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SDE 4.0: A VR-Enabled Stylistic Design Engineering Workflow for Human-Centric Automotive Concept Development: A Design Research Case Study

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Abstract

Industry 4.0 technologies have made immersive tools available to engineering design, while Industry 5.0 calls for human-centric, sustainable and resilient development processes. In automotive styling, proportion and surface assessment still relies largely on screen-based CAD and repeated physical prototypes, and virtual reality (VR) has not yet been embedded in a structured methodology such as Stylistic Design Engineering (SDE). Following a design science research approach, this study presents SDE 4.0, a VR-enabled extension of SDE in which full-scale immersive subdivision modelling introduces a human-in-the-loop review gate during modelling, followed by CAD/NURBS refinement, qualitative aerodynamic visualization, rendering and additive manufacturing. The workflow was demonstrated on a D-segment sport sedan and a derived Sport Wagon and evaluated through an indicative retrospective comparison with CAD-based SDE practice. The designer retrospectively estimated about four weeks of modelling effort and eight revision events for the two configurations, versus about four weeks and 20 events for a single vehicle in the CAD-based reference practice. These estimates derive from one project and one designer and do not establish statistically validated gains. CAD refinement remained necessary and represented the main interoperability bottleneck. A controlled validation protocol is proposed.

Keywords: virtual reality; automotive design; stylistic design engineering; immersive modelling; Industry 5.0; design science research; CAD interoperability; additive manufacturing

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1. Introduction

The fourth industrial revolution has introduced disruptive changes in engineering processes. Manufacturing is now a profoundly digitized reality, where new technologies have reshaped the approach to product conceptualization, production and validation [1,2]. The manufacturing sector has shown a global drive to adopt a growing number of digital strategies into production systems [3]. More recently, the Industry 5.0 perspective has complemented this technology-driven view by placing the human worker at the centre of the industrial system and by adding sustainability and resilience as explicit goals. For creative engineering activities such as vehicle styling, where the judgement of the designer on proportions, surface quality and character cannot be delegated to an algorithm, this shift makes the quality of the human–model interaction a design requirement in its own right.

Virtual Reality (VR) is one of the technologies that most directly acts on this interaction. In immersive environments 3D models become explorable at full scale, which supports the evaluation of geometry, proportions and spatial relationships [4,5]. Traditional screen-based Computer-Aided Design (CAD) systems, by contrast, represent volumes on a two-dimensional display and make the perception of three-dimensional form indirect. The potential of VR in design activities has been discussed in several studies, ranging from design review [6] to VR-based 3D modelling and conceptual sketching [7–9]. VR sketching has also been investigated specifically in automotive concept design as an immersive approach to early form development [10].

Nevertheless, screen-based workflows based on sketching, CAD modelling, physical prototyping and iterative design reviews remain the industrial standard. In automotive design, where engineering requirements must be balanced with aesthetic quality, manufacturing constraints and brand identity, the evaluation of proportions, surface continuity and volumetric relationships still relies on bidimensional visualization and on repeated physical validation cycles.

Stylistic Design Engineering (SDE) is a multidisciplinary methodology that integrates engineering design principles and industrial styling practices within a structured product development process, from trend analysis and sketching to 2D drawings, 3D modelling, prototyping and rendering [11]. Previous applications have shown its use in automotive concept development. In an earlier SDE application to a sport sedan developed with conventional CAD, the authors experienced two recurrent difficulties in the 3D phase: the control of surface curvature and proportions on a flat display, and the need to go through repeated cycles of 3D printing and re-modelling to detect proportion and continuity errors. These difficulties lengthened the schedule and motivated the present work.

Generative artificial intelligence (AI) is now an important companion for early-stage concept development, since it can rapidly generate and vary two-dimensional concepts. These technologies address different stages of the design process: generative AI primarily supports concept generation, whereas immersive modelling enables direct three-dimensional form development and evaluation.

Research gap and questions. To the authors' knowledge, the incorporation of immersive modelling within the SDE methodology has not yet been formalized as a structured workflow with explicit review gates and defined interfaces to downstream CAD and prototyping. This paper addresses the following research questions:

1. RQ1: How can immersive modelling be embedded in the SDE process, that is, which stages are modified, which are preserved, and how are the outputs handed over to downstream tools?
2. RQ2: Which effects on variant-development capacity, revision activity and review modality can be observed, in an indicative way, when the workflow is demonstrated on a real vehicle concept?
3. RQ3: Which limitations, in particular at the VR-to-CAD interface, emerge from the demonstration?

Contribution. We do not claim that VR modelling for automotive design is new in itself. The contribution of this paper is specific and limited: (i) a formalized VR-enabled SDE workflow (SDE 4.0) that keeps the SDE stages, moves stylistic and proportional review into the modelling phase through a full-scale review gate, and defines the VR-to-CAD-to-prototype handover; (ii) a set of explicitly defined process indicators, with formulas and a measurement protocol, that make the assessment of such workflows reproducible; (iii) a demonstration case with indicative, transparently qualified estimates and a documented list of limitations; and (iv) a reading of the workflow in the light of Industry 5.0 and generative

AI, with concrete integration points. The work is framed as design science research, so that the artefact, its requirements, its demonstration and its evaluation are reported separately.

The paper is organized as follows. Section 2 reviews related work and positions SDE 4.0. Section 3 presents the research design, the workflow, the case and the evaluation framework. Section 4 reports the results. Section 5 discusses the contribution, the Industry 5.0 and AI perspectives, generalisability and limitations, and Section 6 concludes.

2. Related Work and Positioning

2.1. VR in Engineering and Product Design

Surveys of industrial practice and of the literature describe VR as a mature technology for design review, training and assembly planning, with product design and styling among the principal application areas. Studies on engineering design review show that immersive review improves spatial understanding of an existing CAD model. A more recent line of work uses VR not only to inspect but also to create geometry, either as a 3D modelling tool for engineering design [12] or as an environment for 3D sketching and conceptual modelling. In these contributions, the immersive environment is generally studied as a tool or as an interaction technique, and not as a stage of a structured, industrially oriented styling methodology.

2.2. Stylistic Design Engineering

SDE organizes the definition of the aesthetic form of a product with an engineering approach, through consecutive stages of trend analysis, sketching, 2D drawings, 3D modelling, prototyping and rendering. It has been applied to automotive concept development, including an extension incorporating augmented reality and additive manufacturing [13]. The concept of immersive design engineering integrates these capabilities in the design process [14].

2.3. Industry 5.0 and AI-Assisted Design

Industry 5.0 does not replace Industry 4.0 but extends it by making human-centricity, sustainability and resilience explicit design objectives of industrial systems. In product design this reading is relevant for two reasons. First, it asks whether a digital tool improves the human capability to perceive, judge and decide, instead of only increasing automation. Second, it directs attention to collaborative work and to resource-efficient development. Generative AI adds a further layer, since generative systems have been proposed to assist the conceptual stage of automotive design. The relationship between such systems and human-driven 3D modelling is therefore a design question that a workflow proposal should address.

2.4. Research Gap and Positioning of SDE 4.0

Table 1 positions the present proposal with respect to the lines of work above. The table describes the typical role of the technology in the design process, as reported in the cited works, and the way SDE 4.0 differs from it.

Table 1. Positioning of SDE 4.0 with respect to related lines of work.

What SDE 4.0 Adds	Typical Role of the Technology in the Process	Line of Work
Review moved into the modelling phase, before a complete CAD model exists	Immersive inspection of CAD models that are already built	VR for design review
Tool embedded in a staged styling methodology, with defined inputs (2D drawings, package hardpoints) and outputs (handover to CAD, rendering, additive manufacturing)	Tool or interaction technique for creating geometry in conceptual design	VR as modelling or 3D sketching tool

Table 1. *Cont.*

What SDE 4.0 Adds	Typical Role of the Technology in the Process	Line of Work
Immersive modelling as the primary environment for early 3D development, with CAD as refinement	Structured styling process, with CAD-based 3D modelling	SDE and SDE with AR/additive manufacturing
Complementary: addresses the three-dimensional, full-scale judgement of a selected concept (see Section 5.3)	Rapid generation and variation of concepts	Generative AI for conceptual design

3. Materials and Methods

3.1. Research Design

The study follows a design science research logic, in which an artefact (here, a workflow) is designed to solve a recognized problem, demonstrated in a real case and evaluated against explicit criteria. Table 2 maps the stages of this logic onto the present study.

Table 2. Mapping of the design science research stages onto this study.

Section	Content in this Study	Stage
Section 1	Limited control of curvature and proportions on a flat display; print-and-remodel cycles in CAD-based SDE	Problem identification
Section 3.3	R1: full-scale review of proportions during modelling. R2: preserve the SDE stages. R3: derive related variants within the same digital process. R4: defined handover to CAD, rendering and additive manufacturing	Objectives and requirements
Sections 3.3 and 3.5	SDE 4.0 workflow and digital pipeline	Design and development
Sections 3.4 and 4.1	D-segment sport sedan and derived Sport Wagon	Demonstration
Sections 3.6 and 4.2	Indicative retrospective comparison with CAD-based SDE practice, using the process indicators	Evaluation
Sections 5 and 6	Discussion, limitations, validation protocol	Communication and limits

The evaluation is ex post and descriptive. It is not an experiment: there is no control group, no randomization and no independent replication. The conclusions must be read at the level of plausibility and of design knowledge, not as statistical evidence.

3.2. Scope and Viewpoint

The investigation adopts the viewpoint of the designer and of the process: it concerns the exterior styling of a vehicle at the concept stage, from 2D drawings to a rendered and prototyped 3D concept. It does not consider vehicle interiors, structural or crash engineering, homologation, cost, or the perception of customers. Aerodynamics is used only as a qualitative design check. The findings therefore concern the early modelling and review activity of styling and should not be extended to later stages of vehicle development.

3.3. SDE 4.0 Workflow

SDE 4.0 keeps the stages of conventional SDE: trend analysis and benchmarking, sketching, 2D drawings, 3D modelling, prototyping and rendering. Five methodological changes define the workflow (Figure 1):

1. Immersive subdivision modelling in Gravity Sketch (Gravity Sketch Ltd. V5.0, London, UK) [15] replaces CAD surface modelling as the primary environment for early 3D development, starting from the 2D drawings and from the package hardpoints.
2. A full-scale review gate is introduced inside the modelling phase: proportions, stance, roofline and surface transitions are judged at 1:1 scale while the model is being built, instead of after a complete CAD model or a physical print.
3. CAD (Rhinoceros 7; Robert McNeel & Associates, Seattle, WA, USA [16]) becomes a refinement environment: the exported geometry is converted to NURBS, corrected and prepared for rendering and printing, and does not create the initial shape.

4. Related variants are derived within the same immersive model, so that a common design language is preserved.
5. Physical prototyping by additive manufacturing is retained as a final verification, instead of the main tool for detecting proportion errors.

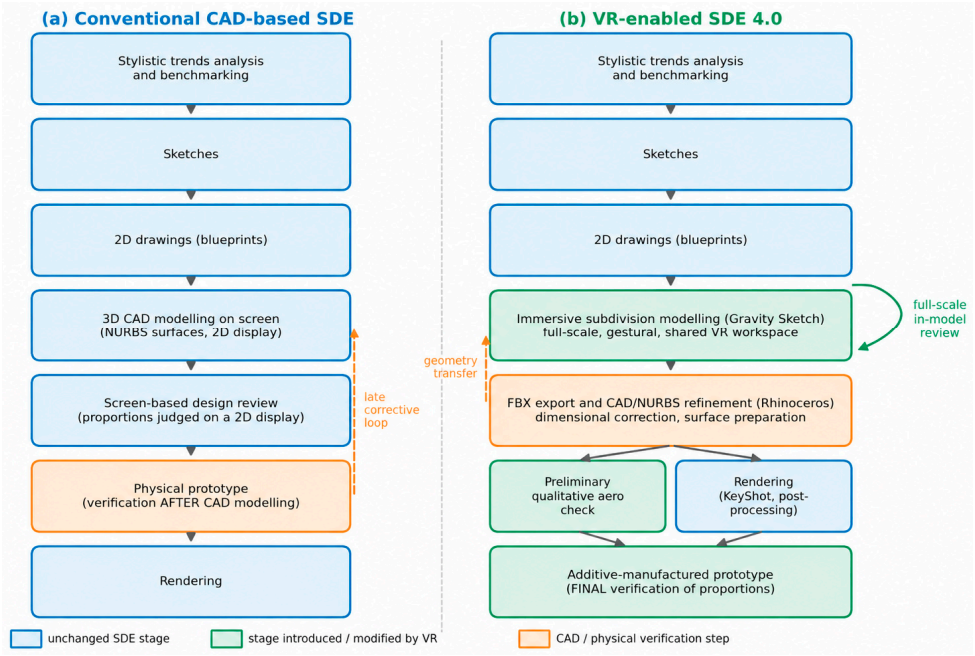


Figure 1. Conventional CAD-based SDE workflow (**a**) versus the proposed SDE 4.0 workflow (**b**). The upstream stages (trend analysis, sketches, 2D drawings) are unchanged. In SDE 4.0 the 3D stage becomes immersive subdivision modelling with an in-model full-scale review loop; CAD/NURBS refinement follows as a separate handover step, and the physical prototype moves from the principal detection tool of proportion errors (with a late corrective loop back to CAD, orange dashed arrow in (**a**)) to a final verification step.

These changes respond to requirements R1–R4 of Table 2. The workflow is intentionally not a new list of tools: its distinctive feature is the position of the human review within the process (Figure 1b) and the definition of the interface to downstream CAD.

Tool selection. Gravity Sketch was used because it provides subdivision modelling with gestural input, shared virtual workspaces and curvature-oriented display modes (zebra analysis, clay material) in the same environment. Rhinoceros was used in continuity with the CAD tools employed in the earlier SDE project [11]. KeyShot 10 (Luxion, Inc., Tustin, CA, USA) [17] and Adobe Photoshop (version 22.0; Adobe Inc., San Jose, CA, USA) [18] were used as established components of the rendering stage and could be replaced by equivalent tools. No comparative evaluation of alternative VR platforms, or of licence and hardware costs, was carried out; the workflow is described in terms of the capabilities it requires (Section 5.4), so that other platforms with these capabilities could be used. The workflow is positioned within the human-centric perspective of Industry 5.0 [19–21] and evaluated according to a design science research approach [22–24]. Generative AI for conceptual automotive design [25] provides a complementary direction for future integration, discussed in Section 5.3.

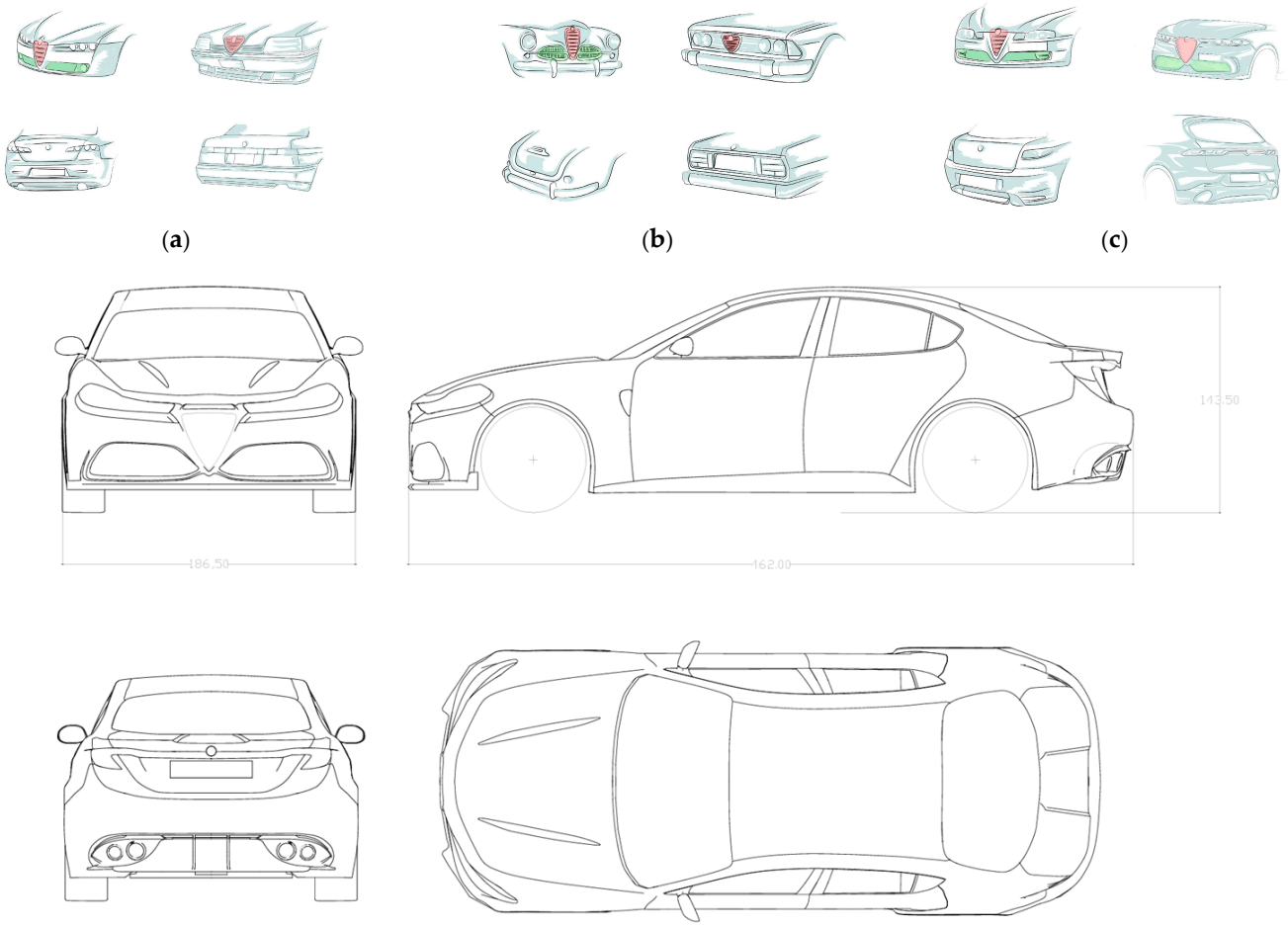
3.4. Automotive Design Case

The workflow was applied to a D-segment sport sedan concept inspired by the design language of Alfa Romeo. The concept was developed within an academic MSc project and is not affiliated with the manufacturer. The brief was informed by a customer survey (426 respondents) and by a benchmark of five competitor sedans of the same segment,

which fed the QFD and top-flop analyses of the project. After trend analysis, several 2D proposals were generated and refined to define the main proportions, stylistic identity and geometric features of the vehicle (Figure 2). The concept development phase included the analysis of characteristic styling elements, the preparation of orthographic representations and the selection of the exterior proposal used as input for immersive modelling. The package was defined by a wheelbase of 2820 mm and by front and rear tracks of 1557 mm and 1625 mm respectively, taken from a platform of the reference vehicle adapted to electrified powertrains.

The 3D modelling was carried out by one designer (A.S.), at the time an MSc student, who knew the CAD-based SDE process from the earlier project but had limited prior experience of VR modelling, which was acquired during the project through self-directed study; the work was carried out under academic supervision, and no formal VR training was provided.

The sedan was developed as the reference configuration and then used as the basis for a derived Sport Wagon, in which the rear volume and roofline were modified while the design language was preserved.



(**a**) (**b**) (**c**)

(**d**)

Figure 2. *Cont.*

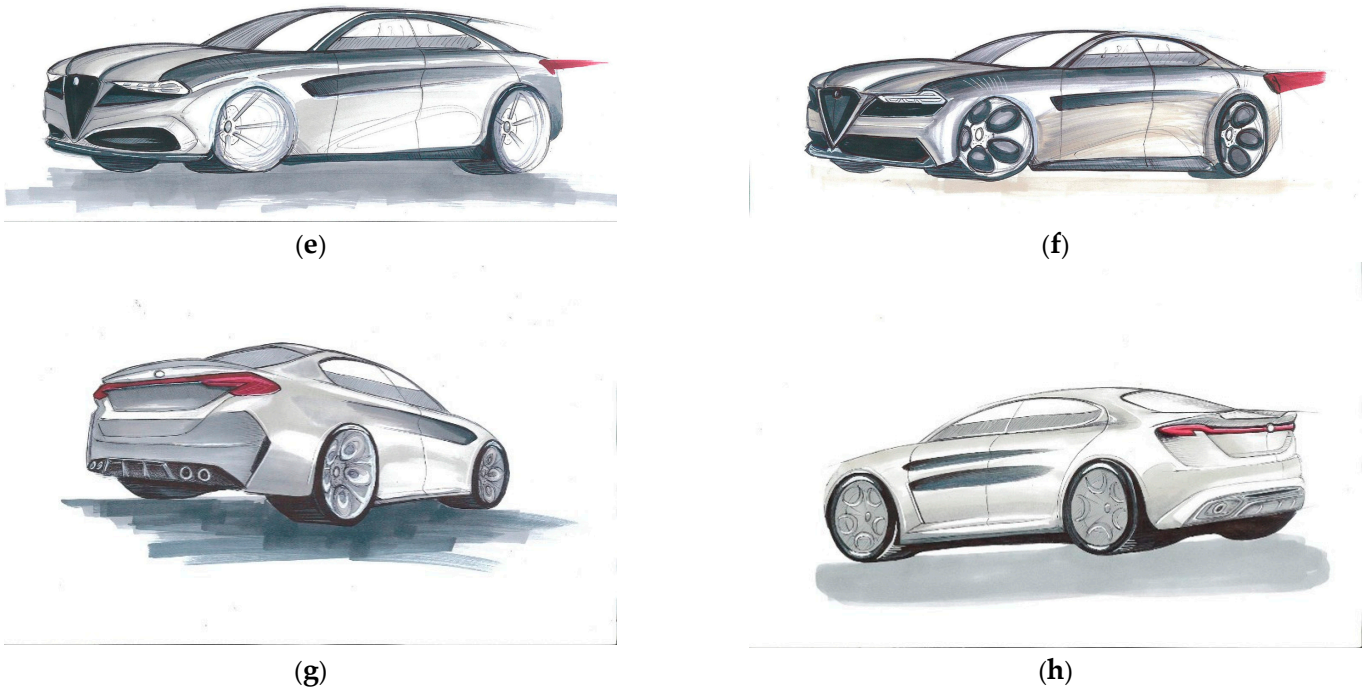


Figure 2. Concept development process. (**a**–**c**) Hand-drawn analysis sketches, produced by the authors, of the recurring front and rear stylistic cues (grille, lower air intakes, tail-light arrangement) of historical Alfa Romeo models, used to define the stylistic language of the concept; highlighted areas mark the elements retained. (**d**) Orthographic views of the selected concept (top row: front and side views; bottom row: rear and top views) with the main overall dimensions in millimetres (width 1865 mm, length 4620 mm, height 1435 mm), used as blueprints for immersive modelling. (**e**–**h**) Exterior design proposals, showing the final stylistic development from front, side and rear three-quarter perspectives. All images are original works of the authors; some of them were previously published by the authors in [11] and are reused here because they are explanatory for the present study. Alfa Romeo and the model names are trademarks of their owner and are cited for identification only.

The sedan and its derived Sport Wagon provide a bounded demonstration of two tasks addressed by the proposed workflow: developing a reference exterior concept from a defined package and adapting that concept to a related body configuration. The sedan establishes the initial proportions and styling language, while the Sport Wagon introduces changes to the roofline and rear volume that require these relationships to be reconsidered within the same design family. Their relevance therefore lies in the modelling tasks they exercise, including full-scale proportion review, variant development and downstream CAD refinement. The two configurations belong to a single project and share substantial design work; they do not constitute independent replications. This case supports an assessment of workflow implementation within the stated scope, while comparative effectiveness and applicability across vehicle segments require additional projects and designers.

3.5. VR-to-CAD-to-Prototype Digital Pipeline

The pipeline connected immersive concept modelling with CAD refinement, aerodynamic assessment, rendering and additive manufacturing (Figure 3).

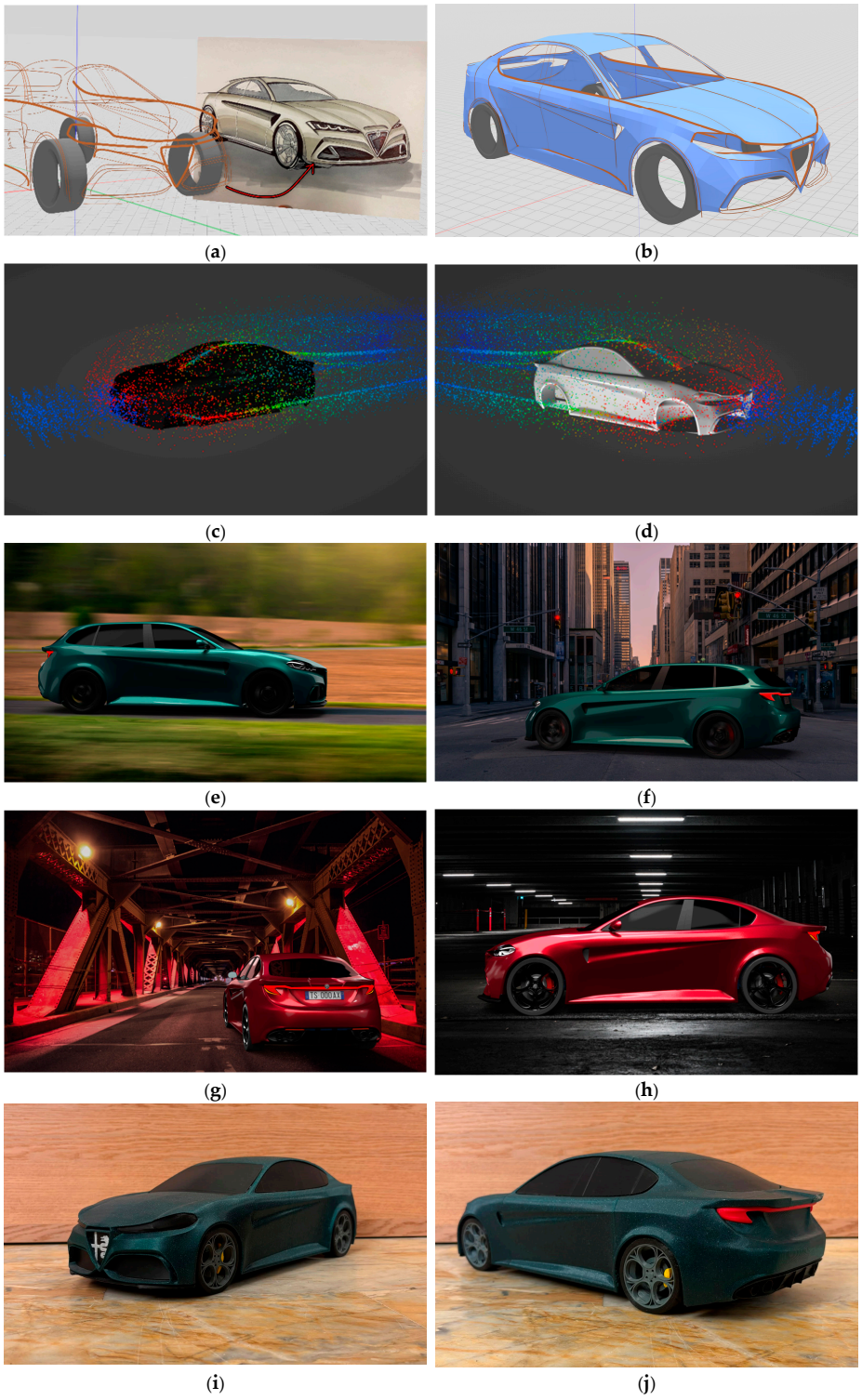


Figure 3. Outputs of the VR-enabled pipeline. (**a**) Initial immersive model in Gravity Sketch built on the selected sketch. (**b**) Refined three-dimensional model after CAD/NURBS refinement. (**c**,**d**) Preliminary qualitative aerodynamic visualization (particle colours: red, higher resistance to the flow; blue, high velocity), which highlights the nose, the windscreen–roof transition and the side, and the effect of front air intakes and wheel-arch outlets. (**e**,**f**) Renderings of the Sport Wagon variant. (**g**,**h**) Renderings of the sport sedan. (**i**,**j**) Physical prototype produced by additive manufacturing (1:10 scale), from front and rear three-quarter perspectives, used for final verification of proportions and overall design coherence. Some of the images were previously published by the authors in [11] and are reused here as original works of the authors because they are explanatory for the present study.

Immersive modelling. The wheels were positioned according to the package hard-points, the 2D blueprints were placed orthogonally, and the main lines were traced and projected on the blueprints. The lines were then extruded and joined into surfaces and refined in subdivision mode, using zebra analysis and clay display for the control of curvature. The original sketches were imported in the workspace to keep a continuous check of the model against the design intent. Full-scale visualization was used for the continuous evaluation of proportions, stance, surface transitions, roofline and volumetric balance, which was particularly relevant for the Sport Wagon variant. The shared virtual workspace also allowed review with other participants remotely.

Handover to CAD. The model was exported from Gravity Sketch in FBX format and imported into Rhinoceros. The geometry was converted and reworked into NURBS-based surfaces to correct local inconsistencies, adjust dimensional relationships and prepare the model for visualization and prototyping.

Preliminary aerodynamic check. The refined vehicle geometry was evaluated in Autodesk Flow Design (Autodesk, Inc., San Rafael, CA, USA) [26], a three-dimensional virtual wind tunnel. The check is qualitative: the flow around the body is visualized with colour-coded particles (red: zones of higher resistance to the flow; blue: high fluid velocity), and no drag coefficient, pressure field or mesh-converged solution was computed. For this reason no mesh, computational domain or boundary-condition set is reported, and no quantitative comparison between the two configurations was attempted. The observed features (Section 4.4) were used to decide local shape adjustments, for example at the nose, at the windscreen–roof transition, at the front air intakes and at the wheel-arch outlets.

Rendering. For visual evaluation, the refined geometry was imported into KeyShot, where materials, HDR environments and lighting conditions were assigned. The renderings were post-processed in Adobe Photoshop to correct shadows, reflections and minor visual artefacts.

Additive manufacturing. The refined model was exported in STL format to obtain a printable solid. A 1:10 scale prototype was produced by fused deposition modelling (FDM) on a Flying Bear Ghost 5 printer with a 0.4 mm brass nozzle and a layer height of 0.1 mm; the slicing was done with Ultimaker Cura 5.1. Because of the limited build volume, the body was divided into three parts; metallised PLA was used for the rigid parts (body, lights, wheels) and TPU for the tires.

3.6. Evaluation Framework and Indicators

The workflow was evaluated ex post through a comparison with CAD-based SDE practice as experienced by the authors, in particular in the earlier project. Table 3 defines each indicator, its unit, the way it was obtained and the availability of the data. Let T be the duration of the 3D modelling phase, N the number of complete vehicle configurations developed within that phase and R the number of revision events. The following derived quantities were used: the variant-development capacity $\Pi = N/T$ (configurations per week) and the revision density $\rho = R/N$ (revision events per configuration).

Table 3. Process indicators: definition, measurement and data status.

Indicator	Definition and Unit	How It Was Obtained	Data Status
Modelling duration T	Duration of the 3D modelling phase, in weeks	Authors' retrospective estimate against the project schedule	Estimate; hours per phase not logged
Configurations N	Number of complete vehicle configurations at concept-model level, count	Design outputs of the project	Recorded

Table 3. *Cont.*

Data Status	How It Was Obtained	Definition and Unit	Indicator
Derived from estimates	Derived	N/T, configurations per week	Variant capacity Π
Estimate; events not individually dated or classified	Designer's retrospective estimate	Distinct interventions requiring a modification of the vehicle geometry during model development, count; the same criterion is applied to both workflows	Revision events R
Derived from estimates	Derived	R/N, events per configuration	Revision density ρ
Qualitative	Process description	Environment and stage in which proportions are reviewed	Review modality
Qualitative	Process description	Stage at which the prototype is used and for which purpose	Role of physical prototype
Qualitative; time cost and geometric deviation not measured	Process description	Processing needed after FBX export	Interoperability effort

Three properties of these data must be stated. First, the reference values are estimates based on experience with CAD-based SDE projects, and not measurements from a documented baseline project. Second, effort per revision event, event complexity and the split of the modelling time between the two configurations were not logged, so that revision events are counted with equal weight. Third, the same designer who had experienced the CAD-based process carried out the VR modelling, and the comparison is therefore subject to recall and observer bias. Section 5.6 proposes the measurement protocol that would remove these limitations.

4. Results

4.1. Design Outputs

The SDE 4.0 workflow was completed for a D-segment sport sedan and a derived Sport Wagon, and produced the immersive and refined 3D models, renderings, a preliminary qualitative aerodynamic visualization and a 1:10 physical prototype (Figure 3).

The completed project provides evidence of implementation for the four workflow requirements defined in Table 2. For R1, full-scale inspection was incorporated into immersive modelling, allowing the designer to review proportions, stance, roofline and surface transitions during geometry development. The available documentation establishes the use of this review modality, although it does not quantify its influence on individual decisions. For R2, the project retained the SDE stages, connecting the upstream sketches and orthographic drawings to three-dimensional modelling, rendering and physical prototyping. For R3, the Sport Wagon was developed from the sedan through modifications to the roofline and rear volume, demonstrating the production of a related configuration within the same digital process. For R4, geometry was transferred from the immersive environment to CAD and subsequently prepared for rendering and additive manufacturing.

These outcomes establish that the proposed sequence could be completed in the reported academic design setting. They also identify a practical constraint: the VR output required further geometric processing in CAD before downstream use. The completed artefacts provide evidence of workflow feasibility; they do not establish improved design quality, reduced workload or greater efficiency relative to conventional SDE.

4.2. Indicative Process Indicators

The designer retrospectively estimated an overall modelling effort of approximately four weeks for the two configurations, compared with approximately four weeks for a single vehicle in the CAD-based reference practice. The modelling phase in the project

schedule spans a longer calendar interval than four weeks, because the designer had limited prior experience with VR modelling and acquired it during the project through self-directed study; the four-week figure therefore refers to the modelling effort and not to the elapsed calendar time, and hours per week were not logged. The number of configurations completed within this effort was two, against one. Approximately eight revision events were estimated in the SDE 4.0 workflow, against approximately 20 in the conventional practice. Table 4 summarizes the indicators. The values of Π and ρ are arithmetic consequences of the estimates and carry the same uncertainty; no percentage improvement is claimed.

Table 4. Indicative process indicators (designer's retrospective estimates; single project).

VR-Enabled SDE 4.0	Conventional CAD-Based SDE (Reference Practice)	Indicator
4 weeks (modelling effort; both configurations)	About 4 weeks	Modelling duration *T*
2 (sedan, derived Sport Wagon)	1	Configurations *N*
About 0.5	About 0.25	Variant capacity Π (configurations per week)
About 8 (estimate)	About 20 (estimate)	Revision events *R*
About 4	About 20	Revision density ρ (events per configuration)
Full-scale immersive review during modelling, followed by final physical verification	Screen-based review followed by physical verification	Design review modality
Final verification of proportions and overall design coherence	Verification of proportions and surfaces after CAD modelling, with a corrective loop	Role of physical prototyping
Additional CAD/NURBS refinement required after FBX export	Performed directly within the CAD environment	Downstream geometric refinement

Two aspects limit the comparability of these figures beyond the estimation uncertainty. The second configuration is derived from the first, so that its revision events are not independent of those of the sedan. Conversely, the VR modelling was performed by a designer who was still acquiring VR skills, which would tend to work against SDE 4.0 in time and revision count. The two effects cannot be separated with the present data.

4.3. VR-to-CAD Interoperability

The transition from immersive modelling to CAD refinement was the main interoperability bottleneck. The FBX geometry exported from Gravity Sketch, a mesh derived from a subdivision model, could not be used directly for the following stages: it required conversion to NURBS surfaces in Rhinoceros, correction of local inconsistencies, adjustment of dimensional relationships and preparation of a solid model suitable for STL export. Downstream CAD refinement therefore remained necessary. The time taken by the conversion, and the deviation between the exported mesh and the final NURBS surfaces, were not measured; the preservation of overall proportions and of the main styling features was judged visually. On the basis of the case, the following practical recommendations are proposed. They derive from the observed bottleneck and have to be tested in future studies:

1. Define the package hardpoints and reference dimensions (wheelbase, tracks, overall dimensions) before starting immersive modelling, so that dimensional correction in CAD is reduced.
2. Keep the subdivision topology clean and regular where surfaces will be rebuilt as NURBS.
3. Plan the CAD/NURBS refinement as a scheduled step with its own time budget.

4. Check curvature continuity in both environments (zebra analysis) before and after the handover.
5. Measure, at least on a sample of surfaces, the deviation between the exported mesh and the final NURBS geometry.

4.4. Preliminary Qualitative Aerodynamic Check

The airflow visualization (Figure 3c,d) showed a zone of higher resistance in the upper part of the nose, at the discontinuity between windscreen and roof and at the side of the vehicle, and showed the front air intakes and the wheel-arch outlets working as flow relief, with the fluid gaining velocity in correspondence of the openings. These observations were used as qualitative design cues for local shape adjustments during modelling. They are not a quantitative characterization of the vehicle, and they do not allow the sedan and the Sport Wagon to be compared.

4.5. Physical Prototype

The 1:10 additive manufacturing prototype was used for the final verification of the proportions and of the overall design coherence, and as a cross-check of the proportion judgements made in VR against a physical object. It was assessed by the design team, and no formal evaluation protocol was applied. Since it was produced after the modelling phase, the study did not record whether the prototype triggered geometry changes; its influence on subsequent design decisions is therefore not documented.

5. Discussion

5.1. Interpretation and Specific Contribution

The results are consistent with the working hypothesis that immersive modelling can strengthen the early stages of SDE, without proving it. The design science reading makes the contribution explicit. The artefact is a workflow that inserts a full-scale review gate inside the modelling stage of a structured styling methodology and defines its handover to CAD, rendering and additive manufacturing. Its scientific value lies less in the individual tools, which are commercially available, than in (i) the explicit specification of the stages that are changed and those that are kept, (ii) the indicators and measurement protocol that make the assessment reproducible, and (iii) the documented boundary conditions, in particular the VR-to-CAD interface. Compared with the works cited in Table 1, the shift is from immersive review of finished CAD models, or from immersive modelling as an isolated tool, to immersive modelling as a stage of a methodology whose outputs are handed over to downstream tools.

The results also indicate that VR and CAD are complementary rather than alternative environments. Immersive modelling supported rapid exploration and full-scale evaluation, while CAD remained necessary for dimensional control, geometric correction and the preparation of the final outputs. Physical prototyping was retained, but as a final verification tool.

5.2. Industry 5.0 Perspective

The Industry 5.0 vision is characterized by human-centricity, sustainability and resilience. The workflow can be discussed with respect to these dimensions, with different levels of support from the data.

Human-centricity. This is the dimension most directly supported by the case. Gestural input and full-scale perception place the designer's embodied judgement of proportion and surface at the centre of the modelling activity and reduce the mediation of the 2D display. The claim is however limited: the study did not measure designers' cognitive load, satisfaction

or perceived usefulness, and it did not test whether full-scale visualization changed design decisions. Such measures are part of the validation protocol proposed below.

Resilience. The shared virtual workspaces allowed review and joint work with participants working remotely, which is relevant for distributed design teams. No quantitative evidence of robustness was collected.

Sustainability. The workflow keeps the physical prototype as the final verification, and not as the main tool of an iterative print-and-remodel cycle, which suggests a potential reduction in prototype iterations and of the associated material use. This is a hypothesis: the number of prototypes and the material consumption were not measured for the reference practice.

5.3. Generative AI and the Positioning of SDE 4.0

Generative AI systems can accelerate concept generation and exploration in the early stages, while VR sketching has been investigated specifically as an immersive approach to automotive concept design. The contribution of SDE 4.0 is not in competition with these tools, because it addresses another problem. Generative tools act mainly on 2D ideation, upstream of the selection of a concept; SDE 4.0 acts on the three-dimensional development and review of the selected concept at the scale of the final product, where the designer must judge stance, volumes and surface continuity. The two can be combined at defined points of the workflow: as an additional source of concept variants in the sketching stage, as a generator of alternative surface treatments to be evaluated in the immersive review gate, and as a support for rendering. These integrations were not implemented in the present study and are proposed here as design implications; the human review gate would remain the place where AI-generated alternatives are judged and selected, which is consistent with a human-centric view of AI-assisted design.

5.4. Generalisability

The findings come from one vehicle type, one VR platform and one designer. The workflow is described in terms of the capabilities it needs from the immersive tool: subdivision or spline-based modelling at full scale, curvature-oriented display, import of blueprints and sketches, and export of geometry to a CAD environment. Platforms with these capabilities could in principle be used, but this transferability was not tested, and the specific performance of Gravity Sketch, including its export formats, cannot be assumed for other tools. Other body styles (for example coupé or SUV) would present different surface and package constraints, and interiors would involve different interaction requirements. The level of experience of the designer influences the results: a designer with more VR experience could obtain shorter modelling times, while a designer with no CAD experience could face the refinement stage with more difficulty. The cost and accessibility of the hardware and licences were not assessed and should be considered for industrial adoption.

5.5. Limitations

The main limitations are the following. (i) The study is a single-case, retrospective demonstration by the authors who developed the workflow, and it is not a controlled experiment. (ii) The reference values are estimates and not measurements from a documented baseline, and the four-week figure refers to the modelling effort and not to logged hours. (iii) Revision events were counted with equal weight, without classification by type, complexity or duration, and the comparison could be affected by recall and observer bias. (iv) The VR modelling was performed by a designer with limited prior VR experience, and the second configuration was derived from the first. (v) The aerodynamic check is qualitative, and the case contains no quantitative CFD. (vi) The VR-to-CAD conversion time and geometric deviation were not measured. (vii) No expert or user evaluation of the full-scale visualization was carried out, and the influence of the prototype on the design

decisions was not recorded. (viii) The results concern exterior styling at the concept stage and one VR platform. For these reasons, the paper does not claim statistically or causally validated efficiency gains.

5.6. Validation Protocol and Future Work

The next cycle of the design research should replace the retrospective estimates with measured data. A within-subject study is proposed, in which several designers with documented VR and CAD experience develop comparable concept tasks with both workflows, in counterbalanced order, with the following measurements: logged hours for each phase; timestamped revision events classified by type (proportion, surface continuity, dimensional) and weighted by duration; time and geometric deviation of the VR-to-CAD conversion; blind expert ratings of proportion and surface quality of the results; and standardized measures of workload and user experience of the designers. The same protocol would allow the assessment of other platforms, other vehicle types and interiors, and of the integration of generative AI in the sketching and review stages.

6. Conclusions

This study presented SDE 4.0, a VR-enabled extension of the Stylistic Design Engineering methodology for early-stage automotive concept development, framed as a design science research contribution. The workflow keeps the stages of SDE, introduces a full-scale review gate in the modelling phase and defines the handover to CAD, rendering and additive manufacturing. The workflow was demonstrated on a D-segment sport sedan and a derived Sport Wagon, for which the designer retrospectively estimated an overall modelling effort of approximately four weeks. The retrospective estimates suggest a lower number of revision events than in CAD-based practice; however, these estimates come from a single project and a single designer, and they do not establish an efficiency gain.

The study identifies the VR-to-CAD/NURBS transfer as the main limitation of the workflow, and it confirms that CAD and physical prototyping remain necessary as refinement and final verification tools. In the Industry 5.0 perspective, the main potential of the approach lies in supporting the designer's embodied judgement and collaborative work; this potential has to be substantiated by the controlled, multi-designer and multi-project studies outlined in Section 5.6, which should also examine the integration of generative AI.

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Data Availability Statement: The process indicators reported in Table 4 are retrospective estimates made by the authors; no dataset of logged hours or timestamped revision events exists for the projects compared. The design outputs are included in the article. The MSc thesis on which the demonstration case is based is held by the University of Bologna. Further information on the case is available from the corresponding author upon reasonable request.

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