather than downstream. This is an articulation competence rather than a technical one.

Cross-trade expert knowledge is its precondition, since making restrictions visible early presupposes that the counterpart can interpret them. Product designers need a working understanding of manufacturing and post-processing restrictions, and manufacturing specialists

enough understanding of the design process to intervene at the right iteration. VR lowers the representational barrier but does not substitute for this shared knowledge base.

Session and process design competence covers defining discrete VR appointments, bundling the data and design iterations relevant to each, and assigning responsibilities across sub-processes. This organisational role sits at supervisory or work-preparation level and determines whether the environment yields efficiency gains or additional coordination effort.

The practical consequence is that VR integration is less a training problem than a role problem. It creates a small number of new responsibilities (data conversion, session facilitation and platform maintenance), which, in organisations with thin personnel reserves, must be assigned explicitly rather than absorbed alongside existing work.

5.3. Expert evaluation

The expert evaluation examined the potential of collaborative VR environments for industrial product development. Six project participants took part, all of whom had acquired extensive practical experience with the platform over the three-year project duration. As members of the project consortium, they cannot be regarded as independent evaluators; this is addressed in Section 6.2. Data were collected in two complementary forms: a survey using a five-point Likert scale [40], and open-ended interviews with the same six domain experts, analysed by qualitative content analysis according to Mayring [41].

5.3.1. Usability, competencies, and application potential

The results indicate a high level of acceptance. All participants have described the application as easy to learn, with immersive visualisation and intuitive spatial interaction supporting orientation and rapid acquisition of the basic functions. More complex tools, such as segment cutting, were reported to need improved user guidance. Hybrid working modes were rated very positively, as the parallel use of VR and desktop modes lowers the barrier to entry while retaining the strengths of immersive interaction. Longer sessions were associated with physical and cognitive strain, though predominantly moderate. Heat development at the headset, fatigue, difficulty concentrating, and temporary disorientation were reported most frequently, while motion sickness symptoms occurred only rarely. These findings point to a need for optimisation in ergonomics and wearing comfort and for limiting sessions to approximately 30 minutes, with individual tolerance remaining a relevant factor.

Regarding the competencies required, the responses indicate that successful collaboration depends only partly on technical expertise. The experts emphasised a willingness to move and adapt within VR, a basic technical understanding, and openness to new forms of interaction. Interdisciplinary competencies received particularly high ratings. Nearly all experts regarded the ability to adopt different disciplinary perspectives and to communicate complex technical relationships intelligibly to other disciplines as essential prerequisites, alongside a willingness to share knowledge and to obtain missing knowledge from the relevant specialists.

All application areas addressed in the survey received favourable ratings, and no negative assessments were recorded. Agreement was strongest regarding the improvement of spatial imagination, which nearly all experts rated as the greatest advantage of immersive technologies, as direct three-dimensional perception conveys spatial relationships more effectively than conventional visualisation and reduces spatial misinterpretation at an early stage. Beyond visualisation, the experts reported that the immersive environment encourages exploratory thinking and allows structural weaknesses, usage conflicts, and ergonomic or functional optimisation opportunities to be identified before physical prototypes are produced.

These potentials were considered particularly evident in additive manufacturing, where collaborative VR was rated as a substantial support for communication and joint decision-making in complex 3D printing projects. Examining models together from different perspectives, including interior views, was

reported to improve interdisciplinary coordination and the quality of technical decisions, and considerable potential was seen in reducing physical prototypes and accelerating iterative development. Possible energy savings and the reliable prediction of real-world malfunctions were assessed more cautiously, suggesting that economic benefits depend on the specific application, whereas the communicative and organisational advantages were rated as substantial across applications. Compared with conventional video conferences, VR meetings were perceived as markedly more active and participatory, since all participants can manipulate virtual objects and adopt spatial perspectives directly.

New demands on moderation were reported. Information losses may occur when participants are positioned differently within the scene or do not view the relevant objects simultaneously, and the absence of visual speaker highlighting requires conversational discipline, as speakers are identified by voice alone. Avatars do not currently convey facial expressions, so the representation of non-verbal communication remains limited, although posture and hand gestures are already implemented and assist speaker identification. The advantages over telephone and email conversations were reported as even more pronounced, as shared spatial visualisation reduces misunderstandings, helps synchronise differing levels of knowledge, and creates a stronger sense of social proximity despite physical distance. VR was not considered to match in-person meetings in non-verbal communication, so the results support a hybrid model rather than a replacement of physical collaboration, particularly in geographically distributed projects.

5.3.2. Socio-technical perspective on collaborative VR implementation

The interview analysis consolidates the individual findings into a consistent picture in which technological, organisational, and individual factors prove closely interrelated. The presentation therefore follows six overarching insights rather than the sequence of the interview questions. These insights form the basis of the socio-technical explanatory model derived from the interviews:

a. VR is evolving beyond a technology trend into a long-term transformation process for collaborative knowledge work.
b. Adoption is influenced less by the occupational sector than by the functional added value in the individual case.
c. Organisational embedding matters more than technological maturity alone.
d. Competence development is a decisive success factor, with individual competencies and education as its two dimensions.
e. Communication is becoming a key competence, and immersive collaboration changes communication itself.
f. Collaborative VR requires a socio-technical transformation of work organisation.

These six key findings are discussed below in more detail:

a. VR is evolving into a long-term transformation process for collaborative knowledge work

The experts predominantly regarded immersive collaboration environments as part of a long-term transformation in digital knowledge work rather than a short-term trend, interpreting current technological, organisational, and user-related challenges as characteristics of an early development stage. This expectation rested on perceived functional added value rather than general enthusiasm: the decisive contribution was located not in digitising existing communication but in supporting collective problem-solving and decision-making, an assessment that has recurred across all six interviews. Technical entry barriers, limited ease of use, and insufficient user experience were described as currently constraining adoption, with more ergonomic headsets, more intuitive interaction concepts, higher-performance networks, and declining costs named as prerequisites for wider diffusion.

b. Functional added value determines the diffusion of collaborative VR into the workplace

Application potential was characterised by the functional requirements of individual tasks rather than by industry boundaries, pointing to a task-oriented diffusion model. The determinants named were spatial and visual complexity, the need for shared three-dimensional interaction, and the necessity of interdisciplinary decision-making. The greatest potential was accordingly seen in knowledge-intensive planning and development processes (architecture, product development, engineering and construction, project management, and production-related activities), where a shared three-dimensional workspace allows virtual prototypes to be optimised iteratively and spatial information to become comprehensible to all participants simultaneously. For operational activities, potential was located primarily in training, process simulation, and safety-critical exercises, which suggests a staged diffusion process. Commercial, administrative, and IT-related activities were seen as offering limited additional value at present, chiefly because they already rely on highly developed digital working environments.

c. Successful implementation is primarily an organizational challenge

Implementation success was described not as a consequence of individual technological innovations but as the result of an interaction between technological performance, organisational embedding, and acceptance among employees. High-performance hardware, ergonomic devices, stable networks, and interoperable platforms were regarded as necessary prerequisites, but integration into existing work processes, systematic qualification, and the willingness of employees to adapt were described as decisive.

d. Competence development is becoming a central success factor for collaborative VR

Specialised technical knowledge was mentioned comparatively rarely as a success factor. Instead, productive use was described as requiring personal, social, and methodological competencies and a willingness to question established working practices. The experts attributed strategic importance to education, arguing that virtual working environments should be incorporated systematically into schools, vocational training, and higher education, with the objective of developing an understanding of spatial interaction, collaborative problem-solving, and interdisciplinary cooperation rather than isolated operating skills. Simulations and project-based learning were regarded as particularly suitable, and the qualification of teachers and instructors was assigned a central role. Openness to technology, willingness to learn, and adaptability were consistently identified as key prerequisites, while initial uncertainty and physical discomfort were reported to diminish substantially with increasing routine.

e. Immersive collaboration transforms communicative work processes

Immersive environments were described as altering established communication patterns rather than replacing them. The simultaneous interaction of several individuals with virtual objects creates new requirements for coordination, moderation, and shared orientation, so effective collaboration requires more structured communication than conventional digital formats. Whereas conventional media operate predominantly through language and documents, collaborative VR adds a spatial-visual layer in which objects can be viewed, manipulated, and discussed jointly in real time, which the experts regarded as an important contribution to reducing misunderstandings. Because facial expressions and eye contact remain only partially available, precise verbal communication becomes considerably more important, complemented by spatial and gestural forms of interaction such as pointing to objects or positioning oneself within the shared workspace.

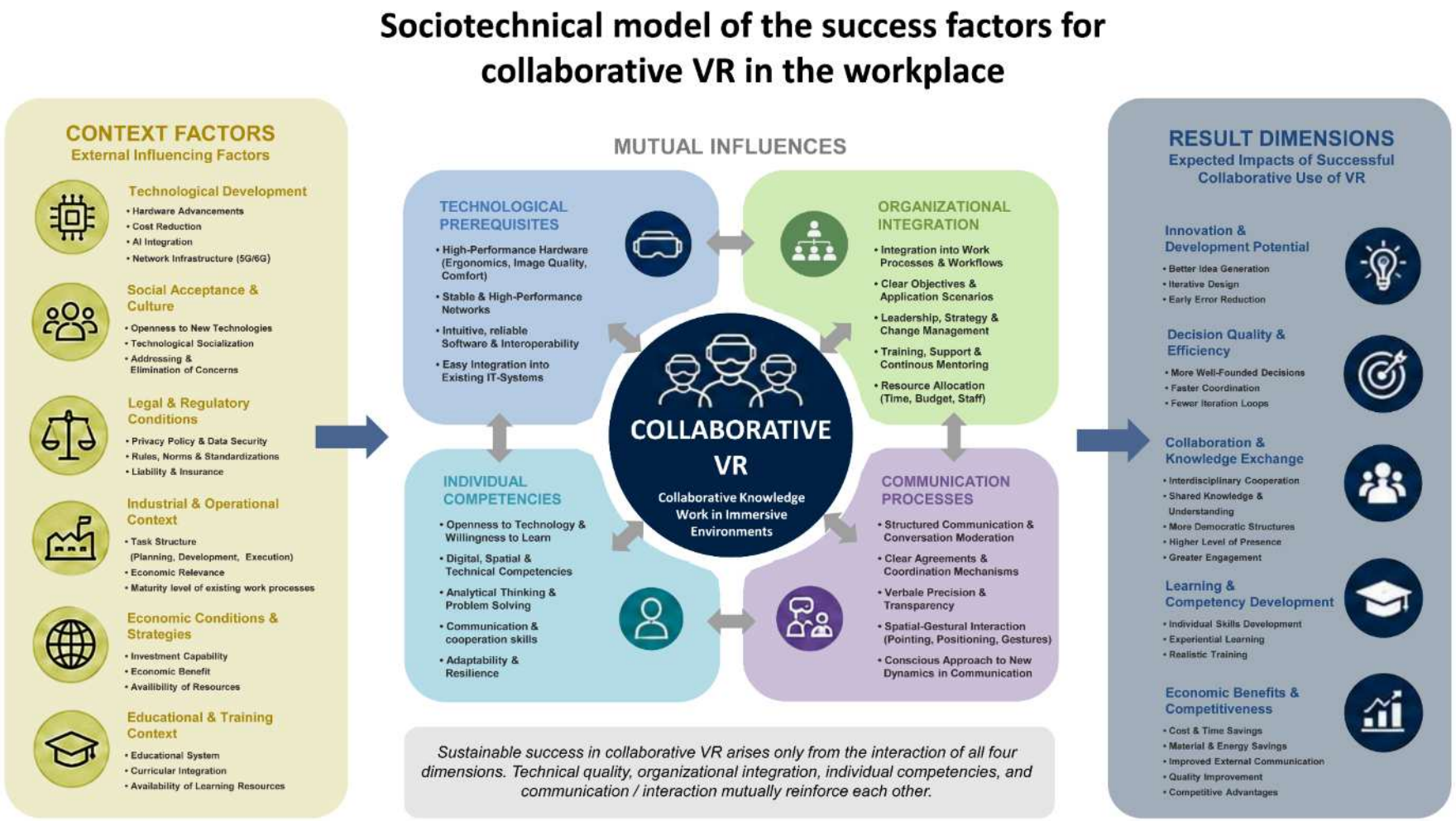


Fig. 14 Socio-technical model of the success factors for collaborative VR in the workplace.

f. Collaborative VR requires a socio-technical transformation of work organisation

The synthesis indicates that technological infrastructure, organisational design, competence development, and communication processes are mutually interdependent, and that none of these dimensions is effective in isolation: technological innovations deliver added value only when embedded organisationally and accepted by employees, while individual competence remains ineffective without suitable technological and organisational conditions.

On this basis, an integrated explanatory model was derived from the interviews (Fig. 14), whose focus is not the technology itself but its function as a medium for shared knowledge work. Fig. 14 shows the reciprocal interdependencies among technological prerequisites, organisational embedding, individual competencies, and communication processes, and their influence on successful implementation.

6. Discussion

6.1. Implications for collaborative AM product development

The results support the view that collaborative VR is most valuable where spatially complex geometry must be negotiated between trades. First-time users have rated the platform as moderately usable (M = 3.52 on a five-point scale) with a low-to-moderate workload, which is consistent with earlier reports that immersive design review improves spatial understanding compared with screen-based review [23, 26]. The expert evaluation adds that the benefit lies less in visualisation itself than in bringing manufacturing and post-processing constraints into the design phase, which addresses the late feedback typical of sequential, V-model-based AM development [17].

The socio-technical model (Fig. 14) is consistent with socio-technical systems theory, which holds that technical and social subsystems must be jointly optimised [42], and with technology acceptance research, in which perceived usefulness and facilitating conditions determine adoption [43, 44]. It extends these frameworks by identifying multilateral communication competence and dedicated roles for data translation and session facilitation as prerequisites specific to cross-trade immersive collaboration. For SMEs, whose adoption of extended reality is constrained by limited resources and awareness [34], these organisational prerequisites are likely to matter at least as much as hardware costs.

6.2. Limitations

This study has several limitations. First, the formative study relied on a small, self-selected group of students without prior AM experience in a seminar setting. Group-level comparisons are based on few groups without a control group, so differences in design performance between integration levels cannot be attributed causally to VR use. Second, usability and workload were measured with adapted, non-validated instruments on a five-point scale, which limits comparison with published SUS and NASA-TLX benchmarks. Third, the expert evaluation involved six members of the project consortium with three years of platform experience, which may bias the assessments in favour of the platform. Fourth, the evaluation covered a single demonstrator and did not include quantitative system performance benchmarks (latency, frame rate, model size or session capacity), cost or cycle-time data, or an assessment of data security and intellectual-property protection. Finally, all participating companies were German SMEs, which limits generalisability to other industrial and cultural contexts. In addition, data conversion currently relies on intermediate steps that require specialised operator intervention.

7. Conclusion

PBF-LB/M inherently couples geometric design with manufacturing and post-processing constraints, demanding continuous cross-disciplinary coordination that conventional, sequential product development workflows cannot effectively accommodate. In SME networks, this challenge is compounded by fragmented software ecosystems and bilateral, file-based data exchange that routinely defer critical manufacturability feedback until late stages, incurring prohibitive redesign and build-failure costs. To overcome these structural barriers, this work demonstrates a web-based multi-user virtual reality (VR) platform developed from an empirical work-process analysis of German SMEs. Built upon open web standards (Three.js, WebRTC, and WebXR), the system facilitates synchronous, true-to-scale CAD inspection, interactive cross-sectioning, spatialised audio communication, and persistent, attributable decision capture without proprietary client-side installations for desktop participants.

The empirical evaluations show the potential of VR integration into SME workflow. Formative testing in a design seminar showed a low-to-moderate workload on an adapted NASA-TLX ($M = 2.75 \pm 0.74$) and moderate baseline usability ($M = 3.52 \pm 0.66$) on a custom five-point questionnaire, indicating that first-time users can navigate and evaluate complex spatial models. Groups that integrated the VR workflow achieve on average a 3.5X higher specific rolling performance of their axle models than groups with minimal VR integration (10.69 m/g vs. 3.07 m/g), although the small, self-selected sample does not permit causal attribution.

According to the expert's survey, embedding collaborative VR into product development enables a "left shift" of design verification within the VDI 2206 V-model, engaging manufacturing, post-processing, and quality assurance specialists as co-developers during the early conceptual and design stages rather than as downstream evaluators. The expert evaluation further indicates that successful VR deployment in industrial practice is fundamentally a socio-technical transformation rather than a purely technological upgrade. The primary integration bottleneck does not reside in basic device interaction, but in organisational adaptation and competence development. Maximising the return on collaborative VR requires establishing clear cross-trade articulation skills, dedicated moderation roles, and specialised data translation routines to bridge parametric CAD models with real-time tessellated representations.

Future work should focus on longitudinal, comparative field trials across distributed industrial SME value chains to quantify reductions in workflow cycle time and cost relative to the status quo, including system performance benchmarks and a data-security assessment. Automated, cloud-based data pipelines that streamline CAD-to-WebXR mesh optimisation, metadata retention and tolerance verification. Finally, the formulation of vocational and academic curricula to systematically cultivate collaborative spatial engineering competencies.

8. Statements and Declarations

8.1. Funding:

This project is funded by the Federal Ministry of Research, Technology and Space of Germany (BMFTR) within the programme 'Zukunft der Wertschöpfung – Forschung zu Produktion' (BMBF Division 521, Future of Work and Value Creation; Industry 4.0) as part of the project KoPro-VR under grant no. 02L22B050-4.

8.2. Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

8.3. Author Contribution

Mehar Prakash Reddy Medapati: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Christina Rullan Lemke:** Methodology, Resources, Data curation, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Johannes Waldschmidt:** Methodology, Validation, Investigation, Writing – Original draft, Writing – review & editing. **Cedrik Fuchs:** Methodology, Resources, Writing – Original draft, Writing – review & editing. **Alwin Wilbert:** Writing – original draft, Writing – review & editing. **Adrian Derstroff:** Writing – Original draft. **Tobias Kilian:** Writing – review & editing. **Bastian Bossen:** Writing – review & editing, Supervision. **Dirk Herzog:** Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Franz Ferdinand Mersch:** Project administration, Funding acquisition. **Ingomar Kelbassa:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

8.4. Data availability:

The datasets generated and analysed during the current study are available from the corresponding author on request.

8.5. Code availability:

The code is proprietary software of Flavia IT-Management GmbH and is not publicly available.

8.6. Use of Generative Artificial Intelligence

The authors have used TUKI, the AI chatbot of Hamburg University of Technology, for language editing and Claude (Opus 5.5) for text formatting.

References

1. Ullah A, Medvedev AE, Herzog D, Molotnikov A, Liu T, Kelbassa I, Brandt M (2026) Role of laser beam shape and energy density in modulating surface quality, porosity, microstructure, and mechanical properties of PBF-LB/M Ti-6Al-4V. Journal of Materials Processing Technology 348:119197
2. Gebhardt A, Hötter JS (2016) Additive manufacturing: 3D printing for prototyping and manufacturing. Hanser, Munich
3. Achillas C, Aidonis D, Iakovou E, Thymianidis M, Tzetzis D (2015) A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. Journal of Manufacturing Systems 37:328–339
4. Qi Q, Tao F, Hu T, Anwer N, Liu A, Wei Y, Wang L, Nee AYC (2021) Enabling technologies and tools for digital twin. Journal of Manufacturing Systems 58:3–21. https://doi.org/10.1016/j.jmsy.2019.10.001
5. Terziovski M (2010) Innovation practice and its performance implications in small and medium enterprises (SMEs) in the manufacturing sector: a resource-based view. Strategic Management Journal 31(8):892–902. https://doi.org/10.1002/smj.841
6. Bella RLF, Leal Filho W, Sigahi TFAC, Rampasso IS, Quelhas OLG, Bella LF, de Moraes GHSM, Anholon R (2024) Small- and medium-sized enterprises: trends and future perspectives for sustainability and digitalization in Germany. Sustainability 16(16):6900. https://doi.org/10.3390/su16166900
7. Sing SL, Wiria FE, Yeong WY (2018) Selective laser melting of lattice structures: a statistical approach to manufacturability and mechanical behavior. Robotics and Computer-Integrated Manufacturing 49:170–180

8. Adam GAO, Zimmer D (2014) Design for additive manufacturing—element transitions and aggregated structures. CIRP Journal of Manufacturing Science and Technology 7(1):20–28. https://doi.org/10.1016/j.cirpj.2013.10.001

9. Poka K, Merz B, Epperlein M (2023) Integration of the whole digital chain in a unique file for PBF-LB/M: practical implementation within a digital thread and its advantages. In: Proceedings of the 2nd International Conference on Industrial Applications of Additive Manufacturing. Springer, Cham, pp 95–108

10. Calignano F (2014) Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. Materials & Design 64:203–213. https://doi.org/10.1016/j.matdes.2014.07.043

11. Kumke M, Watschke H, Vietor T (2016) A new methodological framework for design for additive manufacturing. Virtual and Physical Prototyping 11(1):3–19. https://doi.org/10.1080/17452759.2016.1139377

12. Dörr L, Fliege K, Lehmann C, Kanbach DK, Kraus S (2023) A taxonomy on influencing factors towards digital transformation in SMEs. Journal of Small Business Strategy 33(1):53–69

13. Battistoni E, Gitto S, Murgia G, Campisi D (2023) Adoption paths of digital transformation in manufacturing SME. International Journal of Production Economics 259:108817. https://doi.org/10.1016/j.ijpe.2023.108817

14. Florén H, Frishammar J (2012) From preliminary ideas to corroborated product definitions: managing the front end of new product development. California Management Review 54(4):20–43. https://doi.org/10.1525/mr.2012.54.4.20

15. Chibba A, Florén H, Frishammar J, Halila F, Rundquist J (2008) Product development in SMEs: a literature review. International Journal of Technology Intelligence and Planning 4(3):299–325

16. VDI/VDE 2206 (2021) Development of mechatronic and cyber-physical systems. Beuth, Berlin

17. Roh B-M, Simpson TW, Yang H, Kumara SRT, Witherell P, Jones AT (2023) Ensuring quality in metal additive manufacturing through a V-model framework. IEEE Access 11:123807–123819

18. Wischeropp TM (2021) Advancement of selective laser melting by laser beam shaping. Springer, Berlin, Heidelberg, pp 7–41

19. Gibson I, Rosen D, Stucker B, Khorasani M (2021) Additive manufacturing technologies, 3rd edn. Springer, Cham

20. Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F (2016) Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP Annals 65(2):737–760. https://doi.org/10.1016/j.cirp.2016.05.004

21. Sjarov M, Ceriani N, Lechler T, Franke J (2020) Building blocks for digitally integrated process chains in PBF-based additive manufacturing. In: Behrens B-A, Brosius A, Hintze W, Ihlenfeldt S, Wulfsberg JP (eds) Production at the leading edge of technology. Springer Vieweg, Berlin, Heidelberg, pp 368–377. https://doi.org/10.1007/978-3-662-62138-7_37

22. Savolainen J, Collan M (2020) How additive manufacturing technology changes business models? – Review of literature. Additive Manufacturing 32:101070. https://doi.org/10.1016/j.addma.2020.101070

23. Wolfartsberger J (2019) Analyzing the potential of virtual reality for engineering design review. Automation in Construction 104:27–37. https://doi.org/10.1016/j.autcon.2019.03.018

24. Orton JD, Weick KE (1990) Loosely coupled systems: a reconceptualization. Academy of Management Review 15(2):203–223. https://doi.org/10.5465/amr.1990.4308154

25. Bullinger H-J, Richter M, Seidel K-A (2000) Virtual assembly planning. Human Factors and Ergonomics in Manufacturing & Service Industries 10(3):331–341

26. Berg LP, Vance JM (2017) Industry use of virtual reality in product design and manufacturing: a survey. Virtual Reality 21:1–17. https://doi.org/10.1007/s10055-016-0293-9

27. Gong L, Berglund J, Fast-Berglund Å, Johansson B, Wang Z, Börjesson T (2019) Development of virtual reality support to factory layout planning. International Journal on Interactive Design and Manufacturing 13:935–945

28. Chheang V, Narain S, Hooten G, Cerda R, Au B, Weston B, Giera B, Bremer P-T, Miao H (2024) Enabling additive manufacturing part inspection of digital twins via collaborative virtual reality. Scientific Reports 14:29783. https://doi.org/10.1038/s41598-024-80541-9

29. Anthes C, García-Hernández RJ, Wiedemann M, Kranzlmüller D (2016) State of the art of virtual reality technology. In: 2016 IEEE Aerospace Conference. IEEE, pp 1–19

30. de Silva R, Rupasinghe TD, Apeagyei P (2018) A collaborative apparel new product development process model using virtual reality and augmented reality technologies as enablers. International Journal of Fashion Design, Technology and Education 12(1):1–11

31. Cortés Rodríguez F, Abriata LA, Frattini G, Phloi-Montri S, Teixeira Pinto Meireles F, Terrien DA, Cruz-León S, Dal Peraro M, Schier E, Lindorff-Larsen K, Limpanuparb T, Moreno DM (2025) MolecularWebXR: multiuser discussions in chemistry and biology through immersive and inclusive augmented and virtual reality. Journal of Molecular Graphics and Modelling 135:108932. https://doi.org/10.1016/j.jmgm.2024.108932

32. Mozilla (2024) End of support for Mozilla Hubs. https://support.mozilla.org/en-US/kb/end-support-mozilla-hubs. Accessed 25 September 2026

33. Williamson J, Li J, Vinayagamoorthy V, Shamma DA, Cesar P (2021) Proxemics and social interactions in an instrumented virtual reality workshop. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. AM, New York. https://doi.org/10.1145/3411764.3445729

34. Jalo H, Pirkkalainen H, Torro O, Pessot E, Zangiacomi A, Tepljakov A (2022) Extended reality technologies in small and medium-sized European industrial companies: level of awareness, diffusion and enablers of adoption. Virtual Reality 26(4):1745–1761

35. Kelkkanen V (2021) Synchronous remote rendering for VR. International Journal of Computer Games Technology 2021:6676644. https://doi.org/10.1155/2021/6676644

36. Howe F, Knutzen S (2021) Lern- und Arbeitsaufgaben entwickeln: E-Books für die Ausbildungs- und Unterrichtspraxis. tredition, Hamburg

37. Brooke J (1996) SUS: a ‘quick and dirty’ usability scale. In: Jordan PW, Thomas B, Weerdmeester BA, McClelland IL (eds) Usability evaluation in industry. Taylor & Francis, London, pp 189–194

38. Hart SG, Staveland LE (1988) Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PA, Meshkati N (eds) Human mental workload. North-Holland, Amsterdam, pp 139–183

39. Hart SG (2006) NASA-Task Load Index (NASA-TLX); 20 years later. Proceedings of the Human Factors and Ergonomics Society Annual Meeting 50(9):904–908. https://doi.org/10.1177/154193120605000909

40. Likert R (1932) A technique for the measurement of attitudes. Archives of Psychology 140:1–55

41. Mayring P (2010) Qualitative Inhaltsanalyse. In: Mey G, Mruck K (eds) Handbuch Qualitative Forschung in der Psychologie. VS Verlag für Sozialwissenschaften, Wiesbaden, pp 601–613

42. Trist EL, Bamforth KW (1951) Some social and psychological consequences of the longwall method of coal-getting. Human Relations 4(1):3–38. https://doi.org/10.1177/001872675100400101

43. Davis FD (1989) Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly 13(3):319–340. https://doi.org/10.2307/249008

44. Venkatesh V, Morris MG, Davis GB, Davis FD (2003) User acceptance of information technology: toward a unified view. MIS Quarterly 27(3):425–478. https://doi.org/10.2307/30036540

Appendix

I. Work process analysis matrix

AM Design	Work process phase - Order Acceptance	
Laws, Regulation Standards:	DIN/ISO, Technical, Commercial, Occupational health and safety Ecological aspects, Social norms	Design for Additive Manufacturing: DIN EN ISO/ASTM 52911 AM Design-Requirements, guidelines and recommendations: ISO/ASTM52910-18 Quality Management System: ISO 9001 • Contractual Agreements, Intellectual Property rights • Non-Disclosure agreement (NDA)
Operational Framework:	Personal Resources	**Customer requirements and specifications:** Consider the requirements and specifications of the customer, including material preferences, design requirements, and quality standards **Proposal:** The Project Manager/lead collects detailed information regarding the design requirements and delivery deadlines. Ensure legal and contractual obligations are met **Capacity and resource assessment:** The design lead assesses the feasibility and evaluates challenges (design complexity, material requirements, and available resources) **Order confirmation and documentation:** Confirming the order, generating contracts, and maintaining order records
Requirements of the client/customer:	Service, standards, costs, application-based requirements, guidelines	• Required technical specifications and goal of the intended design application (If available-conceptual design, material requirements, quality and additional functionality) • Industrial guidelines or ISO quality standards (if needed) • Cost estimate quotation • Formal contractual agreement that outlines terms and conditions, and confidentiality agreements
Field of action / Action steps:	1. Initial order review 2. Effective communication 3. Operational requirements 4. Internal communication 5. Risk assessment 6. Quotations and pricing along with the terms and conditional agreement (customer and partners) 7. Internal approval and documentation	1. Review project specifications, deadlines and delivery expectations from the customer to ensure alignment with company capabilities and expertise 2. Communicate with the customer to define precise specifications (design restrictions, timeframe, load cases, and additional design-specific requirements) and sub-contractors to define manufacturing goals and objects 3. Ensure necessary resources and expertise for the project (tools and systems) 4. Communicate customer requirements with the design engineer (customer requirements assessment) 5. Identify potential risks and challenges and develop strategies for mitigation 6. Provide a detailed cost breakdown, present terms and conditions, and formalize the agreement. work with the customer to negotiate contract terms, pricing and deliverables 7. Seek internal approvals from management or relevant departments and ensure all relevant documentation, including project specifications, contracts, and internal approvals, are properly filed and accessible
Work objects:	Technology (Software, tools, equipment) PC and software Documents & other (manuals, catalogues, lists, etc)	• Databased tools, e.g. snipe-IT Data bank • Quotations & contract Templates and software (Joplin) • CRM Software and MS Office tools (Meister Task) • CAD software (Solid Works, Catia V5) • Communication tools (Email, Messaging, Zoom, Big-Blue button, etc.) • Information sharing cloud platform (Vault-cloud)

Fig. 15 Work process matrix for the order acceptance from an AM design service provider.

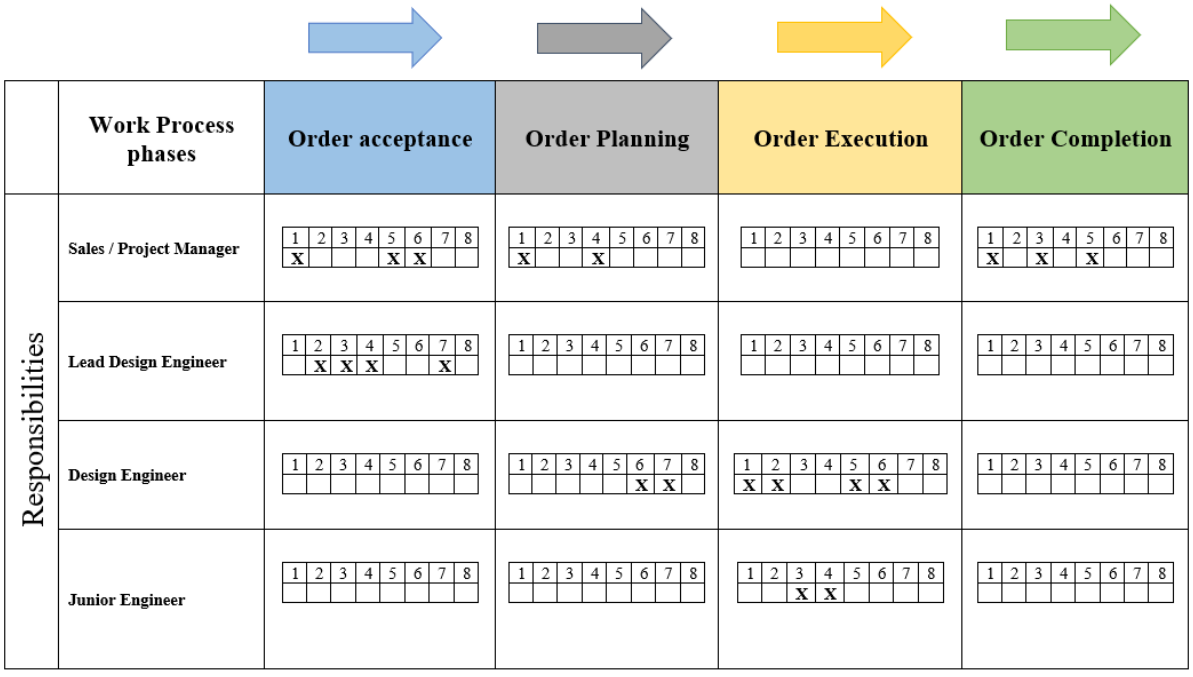


Fig. 16 Roles and responsibilities for each phase of order execution to completion (X - task based involvement in each step).

II. Online survey questions

Section A: VR usability

Rate your agreement with the following statements (X) on a scale of 1 to 5 (1 = Strongly Disagree | 5 = Strongly Agree)

	Statement	1	2	3	4	5
1	The use of the VR environment was appropriate for virtual meetings.					
2	I found the VR environment more engaging than traditional CAD software for viewing and manipulating CAD models.					
3	It was easy for me to manipulate and scale 3D models in the VR environment.					
4	The VR platform enhanced my understanding of design features and design for additive manufacturing (DfAM) guidelines					
5	The screen-sharing features in VR were effective for facilitating group discussions.					
6	VR improved my understanding of 3D modelling and design analysis compared to traditional learning methods.					
7	I was able to successfully import 3D CAD models (e.g., .stl, .ply, .glb, .3mf) into the VR environment.					
8	The VR environment supported effective collaboration and knowledge sharing with my team.					
9	I experienced minimal or no physical discomfort (e.g., motion sickness or eye strain).					
10	I am satisfied with my overall VR experience using the VR platform.					

Section B: NASA TLX - Work Load Analysis:

Rate your agreement with the following statements on a scale of 1 to 5:

1 = Very Low | 5 = Very High

	Statement	1	2	3	4	5
1	How mentally demanding was working in the VR environment (e.g., viewing CAD models, adding annotations, navigating, uploading different models)?					
2	How physically demanding was the task (e.g., wearing the headset, using controllers, or desktop navigation)?					
3	To what extent did you feel rushed or under time pressure during the VR session?					
4	How successful do you feel you were in completing the CAD model inspection and assessment tasks?					
5	How much effort did you have to put in to complete your tasks within the VR?					
6	How frustrated did you feel while interacting with the VR environment?					