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Human-Object Interaction Spatial Constraint-Driven Intelligent Generative Design for Products

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ABSTRACT

The convergence of ergonomics, Kansei engineering and generative artificial intelligence is reshaping intelligent product design. Geometric optimisation alone cannot fully account for the physical usability and affective experience of human–product interaction. This narrative review examines three complementary approaches: quantifying Kansei needs, using AI-assisted generative tools in design exploration, and incorporating spatial and ergonomic constraints into design and evaluation. Research on vehicle interiors provides examples of Kansei quantification and digital human modelling, while studies of furniture and indoor layouts illustrate additional methods for constraint-based generation and screening. These studies indicate promising pathways towards human-centred, constraint-aware design, but do not yet constitute a single fully integrated or standardised workflow. Challenges include translating subjective imagery into design parameters, combining static and dynamic constraints, and evaluating usability across application domains. Future directions include collaborative human–AI workflows, behavioural and physiological evaluation, and better integration of measurable physical constraints into generative processes.

Keywords: Kansei engineering, AIGC, Spatial constraints, Generative design, Ergonomics

INTRODUCTION

Product design is undergoing a fundamental reorientation. For several decades, generative design evolved primarily along the path of geometric optimisation and structural performance, progressing from topology optimisation to parametric modelling and from evolutionary algorithms to deep generative models. These advances substantially improved design efficiency and formal diversity. However, when the designed object entails close interaction between human and product, a purely geometry-driven paradigm reveals a fundamental limitation: a structurally optimal solution is not necessarily one that users can comfortably operate or emotionally accept.

The root of this limitation lies in the nature of human-product interaction space, which is essentially a constrained experiential space. In an automotive cockpit, for instance, the distance between steering wheel and seat is bounded by anthropometric data, yet the user's subjective judgement of spaciousness or enclosure cannot be derived directly from those physical dimensions.

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Spatial constraints are rigid, whereas affective experience is flexible, and both must be satisfied simultaneously during generation.

It is within this tension that the integration of Kansei engineering and AIGC demonstrates distinctive methodological value. Kansei engineering, developed through foundational work by Nagamachi, seeks to quantify users' ambiguous emotional imagery through engineering methods and to construct mapping relationships between affective needs and design elements. AIGC, powered by diffusion models and large language models, can generate high-quality visual solutions from textual prompts. Their combination offers a technical possibility for generating within constraints while responding to emotion.

Ishihara (2024) noted in a review that the methodology of Kansei engineering has expanded from multivariate statistical analysis to 3D CG, image processing and AI techniques, with generative AI being used to explore new design ideas based on Kansei engineering. The bibliometric analysis by Qu et al. (2026) further confirmed that Kansei engineering has shifted from early semantic and statistical methods towards data-driven and AI-assisted methodologies. This paper reviews the state of the art in this interdisciplinary field. Section 2 addresses the quantification of Kansei needs under spatial constraints; Section 3 analyses the principal technical pathways of AIGC-driven generation; Section 4 discusses the embedding strategies of spatial and ergonomic constraints; and Section 5 identifies the limitations and future directions of current research.

Quantifying Kansei Needs Under Spatial Constraints

The methodological core of Kansei engineering can be summarised as the engineering translation of imagery. Its underlying assumption is that users' emotional responses to products are not an impenetrable black box but can be converted into quantitative indices corresponding to specific design elements through systematic experimental design and statistical modelling. The classical procedure comprises extraction and screening of Kansei words, decomposition of design elements, and construction of mapping models.

When Kansei engineering is applied to products with spatial constraints, affective responses should be linked to measurable design characteristics. Tanoue et al. (1997) examined vehicle-interior images in relation to perceived roominess and oppressiveness. Chihara and Sakamoto (2019) used virtual-reality models with varied roof heights and windshield depths to examine perceived cabin spaciousness. Their results illustrate how subjective judgements may be analysed alongside geometric design parameters; the reported relationships should not be interpreted as universal dimensional standards.

Recent studies have broadened the methods available for such analysis. Wang et al. (2026) combined eye tracking and attention-aware rough-set feature selection with a TCN-BiGRU-Attention model to relate interior design features to Kansei evaluations. Aan et al. (2026) applied interval Type-2 fuzzy hesitant AHP and interval 2-tuple q-rung orthopair fuzzy QFD to translate aesthetic and sustainability requirements into design feature priorities. These approaches differ in their input data and outputs, but both make subjective requirements more explicit during design decision-making.

Studies of specific user groups and automotive interiors further illustrate how these methods are applied. Gui et al. (2026) integrated Kansei engineering, entropy-weighted TOPSIS and a backpropagation neural network to inform the emotional design of new-energy-vehicle centre consoles for older users. Liu et al. (2024) combined FAHP, grey relational analysis, Kansei evaluation and FQFD to derive design priorities for adaptable passenger-vehicle interior spaces.

Table 1: Examples of affective and ergonomic design variables reported in the cited literature.

Kansei or Usability Focus	Design Variable or Method	Reported Type of Evidence	Source
Perceived roominess / oppressiveness	Vehicle-interior design dimensions	Kansei-based perception analysis; no universal range implied	Tanoue et al. (1997)
Visual spaciousness	Roof height and windshield depth	VR-based spaciousness ratings across varied cabin geometries	Chihara and Sakamoto (2019)
Interior Kansei imagery	Eye tracking, feature selection and predictive modelling	Relationship between design attributes and Kansei ratings	Wang et al. (2026)
Adaptable interior design	FAHP, Kansei analysis and FQFD	Prioritised user requirements and design associations	Liu et al. (2024)
Aesthetics and sustainability	Fuzzy AHP and fuzzy QFD	Feature priorities balancing multiple requirements	Aan et al. (2026)

AIGC-Driven Generative Pathways

Diffusion-based image-generation systems, including Stable Diffusion, allow designers to explore visual alternatives through text prompts and other conditioning inputs. However, visual generation alone does not establish that an output satisfies anthropometric, biomechanical or manufacturing constraints. Recent design studies therefore combine AI-generated alternatives with Kansei evaluation, geometric modelling or downstream ergonomic assessment.

For electric-vehicle styling, Yi et al. (2026) proposed a workflow combining semantic-differential evaluation, factor analysis, morphological analysis, BP and GA-BP neural networks, and AIGC-supported concept generation. The study describes an approach for mapping users' affective assessments to styling decisions, rather than providing evidence that image generation alone guarantees functional or ergonomic compliance.

Wu and Lu (2026) proposed a three-stage human–AI collaborative Kansei design model. First, GPT-5 was used to synthesise imagery adjectives and define target imagery. Second, representative Midjourney outputs were decomposed into morphological elements and assessed using fuzzy comprehensive evaluation and Kansei questionnaires. Third, a 3D model and its feature curves informed colour generation with Stable Diffusion, followed by AHP-based evaluation. The authors demonstrated the model with two electric-motorcycle case studies.

Related work has considered the consistency of product-family styling. Lin et al. (2025) described a human–AI collaborative framework for product-family DNA definition and styling that integrates deep-learning-based feature analysis, Kansei-related evaluation and AI-assisted generation. This represents an adjacent styling application; it should not be taken as direct evidence of verified ergonomic fit or spatial usability.

Embedding Spatial Constraints in Generative Processes

Spatial and ergonomic constraints can be considered at several stages of an AI-assisted design workflow. The following three categories provide a conceptual distinction between constraints applied before generation, assessment after candidate generation, and constraints represented inside an optimisation process. They are not a claim that the cited studies use an identical generative architecture:

Constraint pre-emption: relevant dimensions, posture conditions or other requirements are specified before candidate generation or optimisation. Perez Luque et al. (2025) combined simulation-based multi-objective optimisation with a digital human modelling tool to investigate occupant packaging configurations subject to anthropometric and postural variation. This makes accommodation criteria measurable, although the feasible design space depends on the model assumptions and selected constraints.

Constraint post-evaluation: candidate concepts are generated and subsequently checked against engineering requirements. In a chair-design study, Zhao (2026) generated chair concepts using a GAN and applied finite-element analysis, ergonomic screening and manufacturing constraints to assess and refine them. The application concerns furniture rather than automotive seating; it illustrates a transferable screening strategy, not direct validation for vehicle seat design.

Constraint internalisation: spatial requirements are expressed as constraints in the layout optimisation process itself. For indoor 3D scene generation, Jin et al. (2026) used vision–language reasoning to infer object–behaviour relationships and translated anthropometric and operational requirements into differentiable layout penalties. Their study concerns room layouts and human use of objects, rather than automotive cabins, and offers an example of behaviour-aware constraint representation.

Table 2: Comparison of spatial constraint embedding strategies.

Strategy	Timing	Advantage	Limitation	Illustrative Application
Constraint pre-emption	Before generation	Precise, verifiable	Narrows innovation space	Occupant packaging (Perez Luque et al., 2025)
Constraint post-evaluation	After generation	Preserves diversity	High computational cost	Chair design (Zhao, 2026)
Constraint internalisation	During generation	Balances constraints and diversity	Technically demanding	Room layout (Jin et al., 2026)

Limitations and Future Directions

A fundamental problem confronting current research is how to quantify the consistency between user Kansei needs and producer design objectives. The core difficulty is the systematic gap between affective perception on the user side and goal expression on the design side. Generative design must not only process Kansei words input by users but also embed the constraint expression of producer design intent within the generation process.

A second limitation is the disconnection between dynamic interaction and static constraints. Existing studies mostly address static spatial constraints, such as operating range in a seated posture or packaging geometry, whereas generative systems struggle to respond effectively to spatial demands in dynamic interaction, including postural change during driving and spatial sequences of multi-step operations.

A further limitation is the lack of common evaluation protocols that permit direct comparisons across these application domains. Kikumoto et al. (2025) used electromyography (EMG) to investigate car-seat lever-grip positions and found that positions receiving lower Kansei ratings tended to correspond to higher muscular load. This illustrates how physiological measures can complement subjective evaluation; it does not itself establish a standard benchmark for AI-generated products.

Qu et al. (2026) mapped historical and emerging trends in Kansei engineering, including increasing interest in AI and multimodal approaches. Ishihara (2024) reviewed the development of Kansei engineering methods from multivariate analysis towards 3D computer graphics, image processing and AI. Together these reviews help motivate cross-disciplinary research, but direct validation of end-to-end Kansei- and ergonomics-constrained generative pipelines remains limited.

Looking ahead, several directions merit attention. Mixed-initiative interaction, in which designers and AI jointly define and adjust constraints, may better suit real design scenarios than fully automatic generation. The development of physically intelligent models capable of reasoning about body morphology, posture, motion and even contact pressure would advance spatially constrained generation from the geometric level to the physical interaction level. In addition, incorporating real-time physiological feedback into the generative loop to enable dynamic adjustment of Kansei constraints represents a highly promising direction.

CONCLUSION

The reviewed studies demonstrate complementary rather than fully unified routes towards human-centred, constraint-aware product design. Kansei engineering supports the translation of emotional impressions into design criteria; digital human modelling and ergonomic optimisation help represent physical accommodation; and generative AI broadens early-stage visual and conceptual exploration. Automotive interior studies offer examples of affective assessment and occupant packaging, whereas chair and indoor-layout studies illustrate post-generation screening and embedded human-use constraints. Future research should examine how these strands can be coupled and evaluated using reproducible measures of physical feasibility, functional use and affective acceptance.

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