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Virtual-Reality Surface Integration and Evaluation Method for Vehicle Interior Design

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Abstract

Innovative vehicle-interior surfaces require the integration of material, functional, component, requirement, and user-related perspectives, which are often addressed separately in material science and engineering design. This study introduces the Virtual-Reality Surface Integration and Evaluation Method (VRSIEM) as a structured approach for identifying, screening, and evaluating potential surface applications in early product development. The method combines a use-case database, VR-based spatial assignment, evidence-based material linking, requirement-based preselection, and a 23-factor potential model. The underlying dataset comprises 323 documented surface use cases from scientific and industrial sources. VRSIEM is demonstrated through an illustrative autonomous-shuttle application. Fifteen use-case–component–material combinations were screened, reducing the set to eleven alternatives, of which three were retained for detailed potential evaluation. The example demonstrates how VRSIEM can make technical, organizational, environmental, and user-related trade-offs transparent while maintaining traceability to supporting evidence and requirements. The method is intended to support interdisciplinary solution ideation and decision-making without replacing detailed engineering validation.

Keywords: vehicle interior surfaces; surface engineering; virtual reality; engineering design; material selection; functional surfaces; requirements-based preselection; design evaluation; decision support; interdisciplinary design

1. Introduction

The development of functional and innovative interior surfaces increasingly requires collaboration between material science and engineering design. However, both domains typically operate at different levels of abstraction. Material scientists focus on material properties, structures, processing routes, and achievable surface characteristics, whereas engineering designers primarily describe required functions, vehicle components, use contexts, and system-level requirements. Consequently, translating a desired function or application into a suitable material–surface–component combination remains difficult, particularly during early development when solution spaces are still open. This creates a need for systematic approaches that connect these perspectives without requiring either domain to adopt the terminology and reasoning structures of the other. A structured method can support this translation by linking intended use cases and component-level functions with relevant surface requirements, material characteristics, and feasible material solutions. Such an approach can make potential combinations transparent, comparable, and traceable throughout the development process. This paper therefore develops a method

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for systematically bridging the material and engineering-design domains in the context of vehicle interior surfaces. Process models provide the organizational framework for structuring the required information and transformation steps, while virtual reality offers an interactive environment in which functions, components, use cases, and potential surface solutions can be jointly explored. Together, these elements support interdisciplinary communication and provide a structured basis for identifying, discussing, and evaluating promising material–surface applications during early design phases.

2. State of the Art

The state of the art focuses on the challenge of connecting material science with engineering design. Relevant terminology and established approaches are examined to clarify how materials, surfaces, functions, components, and requirements relate and where existing methods remain insufficient.

2.1. Challenges in Material-Oriented Product Development

Material decisions in product development require the integration of knowledge from materials science and engineering design, yet the two domains describe design problems through different information structures and levels of abstraction [1,2]. Materials specialists primarily characterize alternatives through measurable properties, processing conditions, and performance, whereas designers additionally rely on contextual, sensory, semantic, manufacturing, and application-related information [2–4]. Consequently, the challenge is not merely accessing material data, but translating material-level knowledge into information that can be related to intended product functions, applications, user interactions, and design constraints [1,5]. Although digital selection systems can organize large material datasets and screen alternatives, formalized property information alone does not represent all criteria relevant to product-design decisions [3,4]. Recent sustainability and circularity research further expands this translation problem by adding life-cycle impact, material origin, durability, recovery, and end-of-life considerations to conventional technical requirements [6–9]. Emerging materials intensify the difficulty because unfamiliar properties, processing routes, and incomplete or dispersed information increase the knowledge required to identify suitable applications [7,8]. At the same time, contemporary selection methods demonstrate that technically viable solutions increasingly require simultaneous consideration of mechanical, thermal, manufacturing, economic, environmental, and application-specific criteria [9,10]. Material integration in early product development can therefore be understood as an interdisciplinary translation problem in which material and surface potentials must be systematically connected with engineering-level functions, components, and requirements before individual solutions can be meaningfully evaluated [1,6,10].

2.2. Basic Concepts in Material-Oriented Product Design

A consistent connection between engineering design and material development requires the principal terms to be distinguished according to their level of abstraction [11,12]. In engineering design, a function describes the intended purpose or transformation of a technical system without prescribing its physical realization; functional modelling therefore decomposes an overall purpose into functions and sub-functions [13,14]. The Function–Behaviour–Structure framework similarly separates what an artefact is for from its behaviour and the structure through which that behaviour is realized [15]. Function should therefore not be equated with a component: product architecture describes how functions are allocated to physical components [16]. A component can thus be understood as a structurally identifiable part of a product that realizes one or more functions and interacts with

other parts through defined relations or interfaces [12,16]. Requirements constitute another information level, expressing needs, conditions, performance targets, or constraints that a system and its elements must satisfy. At the system level, architecture approaches link requirements to functions, parameters, and components [12]. Use cases operate at a more application-oriented level and can group several requirements around a specific interaction or intended application, as demonstrated for automotive system requirements [17]. At the realization level, materials provide the physical basis of components and are characterized by technical properties, processing possibilities, and sensory or experiential qualities relevant to product design [2,4]. These experiential characteristics are strongly influenced by the product surface, where properties such as texture, roughness, and visual appearance affect perception and interaction [4,18]. Material and surface should therefore be related but not treated as synonymous: the material denotes the physical substance or material system, whereas the surface represents the interface through which visual, tactile, protective, or interactive characteristics become relevant [2,4,18]. These distinctions establish the information logic applied in this study: a use case defines the application context, functions describe intended effects, components provide physical allocation, requirements constrain realization, and materials and surfaces constitute the corresponding solution space [12,13,16,17].

2.3. Comparative Analysis of Material–Design Integration

Existing approaches address different parts of the interface between material development and product design, ranging from material-driven exploration to requirement-based engineering integration [19–21]. Material-Driven Design (MDD) structures development around understanding a material technically and experientially, defining a material-experience vision, identifying experience patterns, and developing product concepts [19]. Its strength is the systematic exploration of material potential and the transition from a given material toward possible applications, while component-specific requirements and formal screening of resulting alternatives are not central elements of the method [19]. The Materials in Products Selection (MiPS) tools address another part of this translation by supporting designers and clients in converting desired user interactions into sensorial material properties using questions, reference products, images, and material samples [22]. Although effective for establishing a shared understanding of experiential requirements, the approach concentrates on user–material interaction rather than linking application, component, engineering requirements, and material feasibility [22]. Wilkes et al. explicitly address interdisciplinary translation between designers and material scientists by relating technical material attributes to subjective material experiences through controlled material stimuli and experiments [23]. This establishes a strong cross-disciplinary communication mechanism, but does not constitute a product-level process for identifying use cases, allocating components, and screening alternatives against requirements [23]. Similarly, Prototyping Materials Experience employs material demonstrators and prototyping tools to support shared exploration of the potentials and boundaries of underdeveloped smart-material composites [24]. Its particular strength lies in making dynamic and experiential material behaviour accessible across disciplines, whereas the approach remains focused on exploratory understanding rather than formal requirement-based selection and traceability [24]. From an engineering perspective, the inverse decision-based approach of Nellippallil et al. integrates materials, products, and manufacturing processes by connecting processing–structure–property–performance relations with product performance goals [20]. Hereafter, processing–structure–property–performance is abbreviated as PSPP. It therefore provides systematic and technically traceable design exploration, but requires formal models and defined performance objectives and is less suited to open-ended iden-

tification of new material applications in early design [20]. For automotive interiors, Yu et al. provide a particularly relevant card-based co-design toolkit combining design objectives, smart-material technologies, evaluation criteria, and an interior layout board within workshops involving technical researchers, designers, and industrial stakeholders [25]. The method strongly supports application generation, contextualization, and interdisciplinary communication, while engineering requirements and the traceable exclusion or preselection of material–component combinations remain comparatively informal [25]. Most directly related to functional surfaces, Kizgin et al. propose a multi-level framework connecting system requirements and component functions with surface properties, microstructure, process parameters, design catalogues, and PSPP-based validation [21]. The framework establishes a particularly strong technical bridge between engineering design and surface engineering, but is presently conceptual, depends on the future population and validation of effect catalogues and PSPP models, and provides limited support for collaborative identification of application opportunities [21]. Taken together, these approaches provide complementary capabilities, but none simultaneously integrates systematic application identification, component allocation, requirement-based screening, material and surface potential, interdisciplinary translation, decision traceability, and collaborative contextual exploration [19,21,25]. The comparative capability assessment in Figure 1 summarizes these differences using Harvey balls and shows that the required capabilities are distributed across several approaches rather than comprehensively addressed by a single method. In particular, the strongest related approaches combine either exploratory material–application development, interdisciplinary co-design, or technical requirement integration, but do not integrate all three perspectives within one traceable process. The comparative assessment in Figure 1 evaluates the extent to which the reviewed approaches explicitly operationalize the capabilities required for connecting material and engineering-design perspectives.

Method/Paper	Application / use-case discovery	Component allocation	Formal requirements	Material / surface potential	Cross-domain translation	Constraint-based screening	Decision traceability	Collaborative context
MDD — Karana et al. (2015)	◕	◔	◔	●	◑	◔	◔	◔
MIPS — van Kesteren et al. (2007)	◑	◔	◔	◑	◑	◔	◔	◑
Interdisciplinary Translation — Wilkes et al. (2016)	◔	○	◔	◕	●	○	◔	◑
Prototyping Materials Experience — Barati et al. (2019)	◑	◔	◔	●	◕	○	◔	◕
Inverse Integrated Design — Nellippallil et al. (2018)	○	◔	◕	◕	◕	◕	◕	○
Card-based Co-Design — Yu et al. (2025)	◕	◑	◔	◕	◕	◔	◔	●
Functional-Surface Framework — Kizgin et al. (2026)	◔	◑	◕	◕	◕	◑	◑	◔

○ Not covered ◔ Low ◑ Partial ◕ Substantial ● Full

Figure 1. Capability comparison of material–design integration approaches using Harvey balls [19–25].

The Harvey-ball assessment uses a five-level ordinal rubric: Not covered = the capability is absent; Low = the capability is mentioned or only indirectly supported; Partial = individual method elements operationalize the capability; Substantial = the capability is systematically implemented but remains incomplete or secondary; and Full = the capability is explicitly and comprehensively implemented as a central element of the method. Ratings were assigned by the authors based on the documented procedures of the cited methods and should therefore be interpreted as a structured comparative assess-

ment rather than measured performance data. The comparison reveals complementary but fragmented strengths: material-oriented approaches support exploration of material potential, engineering-oriented methods provide more structured requirement integration, and co-design approaches facilitate interdisciplinary application development. However, none simultaneously provides systematic use-case identification, component allocation, requirement-based screening, decision traceability, and collaborative exploration, thereby indicating the need for an integrated methodological approach. These deficits define the methodological requirements addressed by the approach developed in this study. The assessed capabilities cover material exploration, engineering integration, and interdisciplinary collaboration.

3. Methods

Section 3 develops the individual VRSIEM elements, while Section 4 integrates them into the complete workflow. In brief, use cases are assigned to components in VR, linked to documented material alternatives, screened against requirements, evaluated against reference solutions, and transferred to a continuation decision.

3.1. Use Case Dataset Design

The dataset was developed through a structured use-case review to capture innovative surface applications across a broad range of vehicle-interior contexts and technological maturity levels. Scientific publications were combined with publicly documented industrial and real-world applications. This combination was selected to include both experimentally investigated technologies and solutions already implemented under practical operating conditions. Candidate cases were identified through manual searches and generative-AI-supported internet research using OpenAI ChatGPT (ver 5.5). The AI was used to identify potentially relevant use cases and source leads, but was not treated as an evidence source. Every retained case was subsequently verified against the corresponding scientific publication or industrial source before inclusion.

Candidate collection and consolidation were conducted between July and early August 2026. The search combined the scientific literature with publicly documented industrial applications. Scientific candidates were identified from peer-reviewed publications, while industrial candidates were identified through official OEM and supplier websites, product and project documentation, technical communications, trade-event material, industry platforms, and, where necessary, credible trade publications. Searches targeted vehicle-interior applications involving innovative, functional, smart, sustainable, circular, interactive, hygienic, sensing, lighting, display, comfort, or protective surface functions. AI-supported internet research was used to broaden candidate discovery and identify potentially relevant source leads, while inclusion was based exclusively on the subsequently verified underlying source.

A candidate was retained when it described a concrete vehicle-interior surface or material application, provided sufficient information to identify its intended function or use case and application context, and was supported by a traceable scientific or industrial source. Candidates were excluded when the source could not be verified, the application was outside the vehicle-interior surface scope, or the available information was insufficient to establish the relevant use-case, component, or material relationship. During initial source extraction, potentially duplicate entries were intentionally retained to avoid premature information loss. Duplicates referring to the same underlying application were subsequently removed during dataset consolidation. The resulting 323 entries therefore constitute a verified evidence corpus rather than an exhaustive or statistically representative sample of all available vehicle-interior surface technologies.

After collection, the retained entries were consolidated into a common database structure. Source terminology and levels of technical detail differed considerably; therefore, technology readiness level, surface use case, material or material combination, and vehicle-interior component were harmonised into common categories, allowing cases from heterogeneous sources to be compared within a unified structure.

The TRL distribution, shown in Figure 2, confirms that the dataset covers both research-oriented concepts and mature industrial applications. Although the cases are concentrated around intermediate development stages and fully implemented solutions, early-stage research and validation activities are also represented. The dataset therefore provides a sufficiently broad maturity spectrum for identifying transferable surface applications rather than focusing exclusively on either laboratory research or current production vehicles.

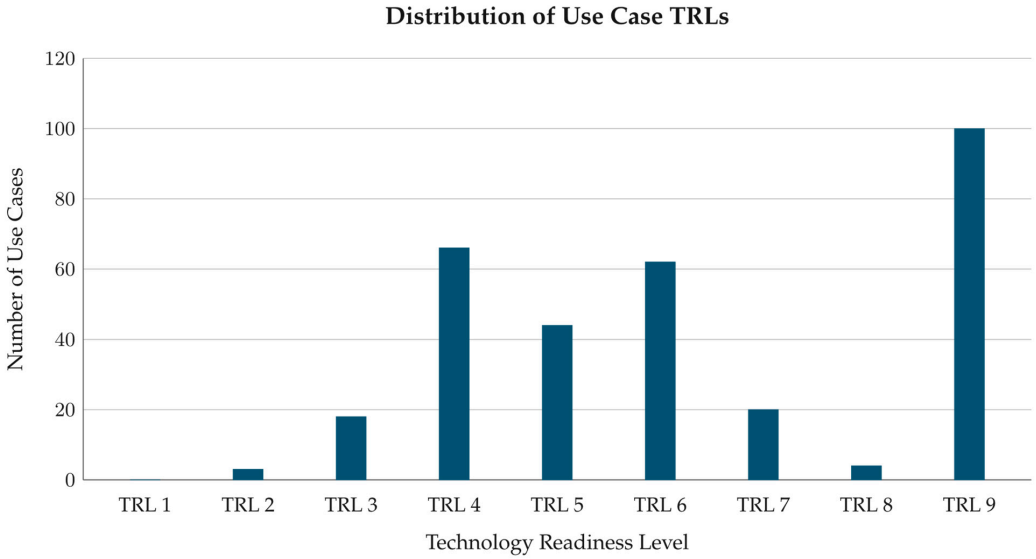


Figure 2. Distribution of the identified surface use cases across technology readiness levels.

The material–component matrix, shown in Figure 3, demonstrates that the dataset includes a diverse range of material approaches and interior application locations. It also reveals that certain materials are applicable across several components, whereas others remain associated with more specialised applications.

The use-case matrix, shown in Figure 4, similarly indicates broad functional and spatial coverage. Some surface functions occur across multiple interior components, while others are strongly linked to specific interaction areas or component requirements. Together, the three figures characterise the dataset's maturity, material, component, and functional coverage.

3.2. Use-Case Card Design

Building on the consolidated use-case dataset, "digital sticky notes" were developed as movable prompts for identifying potential surface applications within the virtual vehicle interior. Each card represents a functional theme and can be positioned, compared, rearranged, or removed within the spatial context. Each parent card represents one consolidated use-case category from Figure 4, while its selectable sub-use cases represent more specific applications derived during dataset consolidation. The revised design uses a dual-layer structure: the first layer presents a short title and functional prompt, while an information symbol provides clarification and an options button opens selectable sub-use cases. Participants can therefore begin with a manageable overview and explore detail only where a function appears relevant to an interior location.

		Interior Components																
		Armrest	Center console	Displays and controls	Door trim	Floor trim	General interior trim	Instrument panel	Interior insulation	Interior lighting	Luggage compartment	Multiple components	Overhead console	Roof trim	Sanitization system	Seat	Seat belt	Steering wheel
Utilized Material Type	Bio-based polymer and biomaterial				2		3	1										
	Coating and surface finish			1	4		8	4				3						2
	Display and optical laminate		1	3	3	1	3	3		2		2	2	1	1			
	Electronic textile and smart laminate	4	4	14	5		3	3				2	4	1		11	1	4
	Insulation and acoustic material								5					1				
	Metal mineral and glass						2					1						
	Mixed fiber textile			1		5	5	2	1					1		7		
	Natural fiber composite				6	1	7	2	2			3		3		1		
	Natural fiber textile				1	2	4		1			2		1		1		
	Natural leather						2					1				4		
	Polyamide textile					5										2		
	Polyester textile	1	1		4	10	3	2			3	2		4		17		
	Polymer composite	1		1	5		1	2				2				4		
	Polymer foam and cushioning								1							7		
	Synthetic leather and coated textile		1	1	1		4					2		1		9		2
	Thermoplastic polymer				3		7	1	1					1		3	1	
	Unspecified hybrid material		1		2	2	2	1			2	1	1	1		1		
	Wood and cork		2	2	1		4	2				1						

Figure 3. Distribution of consolidated material categories across vehicle-interior components. Cell values represent the number of identified use cases. (The color gradient indicates the number of relevant entries).

		Interior Components																
		Armrest	Center console	Displays and controls	Door trim	Floor trim	General interior trim	Instrument panel	Interior insulation	Interior lighting	Luggage compartment	Multiple components	Overhead console	Roof trim	Sanitization system	Seat	Seat belt	Steering wheel
Surface Use Cases	Acoustic Comfort				1	4	2		11		1	1						
	Aesthetic Enhancement		2		9		9	5				5		1		1		
	Cabin Air Quality and Scent						2						2	1		1		
	Circularity and Recycling	1			5	4	2	2				1		1		4	1	
	Comfort and Ergonomics		1		4		3	2				2		2		9		2
	Environmental Sustainability		1		1	5	6	2			1	2		3		24		1
	Floor and Cargo Protection					11					3							
	Functional Integration			2	1								1					
	Human Machine Interaction	2	4	16	3		1	6				2	3			2	1	3
	Hygiene Protection						14					2	1		1	4		1
	Information Display		1	3			1	2				1		1				
	Interior Lighting and Signaling			1	4	1	7	1		2		1		1				
	Occupant Sensing and Monitoring															5		1
	Structural Support and Lightweighting				7		3	2				3		3		5		
	Surface Protection	1		1	1	1	8	1				2				6		
	Thermal Comfort	2	1		1									2		6		

Figure 4. Distribution of consolidated surface-use-case categories across vehicle-interior components. Cell values represent the number of identified use cases. (The color gradient indicates the number of relevant entries).

The approach combines principles from the card-based co-design toolkit for smart-material applications developed by Yu et al., which makes specialist knowledge accessible and supports stakeholder dialogue, with Material-Driven Design published by Karana et al., which connects technical and experiential material qualities to meaningful application concepts [19,25].

However, neither method was adopted without modification. In contrast to the material-first logic of MDD, the present process initially withholds specific materials and begins with evidence-based surface functions derived from the dataset. This reduces premature fixation on a solution and directs attention first to where a function could provide value. The hierarchical structure separates orientation from detailed selection: the parent card supports rapid scanning and spatial assignment, whereas selectable sub-use cases specify the intended application without overloading the workspace. The cards retain MDD's emphasis on what materials can do, while postponing material selection until a relevant function–location combination has been established. The approach shifts from a physical toolkit to spatially assignable VR objects, making the vehicle interior part of the ideation process. As shown in Figure 5, the parent card remains visible by default, while the information and options controls reveal explanations and alternatives when required. Detailed card contents and the complete card pool are provided in Table A1.

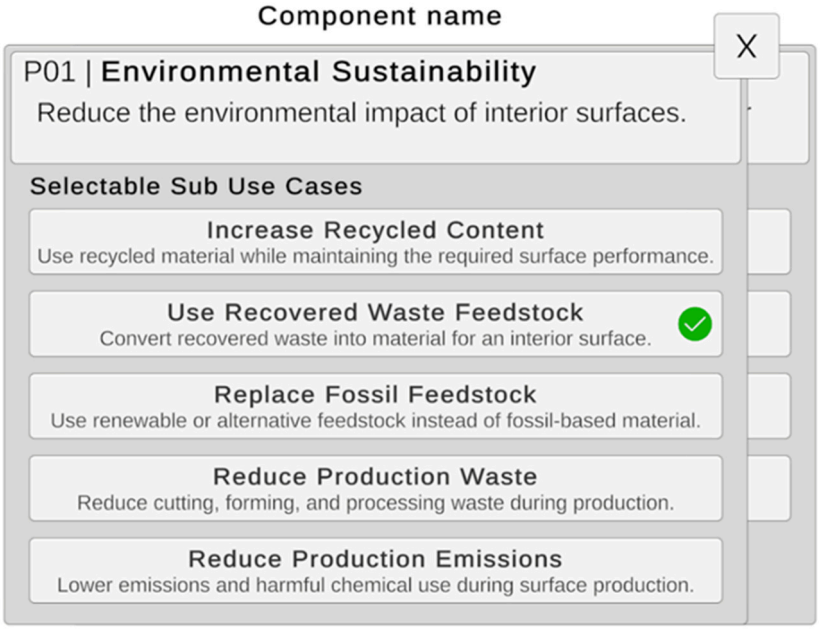


Figure 5. Example of a use-case card in the VR environment.

3.3. VR-Model Setup

To enable the assignment of use cases to individual components of a system, a VR-based application was developed that enables an intuitive, spatially anchored assignment process. The goal was to allow users to select and assign concrete use cases directly on the 3D model of the respective component, rather than working abstractly through lists or spreadsheets.

The use of VR is intended to provide an immersive, spatially contextualized design environment in which users experience the vehicle interior from an occupant perspective while assigning potential surface functions. This enables component location, scale, adjacency, visibility, accessibility, and the surrounding interior configuration to be considered simultaneously rather than as isolated list entries. The immersive representation therefore supports the assessment of whether a surface function appears meaningful at a specific location within the complete vehicle context and facilitates interdisciplinary discussion

around the same spatial reference. The VR-supported assignment should involve participants from diverse vehicle-relevant disciplines, with the resulting inputs consolidated by the design engineering team.

The application was implemented in the game engine Unity. The system of interest is represented as a 3D model with individual components, each equipped with dedicated colliders and scripts to enable targeted interaction per part. Use case data is not hardcoded during development, but is instead imported automatically from an Excel spreadsheet when the simulation is started. Each use case is defined by a title, a short description, and several selectable sub-categories. This import mechanism decouples content maintenance from software development, allowing domain experts to add, revise, or extend use cases and components directly in the spreadsheet without requiring changes to the underlying code. Once the assignment process is complete, the resulting mappings are exported back into a structured CSV file. This export forms the basis for the subsequent analysis steps described in the following sections of this study, ensuring a consistent and traceable data flow from data collection in VR to its further evaluation.

The interaction flow was deliberately kept simple to minimize cognitive load within the VR environment. When hovering over a geometric component with the VR controller, the component is highlighted through a visual color change, making interactive areas clearly identifiable before a selection is made. Pushing the controller's trigger button while pointing at a component opens the collection of available use cases, listed in Table A1. The use cases are presented as individual cards that can be browsed sequentially and are positioned directly within the user's field of view. Each card contains a title, a short description, and several selectable sub-use cases, allowing the respective use case to be further specified in detail. Additionally, the name of the currently selected component is displayed above the use case cards, ensuring clear context of which component the use case is being assigned to. Users can navigate through the cards and select the sub-use cases relevant to the chosen component. An additional UI button allows the completed assignments to be exported, so that results from multiple sessions can be collected and consolidated consistently for subsequent evaluation. Figure 5 shows an exemplary use case category card in the VR environment.

The focused card displays the use case category "Environmental Sustainability", including its description and its associated selectable sub use cases, which define the specific configuration of the assignment. When a sub use case is selected by pushing the controller's trigger button while pointing at it, a green checkmark is displayed to visually confirm the selection as shown in Figure 5. At the same time, the selected use case is stored internally together with a reference to the associated component, allowing the assignment to be retrieved and exported as a CSV file at a later stage.

3.4. Requirement-Based Preselection

Following VR assignment, each use-case–component combination is linked to documented material alternatives and screened against applicable requirements. Exact material matches from the evidence database are preferred; sufficiently analogous applications may be retained with an explicit evidence classification. Several material alternatives may therefore be assessed for one use-case–component combination. Emerging materials may also be added to the evidence database when supported by traceable scientific, supplier, prototype, or comparable application evidence; prior use in the same vehicle-interior application is not required. Materials without traceable supporting evidence are not introduced into formal preselection.

Each material variant is subsequently checked against the potentially applicable regulatory, normative, and strategically relevant requirements. Applicability is determined

from the vehicle category, jurisdiction, operating context, component, use case, material, and relevant exposure conditions. The screening is coordinated by the design engineering team and supported by participants with expertise relevant to the respective requirement domains; unresolved cases are retained for Human Review. The requirement domains, sources, applicability conditions, and decision effects are summarized in Tables A4 and A5, while Table A6 provides an overview and representative examples of the documented material–use-case–component combinations. Individual requirements are consolidated into requirement domains for the visual overview, while stable requirement identifiers maintain traceability to the detailed catalogue. Applicable requirements are selected from the catalogue based on vehicle, component, use case, material, operating context, and exposure conditions and are then assessed using the statuses defined in Table A5.

Each requirement is linked to a stable requirement subcategory identifier (e.g., D01.07), which provides traceability between the preselection matrix and the underlying detailed requirement catalogue. As illustrated by the representative examples in Figure A1, the preselection matrix combines the parent use-case–component definition, its material alternatives, and the corresponding requirement assessment within one view. The symbols indicate whether a requirement is not applicable, demonstrably fulfilled, requires verification or human judgement, remains unclear, or presents an explicit conflict.

Final traffic-light classifications are derived through non-compensatory decision rules rather than an aggregated score. Each requirement assessment is interpreted together with its mandatory level and decision effect defined in the requirement catalogue. An explicit failure or conflict (×) in an applicable hard-gate requirement results in exclusion. If no such conflict exists but a mandatory or conditionally mandatory requirement remains unresolved (△ or ?), the material variant is classified as Human Review. A material variant is classified as Carry Forward only when no mandatory or conditionally mandatory requirement remains unresolved. Requirements classified as advisory or informational may remain marked for subsequent verification without independently preventing Carry Forward. Analogous material evidence remains under Human Review until its transferability has been confirmed. At parent-combination level, a combination is retained when at least one material variant is classified as Carry Forward, assigned Human Review when no variant is carried forward but at least one remains under review, and excluded or reformulated when all material variants are excluded.

3.5. Use-Case Potential Model Design

The potential model compares a retained use-case–component–material solution with a reference solution across 23 factors. The reference solution is defined before candidate scoring and represents the currently used or planned baseline that fulfils the same primary function within the same component and use context. Where several baseline solutions are plausible, the most representative current solution is selected and the selection rationale is documented. The same reference must then be retained for all candidate alternatives within that comparison. This prevents the baseline from being adjusted retrospectively to favour or disadvantage an investigated surface solution. These factors represent technical, economic, environmental, implementation-related, and user-related consequences and make relative advantages, disadvantages, and trade-offs visible for decision-making.

The evaluation factors were developed through a three-stage coding process of the original use case descriptions. First, the collected descriptions of vehicle-interior surface applications were analysed using inductive open coding. Relevant statements were assigned concise codes describing explicitly reported implications of introducing a material or surface solution. The coding focused on generic evaluation aspects rather than individual technologies, materials or components. This enabled the identification of recurring consid-

erations applicable across different surface–component–use-case combinations, including environmental, economic, technical, implementation-related and user-oriented aspects.

Second, the inductively generated codes were consolidated into a structured codebook. Semantically equivalent codes were merged, overlapping factors were separated or removed, and overly specific codes were generalised. Each factor was defined using inclusion, exclusion and boundary criteria to support consistent application. This process resulted in a final codebook of 23 factors, including Material Circularity, Environmental Impact, Total Cost, Manufacturing Compatibility, Implementation Maturity, Technical Performance, Service-Life, Surface Perception, Physical Comfort, Safety, and User Acceptance.

Third, the complete dataset of 323 use cases was independently recoded by two coders using the final codebook. Both coders were affiliated with the Institute for Engineering Design at TU Braunschweig and therefore shared an institutional background in engineering-design research. Before independent recoding, both coders were provided with the final factor definitions, inclusion/exclusion criteria, and boundary rules. Coding was then performed independently, and Krippendorff's alpha was calculated before reconciliation of disagreements. Each factor was treated as a binary decision indicating whether it was explicitly supported by the corresponding source excerpt. Intercoder reliability was evaluated using Krippendorff's alpha. The overall Krippendorff's alpha was $\alpha = 0.88$. An overview of the coding procedure and intercoder reliability assessment is provided in Table A2.

The resulting factors provide the basis for a technology-independent potential model. The structure of the derived potential model is presented in Figure 6; a detailed overview of the factors is provided in Table A3.

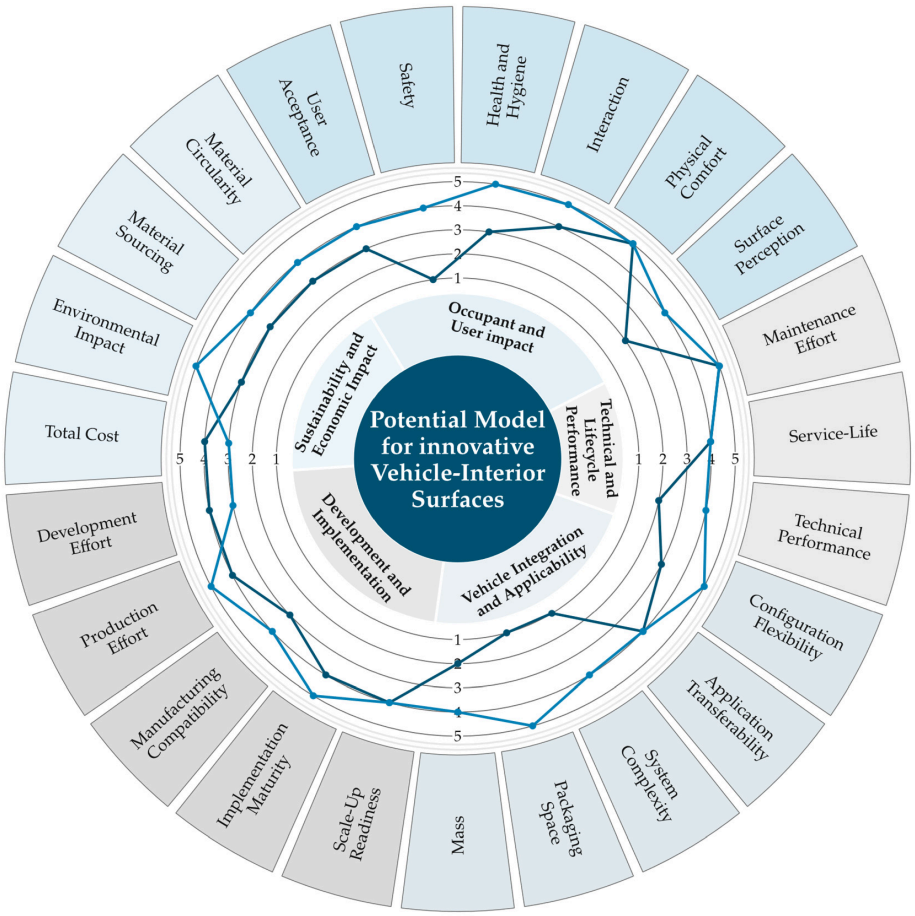


Figure 6. Potential model for evaluating innovative vehicle-interior surfaces; lines illustrate independently assessed reference (dark blue) and investigated (light blue) solution profiles.

The potential values are ordinal engineering-design assessments rather than absolute measurements. Both the reference solution and the investigated solution are assessed independently using the same factor definitions in Table A3 and the same five-point scale: 1 = Critical engineering weakness, indicating a major technical, implementation, or lifecycle disadvantage requiring substantial redesign or mitigation; 2 = Engineering weakness, indicating a clear disadvantage with relevant remaining development effort, uncertainty, or mitigation; 3 = Engineering adequacy, indicating an acceptable condition for the intended application without a pronounced strength or critical weakness; 4 = Engineering strength, indicating a clearly favourable characteristic with manageable remaining limitations; and 5 = Pronounced engineering strength, indicating a highly favourable characteristic with clear engineering benefit and only minor relevant limitations. The direction of each factor is normalized so that a higher value always represents the more favourable engineering outcome; for example, lower cost, development effort, production effort, or mass corresponds to a higher score. If the available evidence is insufficient to support an assessment, the factor is marked as unresolved rather than being assigned a default value of 3. The reference and investigated solutions are compared only after both profiles have been assessed independently.

The potential evaluation is coordinated by the early-stage design engineering team and involves participants from diverse vehicle-relevant disciplines. Individual ratings are consolidated by the design engineers, using median values where multiple ratings are available, while substantial disagreement remains visible and triggers review. Ratings should be supported where possible by measurement or simulation results, supplier documentation, published evidence, or documented engineering estimates. The median rating is used for the comparative profile, while substantial disagreement between evaluators should remain visible and trigger review rather than being concealed through averaging.

4. Virtual-Reality Surface Integration and Evaluation Method

The resulting Virtual-Reality Surface Integration and Evaluation Method (VRSIEM) integrates the methodological elements described in Section 3 into a continuous process for identifying and evaluating potential surface applications, as illustrated in Figure 7. The method consists of five sequential steps supported by four dedicated resources and several defined customization options.

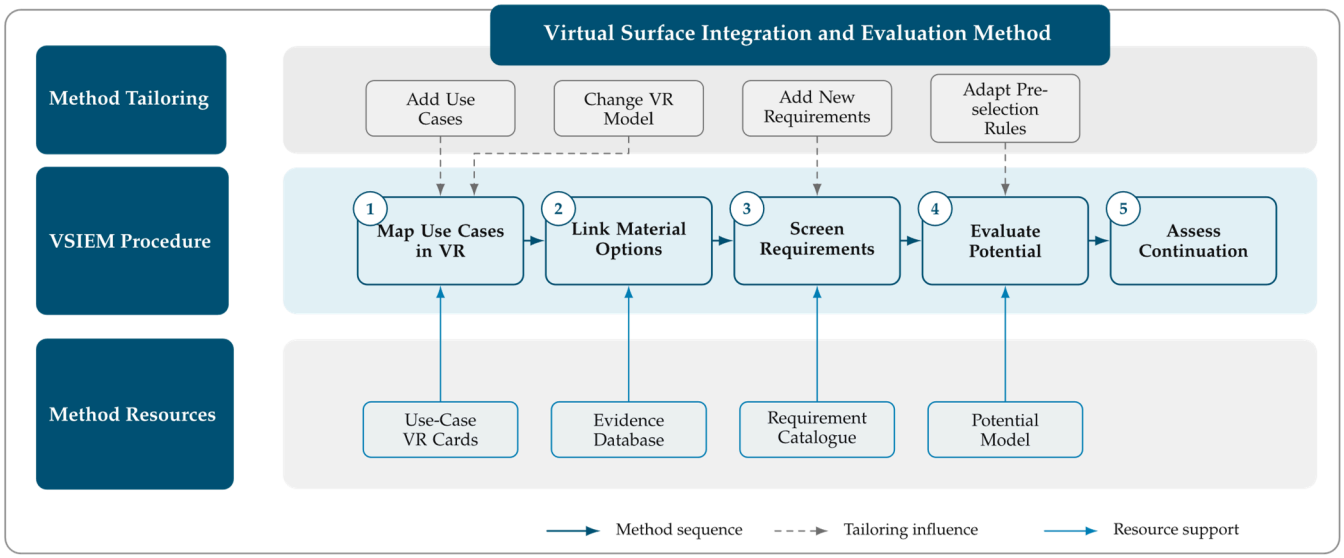


Figure 7. VRSIEM process, resources, and customization options.

VRSIEM is coordinated by the early-stage design engineering team, while individual activities involve participants from diverse vehicle-relevant disciplines to capture complementary perspectives; the resulting inputs are subsequently consolidated by the design engineers. In Step 1, relevant surface use cases are selected from the use-case VR cards and mapped to suitable vehicle-interior components within the virtual environment. This establishes the application-specific use-case–component combinations without initially prescribing a material solution. In Step 2, these combinations are linked to material options contained in the evidence database. The database restricts the considered alternatives to documented material–use-case–component relationships and thereby maintains traceability to the underlying evidence. Step 3 screens the resulting combinations against the applicable requirements contained in the requirement catalogue. Conflicting alternatives can be excluded, while unresolved requirements remain visible for verification or human assessment. In Step 4, combinations retained after preselection are evaluated using the potential model. The candidate surface solution is compared with a reference solution across the derived evaluation factors to identify potential benefits, disadvantages, implementation requirements, and trade-offs. Step 5 uses the combined results of preselection and potential evaluation to assess whether the use case should be continued, revised, or discontinued.

VRSIEM is designed to remain adaptable without changing its fundamental process. New use cases can be added to extend the application space, while the VR model can be exchanged or modified for different vehicle concepts or spatial contexts. The requirement catalogue can be extended when additional standards, regulations, or application-specific requirements become relevant, and the preselection rules can be adapted to different decision contexts. The method therefore combines spatial use-case identification, evidence-based material linking, requirement screening, and comparative potential evaluation within a configurable and traceable workflow.

5. Application of VRSIEM to an Autonomous Shuttle Interior

VRSIEM is applied to an autonomous shuttle interior through an illustrative demonstration case. The application does not represent a completed industrial development project or empirical validation study; instead, it is constructed to demonstrate the operation and interaction of the individual method steps. Selected surface use cases are assigned in VR, linked to documented material options, screened against applicable requirements, and subsequently evaluated to support a continuation decision.

5.1. VR-Based Use-Case Assignment

The application was conducted using a virtual model of a short-range public-transport shuttle. For the illustrative application, an EU/German regulatory context was assumed, with the shuttle considered as a road vehicle for public passenger transport. Accordingly, EU and UNECE requirements were treated as the primary regulatory basis, while requirements from other jurisdictions were considered only as supplementary technical references where relevant. Due to the shared-use context and frequent passenger turnover, a broad range of surface functions was initially considered without restricting the exploration to specific materials. The available VRSIEM cards were positioned at vehicle components where the respective function was considered applicable, thereby creating an initial set of use-case–component combinations. Figure 8 shows representative views of this spatial assignment within the virtual shuttle environment.



Figure 8. Use case selection process in the VR environment.

5.2. Material Linking and Requirement Preselection

The use-case–component combinations selected in Section 5.1 were subsequently linked to documented material alternatives using the existing evidence database. For each combination, material solutions previously reported for the same or a sufficiently comparable application were identified and classified according to their evidence basis.

The requirement-based preselection was first applied to the 15 initially identified use-case–component–material combinations. By checking each combination against the applicable requirements and available evidence, the procedure reduced the candidate set to 11 alternatives, while four combinations were directly excluded due to identified requirement conflicts. Within the remaining set, the alternatives for Antimicrobial Contact Surface–General Interior Trim, Increase Recycled Content–Seat, and Hidden Surface Display–Instrument Panel comprised three, three, and two material variants, respectively. These included thermoplastic polymer, coating and surface finish, and natural leather; synthetic leather and coated textile, polyester textile, and mixed-fiber textile; and wood and cork and display and optical laminate. The corresponding evidence was classified as exact or analogous, depending on the specific combination, and no material option without documented evidence was introduced.

Each material variant was then assessed using the requirement-based preselection procedure defined in Section 3.4. Applicable requirements were determined from the vehicle context, component, use case, material, and anticipated exposure conditions. The assessment particularly affected the domains Hygiene/Cleanability and Chemical/Cabin Air for the antimicrobial surface, Circularity/EoL and Mechanical/Durability for the recycled-content seat surface, and Usability/HMI/Visibility and Electrical/EMC/Functional Safety for the hidden surface display. Detailed requirement definitions and decision symbols are provided in Tables A4 and A5, while an overview and representative examples of the documented material–use-case–component evidence are provided in Table A6.

As summarized in Figure 9, three alternatives were retained, eight required further verification or human review, and four were excluded, primarily because of conflicts between display integration and safety-critical seat-belt functionality. The complete set of

15 investigated combinations and their resulting preselection classifications is provided in Figure A1. The retained alternatives—thermoplastic polymer for the antimicrobial interior trim, synthetic leather and coated textile for the recycled-content seat surface, and wood and cork for the hidden surface display—were subsequently transferred to the potential evaluation described in Section 5.3.

Selected application	Material alternative	Main requirement finding	Preselection result
Antimicrobial Contact Surface — General interior trim	Thermoplastic polymer	Exact evidence; hygiene, cleanability and durability requirements applicable	**CARRY FORWARD**
	Coating and surface finish	Analogous evidence; coating durability and chemical resistance require verification	**HUMAN REVIEW**
	Natural leather	Analogous evidence; cleanability and long-term antimicrobial performance require verification	**HUMAN REVIEW**
Increase Recycled Content — Seat	Synthetic leather and coated textile	Exact evidence; recycled content demonstrated for seat upholstery	**CARRY FORWARD**
	Polyester textile	Analogous evidence; recycled content demonstrated, but seat-specific performance requires verification	**HUMAN REVIEW**
	Mixed-fiber textile	No exact or analogous dataset match identified Human review required	**HUMAN REVIEW**
Hidden Surface Display — Instrument panel	Wood and cork	Exact evidence; display integration into wooden interior surface demonstrated	**CARRY FORWARD**
	Display and optical laminate	Analogous evidence; visibility, integration and functional-safety requirements require verification	**HUMAN REVIEW**

Figure 9. Preselection results for the three selected applications.

5.3. Potential Evaluation and Decision

The material alternatives retained after requirement-based preselection were subsequently evaluated using the potential model introduced in Section 3.5. For each application, the reference solution and the investigated surface solution were assessed independently across the 23 evaluation factors using the common five-point engineering-design scale defined in Section 3.5. The resulting profiles were subsequently compared factor by factor to identify relative advantages and disadvantages. For this illustrative demonstration, the authors assigned example values using the common scale defined in Section 3.5 solely to exercise the potential-evaluation workflow. No independent expert panel, measurements, or inter-rater aggregation were used for these values; the resulting numerical profiles therefore demonstrate the evaluation format and not empirical superiority of the investigated solutions. The investigated comparisons comprised an antimicrobial thermoplastic interior trim versus conventional thermoplastic trim, a recycled-content seat surface versus conventional virgin-material upholstery, and a wood-integrated hidden surface display versus a conventional visible information display. The values illustrate the resulting trade-offs rather than empirical performance.

Figure 10 illustrates the detailed potential evaluation for the antimicrobial contact surface. Compared with the reference surface, the new solution was assigned higher illustrative values regarding health and hygiene, technical function performance, maintenance

effort, application transferability, and user acceptance. Lower values were assigned for total cost, implementation maturity, and manufacturing compatibility. Across the 23 factors, the illustrative comparison showed a difference of +8 points. The sum is reported only for descriptive comparison and does not determine the decision. Factors receiving equal ratings indicate no relevant difference within the illustrative assessment. The potential model therefore makes both improvements and implementation-related disadvantages visible instead of relying only on a single aggregated value.

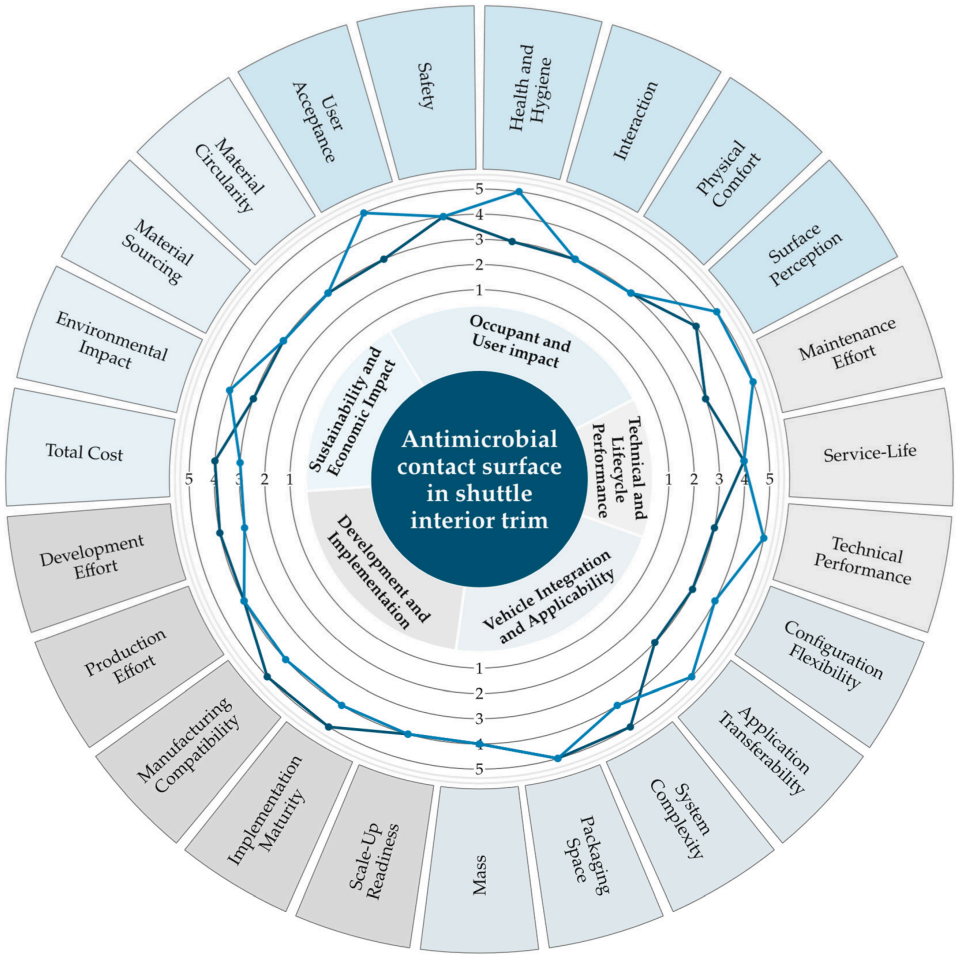


Figure 10. Illustrative potential-model comparison for the baseline solution (dark blue) and the antimicrobial (light blue) contact surface; both profiles are independently assessed using the common five-point engineering-design scale.

The corresponding evaluations for all three applications are summarized in Table A7. The antimicrobial contact surface showed the clearest positive profile (+8), resulting in an illustrative proceed decision. The recycled-content seat surface showed a smaller positive profile (+2), resulting in an illustrative proceed decision with several factors requiring verification. The hidden surface display showed a slightly lower profile than its reference (−3). Advantages in surface perception, packaging space, and configuration flexibility were offset by disadvantages in manufacturing compatibility, maturity, robustness, and implementation effort, resulting in an illustrative revise decision. Table A7 provides the complete factor-level evaluations for all three applications. These illustrative decisions demonstrate how VRSIEM translates screened concepts into recommendations for further development or revision.

The potential model, as well as the VRSIEM, is intended to support decision-making and solution ideation by making relevant benefits, limitations, and trade-offs transparent.

At the same time, VRSIEM provides technical solutions with broader organizational context by considering factors such as cost, implementation maturity, scalability, development effort, and user acceptance.

6. Validation

To validate the developed method systematically, the Validation Square proposed by Pedersen et al. is applied. The framework treats validation as a process of building confidence in a design method's usefulness with respect to its intended purpose and distinguishes theoretical and empirical structural validity from empirical and theoretical performance validity. The present assessment therefore evaluates both the consistency of VRSIEM and the evidence of usefulness provided by the illustrative application [26].

6.1. Theoretical Structural Validity

Theoretical structural validity assesses whether the individual constructs of a method and their integration can be accepted on the basis of existing knowledge and logical reasoning [26]. For VRSIEM, the underlying information structure distinguishes use cases, functions, components, requirements, materials, and surfaces according to established engineering-design concepts, as outlined in Section 2.2. The individual methodological elements further build on existing approaches: the use-case cards combine principles of Material-Driven Design and card-based co-design [19,25], while the requirement-based preselection connects identified alternatives with documented engineering constraints and the potential model provides a structured comparison across empirically derived evaluation factors.

The integration of these elements follows a consistent information flow. A use case is first assigned to a component, documented material alternatives are subsequently linked, incompatible alternatives are screened through applicable requirements, and retained solutions are finally evaluated before a continuation decision is made. This sequence, illustrated in Figure 7, preserves traceability between the individual method steps and directly addresses the methodological gaps identified in Section 2.3. VRSIEM is therefore considered to provide theoretical structural validity for its intended purpose.

6.2. Empirical Structural Validity

Empirical structural validity considers whether the method can be applied to a problem that adequately represents its intended field of use [26]. For VRSIEM, the autonomous-shuttle interior presented in Section 5 provides such an application case because it combines multiple interior components, surface functions, material alternatives, operating conditions, and engineering requirements within one vehicle context. The assumed public-transport use additionally introduces relevant constraints related to frequent passenger interaction, hygiene, durability, safety, and regulatory compliance.

The case activates all principal elements of VRSIEM: use cases are spatially assigned to components in VR, material alternatives are linked from documented evidence, combinations are screened against applicable requirements, and retained alternatives are transferred to the potential evaluation. The initial set of 15 use-case–component–material combinations also contains both feasible, conditionally feasible, and conflicting alternatives, allowing the method's different decision paths to be exercised. The shuttle case is therefore considered sufficiently representative for demonstrating the structural applicability of VRSIEM within its intended vehicle-interior context.

6.3. Empirical Performance Validity

Empirical performance validity assesses whether a method provides useful results for the selected application and whether this usefulness can reasonably be attributed to

application of the method [26]. In the shuttle case, VRSIEM produced the intended outputs throughout its complete process. Requirement-based preselection reduced the initial 15 use-case–component–material combinations to 11 alternatives by identifying four explicit conflicts. Three retained alternatives were subsequently evaluated in detail, resulting in differentiated illustrative proceed or revise decisions rather than an undifferentiated ranking.

The resulting information can be directly traced to the individual VRSIEM steps: candidate applications originate from the VR-supported assignment, material alternatives are restricted to documented evidence, exclusions result from explicit requirement conflicts, and the final decisions combine these screening results with the factor-based potential evaluation. The validity assessment concerns the operation and usefulness of VRSIEM, not the empirical validity of the illustrative factor values.

The application therefore provides preliminary empirical performance evidence for VRSIEM's intended purpose of generating structured and traceable decision-support outputs. This evidence concerns the operation and resulting information structure of the method, not the empirical validity of the illustrative factor values or superiority over alternative development procedures. Independent-user and comparative studies are therefore required to strengthen empirical performance validity.

6.4. Theoretical Performance Validity

Theoretical performance validity considers whether the usefulness demonstrated for the selected application can reasonably be expected to extend to further problems within the intended application domain [26]. VRSIEM was designed as a configurable process rather than as a shuttle-specific procedure. Its fundamental sequence remains unchanged when the VR model, use-case set, evidence database, requirement catalogue, or preselection rules are adapted to another vehicle concept or development context. The method therefore separates its general process logic from the application-specific information used within the individual steps.

The demonstrated workflow is consequently considered transferable in principle to comparable vehicle-interior surface-development tasks in which functions, components, materials, requirements, and competing solution alternatives must be connected and evaluated. However, the present study investigates only one illustrative vehicle context and does not provide evidence for general applicability across different vehicle classes, organizations, or development environments. Theoretical performance validity is therefore considered preliminarily supported, while further application cases are required to substantiate broader transferability.

6.5. Validation Results

Overall, the Validation Square assessment supports the structural validity of VRSIEM and provides preliminary performance evidence within the investigated application. Broader performance validity remains to be strengthened through independent users, additional application contexts, and comparative evaluation with alternative development procedures.

7. Discussion

The developed Virtual-Reality Surface Integration and Evaluation Method (VRSIEM) addresses the difficulty of connecting material- and surface-oriented knowledge with functions, components, and requirements in engineering design. While existing approaches support material-driven exploration, interdisciplinary co-design, or technical surface development individually [19,21,25], VRSIEM integrates these perspectives within one traceable development process.

A central characteristic is the separation of exploration from evaluation. VR-supported assignment enables surface functions to be considered spatially before committing to specific materials, while subsequent evidence-based material linking and requirement preselection progressively constrain the solution space. The potential model then complements technical screening by retaining trade-offs across implementation, environmental, technical, and user-related factors rather than reducing them to a single aggregated score. VRSIEM therefore supports structured decision-making while preserving expert judgement.

The validation in Section 6 indicates that the method is structurally consistent and applicable within the investigated vehicle-interior context, while its performance validity and transferability remain preliminary. This distinction is important because the method is intentionally configurable: use cases, vehicle models, requirements, evidence, and preselection rules can be adapted without changing the fundamental process. Such modularity supports application to further contexts but does not itself demonstrate equivalent performance across them.

The principal limitations therefore concern the quality and scope of the information entering the method. Material linking depends on the coverage and reliability of the evidence database, and documented prior applications do not guarantee suitability under different component or operating conditions. Requirement preselection cannot replace testing, simulation, certification, or detailed engineering development, while the potential evaluation remains partly dependent on expert judgement. VRSIEM should consequently be understood as an early-stage integration and decision-support method rather than as a substitute for detailed technical validation. The present study additionally does not isolate the contribution of VR from the remaining VRSIEM elements or establish that VRSIEM improves decision quality relative to conventional development procedures; both require independent comparative validation.

8. Conclusions

The principal result of this study is VRSIEM as an integrated method for connecting material and surface opportunities with engineering-design information. The resulting workflow combines five successive activities: VR-supported use-case assignment, evidence-based material linking, requirement-based preselection, comparative potential evaluation, and the decision to continue, revise, or discontinue an investigated use case. The method establishes traceable transitions between application-oriented and material-oriented information while retaining the different levels of abstraction required by both domains. The use-case and component assignment defines where a surface function could provide value, documented material evidence defines possible realizations, and the requirement catalogue constrains these alternatives according to the relevant engineering context. Retained alternatives are subsequently compared with reference solutions through the potential model, allowing benefits and disadvantages to be considered without reducing the assessment to a single score. Application of the complete workflow demonstrated that these previously separate elements can be used consecutively within one process and that unresolved evidence or requirements can remain visible rather than being concealed by an aggregated decision. The methodological result is therefore not an individual surface application, but a configurable and traceable process for interdisciplinary surface identification and evaluation. The current study therefore establishes and demonstrates the method structure, but does not yet establish comparative efficiency, decision quality, or robustness across independent users and additional application cases.

9. Outlook

Further work should primarily evaluate the robustness and transferability of VRSIEM. A subsequent comparative study should apply VRSIEM and a conventional 2D/3D or list-based baseline with independent participants. Relevant outcomes include task-completion time, number and traceability of identified alternatives, consistency between evaluators, usability, unresolved-information detection, and decision confidence. Such a study would enable the empirical performance contribution of both the complete method and the VR-supported assignment step to be assessed separately. Application with larger and more diverse groups of material scientists, engineering designers, and other relevant stakeholders should investigate usability, consistency of assignments, inter-rater variation in the potential evaluation, and the influence of disciplinary background on decisions. The evidence database should be continuously extended with newly documented material and surface applications, while requirement catalogues and preselection rules can be adapted to additional vehicle types, markets, and operating contexts. Transfer to other products with similarly strong interactions between materials, surfaces, users, and technical requirements would provide further evidence regarding the general applicability of the method. Future digital development could also integrate the VR environment, evidence database, requirement assessment, and potential model more closely within a common software environment. Such studies should determine whether VRSIEM can support interdisciplinary surface-development decisions more consistently and efficiently across different development contexts. Future implementations may extend this principle through augmented or mixed reality, where virtual use-case information can be overlaid onto physical vehicle interiors or mock-ups, further strengthening the connection between spatial context and surface-function evaluation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Explanation
AI	Artificial Intelligence
ASTM	ASTM International
CLP	Classification, Labelling and Packaging
CRMs	Critical Raw Materials

CSVs	Comma-Separated Values
ELVs	End-of-Life Vehicles
EMC	Electromagnetic Compatibility
EU	European Union
FMEA	Failure Mode and Effects Analysis
FMVSS	Federal Motor Vehicle Safety Standards
GADSL	Global Automotive Declarable Substance List
GDPR	General Data Protection Regulation
HMI	Human–Machine Interface
IATF	International Automotive Task Force
IMDS	International Material Data System
ISO	International Organization for Standardization
LkSG	German Supply Chain Due Diligence Act
MDD	Material-Driven Design
MiPS	Materials in Products Selection
POP	Persistent Organic Pollutants
PSPP	Processing–Structure–Property–Performance
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SAE	SAE International
StVZO	German Road Traffic Licensing Regulations
TRL	Technology Readiness Level
UI	User Interface
UN	United Nations
VR	Virtual Reality
VRSIEM	Virtual-Reality Surface Integration and Evaluation Method

Appendix A

Table A1. Use-case card categories and selectable sub-use cases.

ID and Parent Card	Selectable Sub-Use Cases
P01 Environmental Sustainability	Increase Recycled Content; Use Recovered Waste Feedstock; Replace Fossil Feedstock; Reduce Production Waste; Reduce Production Emissions
P02 Aesthetic Enhancement	Natural Material Appearance; Premium Surface Appearance; Decorative Colour and Pattern; Decorative Texture
P03 Comfort and Ergonomics	Soft-Touch Surface; Grip-Enhancing Surface; Breathable Contact Surface; Cushioning and Support
P04 Floor and Cargo Protection	Wear-Resistant Floor; Removable Floor Protection; Cargo-Area Protection; Load-Bearing Cargo Floor
P05 Structural Support and Lightweighting	Lightweight Structural Surface; Semi-Structural Interior Panel; Structural and Decorative Surface; Part Consolidation
P06 Circularity and Recycling	Design for Disassembly; Replaceable Surface; Repairable Surface; Mono-Material Construction; Closed-Loop Material Recovery
P07 Surface Protection	Scratch and Abrasion Resistance; Chemical Resistance; UV and Aging Resistance; Moisture and Stain Resistance; Self-Healing Surface
P08 Acoustic Comfort	Sound-Absorbing Surface; Vibration-Damping Surface; Acoustic Insulation
P09 Thermal Comfort	Localized Surface Heating; Surface Heating and Cooling; Ventilated Contact Surface; Thermal Insulation; Solar Heat Reflection
P10 Human Machine Interaction	Touch Input; Force-Sensitive Input; Hidden-Until-Needed Controls; Haptic Feedback; Contact-Free Control
P11 Interior Lighting and Signaling	Ambient Lighting; Task Lighting; Warning and Status Lighting; Hidden-Until-Lit Symbols; Dynamic Decorative Lighting

Table A1. *Cont.*

ID and Parent Card	Selectable Sub-Use Cases
P12 Hygiene Protection	Easy-Clean Surface; Anti-Fingerprint Surface; Antimicrobial Contact Surface; Self-Cleaning Surface; Active Surface Sanitization
P13 Information Display	Hidden Surface Display; Projected Display; Transparent Display; Privacy Display
P14 Functional Integration	Multi-Function Smart Surface; Embedded Electronics; Surface-Integrated Antenna; Reduced Hardware and Thickness
P15 Cabin Air Quality and Scent	Low-Emission Surface; Odor Reduction; Odor and Pollutant Filtration; Selectable Cabin Scent
P16 Occupant Sensing and Monitoring	Occupancy Detection; Person and Object Detection; Pressure Distribution Sensing; Posture Monitoring; Contact Detection

Table A2. Overview of the coding process and intercoder reliability.

Stage	Procedure	Coding Rule/Output	Result
1. Inductive coding	Open coding of collected use-case descriptions	Only explicitly reported implications of the surface solution were coded; technology-specific statements were generalized where appropriate	Initial set of recurring evaluation aspects
2. Codebook consolidation	Semantically equivalent codes merged; overlaps separated or removed; overly specific codes generalized	Each factor defined by inclusion, exclusion, and boundary criteria	23-factor codebook
3. Independent recoding	Complete dataset independently coded by two coders using the final codebook	Binary coding for each factor based only on explicit source evidence; contextual implications were not inferred	Two independent coding datasets
4. Reliability assessment	Agreement between both coding datasets assessed using Krippendorff's alpha	Overall reliability calculated across the recoded dataset	Krippendorff's $\alpha = 0.88$

Table A3. Potential-model factors and compressed definitions.

Factor	Compressed Definition
Material Circularity	Changes in material circulation through reuse, repair, recycling, recovery, disassembly, or closed loops.
Material Sourcing	Changes in material origin, renewability, availability, traceability, certification, locality, or ethical sourcing.
Environmental Impact	Changes in life-cycle resource demand, emissions, pollution, waste, toxicity, or biodiversity impacts.
Total Cost	Changes in monetary expenditure across development, production, use, maintenance, and end-of-life.
Development Effort	Changes in engineering time, workload, iterations, coordination, and decision-making effort.
Production Effort	Changes in manufacturing time, process steps, setup, labour, automation, or rework.
Manufacturing Compatibility	Compatibility with automotive materials, processes, equipment, tolerances, assembly, and quality control.
Implementation Maturity	Progress from concept or laboratory research to validation, series production, or commercial use.

Table A3. *Cont.*

Factor	Compressed Definition
Scale-Up Readiness	Ability to standardize and expand production across volumes, suppliers, sites, models, or platforms.
Mass	Changes in the mass of the component, system, interior, or vehicle.
Packaging Space	Changes in the installation space, thickness, area, or volume required in the vehicle.
System Complexity	Changes in components, layers, interfaces, wiring, control units, and system dependencies.
Application Transferability	Applicability of the same surface principle across different components, materials, vehicles, or contexts.
Configuration Flexibility	Ability to vary the surface's appearance, geometry, properties, functions, content, or controls.
Technical Performance	Effectiveness, accuracy, consistency, response, range, and quality of the intended function.
Service-Life	Retention of function, appearance, and integrity under wear, aging, and vehicle conditions.
Maintenance Effort	Cleaning, inspection, servicing, repair, removal, replacement, and restoration effort during use.
Surface Perception	Changes in the perceived visual and passive tactile quality of the interior surface.
Physical Comfort	Changes in occupants' physical, thermal, acoustic, ergonomic, vibration, or spatial comfort.
Interaction	Changes in how users understand, access, operate, control, and interpret the surface.
Health and Hygiene	Changes in pathogens, allergens, emissions, air quality, odours, contamination, or harmful exposure.
Safety	Changes in occupant protection, distraction, errors, hazards, warnings, fire behaviour, or compliance.
User Acceptance	Changes in users' willingness to trust, select, adopt, or continue using the solution.

Table A4. Requirement-domain catalogue and decision logic for surface preselection.

ID	Requirement Domain	Example Sources	Applied When	Decision Effect
D01	Occupant Safety and Interior Fittings	UN R21 [27]; UN R17 [28]; UN R14 [29]; UN R16 [30]	Surfaces affect contact, crash, seats, airbags, or restraints	Hard or conditional gate; conflicts exclude
D02	Fire and Thermal Safety	ISO 3795 [31]; UN R118 [32]; FMVSS 302 [33]	Interior materials or temperature-controlled surfaces are used	Hard or conditional gate; unresolved cases require review
D03	Mechanical Performance and Durability	ISO 12947 [34]; ASTM D4060 [35]; ASTM D3363 [36]	Surfaces experience wear, loads, scratching, or aging	Verification or advisory requirement
D04	Chemical Compliance and Cabin Air	REACH; CLP; POP Regulation; ISO 12219 [37]	Materials, coatings, adhesives, or emissions enter the cabin	Hard or conditional gate; conflicts exclude
D05	Hygiene and Cleanability	ISO 20743 [38]; ISO 22196 [39]; ASTM D1308 [40]	Surfaces are touched, cleaned, stained, or publicly used	Claims and cleanability require verification
D06	Usability, HMI and Visibility	UN R121 [41]; ISO 15008 [42]; UN R125 [43]	Controls, displays, lighting, or visibility are affected	Hard or conditional gate; HMI conflicts exclude

Table A4. *Cont.*

ID	Requirement Domain	Example Sources	Applied When	Decision Effect
D07	Electrical, EMC and Functional Safety	UN R10 [44]; ISO 26262 [45]; ISO 16750 [46]	Electronics, heating, sensing, or antennas are integrated	Hard or conditional gate; safety conflicts exclude
D08	Cybersecurity, Software and Data	UN R155 [47]; ISO/SAE 21434 [48]; GDPR	Data, software, connectivity, or monitoring are used	Review, mitigation, or exclusion when conflicting
D09	Circularity and End-of-Life	Directive 2005/64/EC [49]; ELV Directive; VDA 260 [50]	Recycling, repair, separation, or recovery is intended	Evidence and end-of-life verification required
D10	Environmental and Sustainability Reporting	ISO 14040 [51]; ISO 14044 [52]; ISO 14021 [53]	Environmental benefits or material claims are reported	Claims must be documented and substantiated
D11	Supply Chain and Responsible Sourcing	LkSG; Conflict Minerals Regulation; CRM Regulation	Critical, recycled, bio-based, or sourced materials are used	Supplier evidence and sourcing review required
D12	Production, Quality and Material Declarations	IATF 16949 [54]; FMEA; IMDS; GADSL	The solution is prepared for industrial production	Production and material evidence required
D13	Approval, Documentation and Market Access	EU 2018/858 [55]; EU 2020/683 [56]; StVZO	Market approval or regulatory documentation is required	Hard or conditional gate
D14	Operational Context and Strategic Robustness	FMEA; ASTM D1308 [40]; ISO 12219 [37]	Public use, misuse, cleaning, or project constraints apply	Conditional or advisory human review

Table A5. Requirement Symbols and Their Preselection Effects.

Symbol	Meaning	Preselection Effect
—	Not applicable	No effect
○	Fulfilled	No blocking effect
△	Applicable; verification required	Verification remains visible; unresolved mandatory/conditional cases require Human Review
?	Applicability or evidence unclear	Human Review when decision-relevant
×	Explicit failure or conflict	Exclude if an applicable hard-gate conflict exists

Table A6. Overview of Documented Material–Use Case–Component Combinations.

Main Use-Case Category	Exact Combinations	Example Sub-Use Case	Component	Material	Source Case
Environmental Sustainability	4	ES-01 Increase Recycled Content	Seat	Synthetic leather and coated textile	UC081
Aesthetic Enhancement	0	—	—	—	—
Comfort and Ergonomics	1	CE-03 Breathable Contact Surface	Door trim	Unspecified hybrid material	UC170
Floor and Cargo Protection	4	FC-03 Cargo-Area Protection	Luggage compartment	Unspecified hybrid material	UC138
Structural Support and Lightweighting	3	SL-01 Lightweight Structural Surface	Seat	Polymer composite	UC247
Circularity and Recycling	0	—	—	—	—
Surface Protection	4	SP-02 Chemical Resistance	Multiple components	Coating and surface finish	UC049

Table A6. *Cont.*

Main Use-Case Category	Exact Combinations	Example Sub-Use Case	Component	Material	Source Case
Acoustic Comfort	7	AC-01 Sound-Absorbing Surface	Interior insulation	Insulation and acoustic material	UC034
Thermal Comfort	7	TC-01 Localized Surface Heating	Seat	Electronic textile and smart laminate	UC191
Human Machine Interaction	1	HMI-02 Force-Sensitive Input	Displays and controls	Electronic textile and smart laminate	UC318
Interior Lighting and Signaling	6	IL-01 Ambient Lighting	Door trim	Display and optical laminate	UC172
Hygiene Protection	8	HP-03 Antimicrobial Contact Surface	General interior trim	Thermoplastic polymer	UC047
Information Display	5	DISP-01 Hidden Surface Display	General interior trim	Display and optical laminate	UC233
Functional Integration	3	FI-01 Multi-Function Smart Surface	Door trim	Electronic textile and smart laminate	UC052
Cabin Air Quality and Scent	6	AQ-01 Low-Emission Surface	General interior trim	Bio-based polymer and biomaterial	UC310
Occupant Sensing and Monitoring	1	OSM-01 Occupancy Detection	Seat	Electronic textile and smart laminate	UC284
Total	60	—	—	—	—

Main_Use_Case	Sub_Use_Case	Component	Use_Context	Material	Material_Variant_Result	Parent_Combination_Result
Hygiene Protection	Antimicrobial Contact Surface	General interior trim	Public transport	Thermoplastic polymer	CARRY FORWARD	RETAIN_WITH_ALTERNATIVES
Hygiene Protection	Antimicrobial Contact Surface	General interior trim	Public transport	Coating and surface finish	HUMAN REVIEW	RETAIN_WITH_ALTERNATIVES
Hygiene Protection	Antimicrobial Contact Surface	General interior trim	Public transport	Natural leather	HUMAN REVIEW	RETAIN_WITH_ALTERNATIVES
Environmental Sustainability	Increase Recycled Content	Seat	Public transport	Synthetic leather and coated textile	CARRY FORWARD	RETAIN_WITH_ALTERNATIVES
Environmental Sustainability	Increase Recycled Content	Seat	Public transport	Polyester textile	HUMAN REVIEW	RETAIN_WITH_ALTERNATIVES
Environmental Sustainability	Increase Recycled Content	Seat	Public transport	Mixed fiber textile	HUMAN REVIEW	RETAIN_WITH_ALTERNATIVES
Information Display	Hidden Surface Display	Instrument panel	Public transport	Wood and cork	CARRY FORWARD	RETAIN_WITH_ALTERNATIVES
Information Display	Hidden Surface Display	Instrument panel	Public transport	Display and optical laminate	HUMAN REVIEW	RETAIN_WITH_ALTERNATIVES
Information Display	Hidden Surface Display	Seat belt	Public transport	Display and optical laminate	EXCLUDE	EXCLUDE_OR_REFORMULATE
Interior Lighting and Signaling	Warning and Status Lighting	Seat belt	Public transport	Display and optical laminate	EXCLUDE	EXCLUDE_OR_REFORMULATE
Interior Lighting and Signaling	Hidden-Until-Lit Symbols	Seat belt	Public transport	Display and optical laminate	EXCLUDE	EXCLUDE_OR_REFORMULATE
Interior Lighting and Signaling	Ambient Lighting	Seat belt	Public transport	Display and optical laminate	EXCLUDE	EXCLUDE_OR_REFORMULATE
Acoustic Comfort	Sound-Absorbing Surface	Roof trim	Public transport	Natural fiber textile	HUMAN REVIEW	HUMAN REVIEW
Hygiene Protection	Easy-Clean Surface	Floor trim	Public transport	Coating and surface finish	HUMAN REVIEW	HUMAN REVIEW
Hygiene Protection	Easy-Clean Surface	Floor trim	Public transport	Thermoplastic polymer	HUMAN REVIEW	HUMAN REVIEW

Figure A1. Application-example combinations with preselection results and requirement information.

Table A7. Representative independently assessed potential-model values for the three application comparisons.

Factor	Conventional Interior Trim	Antimicrobial Interior Trim	Conventional Seat Surface	Recycled-Content Seat Surface	Conventional Visible Display	Hidden Surface Display
Material Circularity	3	3	2	4	2	3
Material Sourcing	3	3	3	5	3	4
Environmental Impact	3	4	3	4	3	3
Total Cost	4	3	4	3	4	3

Table A7. *Cont.*

Factor	Conventional Interior Trim	Antimicrobial Interior Trim	Conventional Seat Surface	Recycled-Content Seat Surface	Conventional Visible Display	Hidden Surface Display
Development Effort	4	3	4	3	4	3
Production Effort	4	4	4	4	4	3
Manufacturing Compatibility	5	4	5	4	5	3
Implementation Maturity	5	4	5	4	5	3
Scale-Up Readiness	4	4	4	4	4	3
Mass	4	4	4	4	3	3
Packaging Space	5	5	4	4	3	5
System Complexity	5	4	5	5	4	3
Application Transferability	3	5	3	4	3	4
Configuration Flexibility	3	4	3	4	3	5
Technical Performance	3	5	4	4	5	4
Service-Life	4	4	5	4	5	3
Maintenance Effort	3	5	4	4	4	3
Surface Perception	4	5	4	4	3	5
Physical Comfort	3	3	4	4	3	3
Interaction	3	3	3	3	4	4
Health and Hygiene	3	5	3	3	3	3
Safety	4	4	5	4	4	4
User Acceptance	3	5	3	4	3	4
Sum of factor values	**85**	**93**	**88**	**90**	**84**	**81**
Δ (Investigated–Reference)		**+8**		**+2**		**−3**

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