Mapping Knowledge Domains in Contemporary Engineering Design: A Conceptual Review and Implications for Interdisciplinary Engineering Education

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ABSTRACT

Engineering design education must develop more than proficiency in technical design procedures. Contemporary graduates are also expected to reason reflectively, generate creative alternatives, understand diverse users, and account for sustainability and wider socio-technical consequences. Yet these capabilities are often taught through separate methods without an explicit account of the forms of knowledge that connect them. This integrative conceptual review maps established creative and design methodologies into knowledge domains and examines their implications for interdisciplinary engineering education. Three analytical methods were employed: literature identification and comparative review, knowledge-function analysis and conceptual clustering, and cross-domain interpretive synthesis. The synthesis identifies six complementary domains: design cognition and foundational thinking, creative ideation, systematic engineering design, human-centred design, systems and sustainable design, and design research and reflective practice. Their development is interpreted through two interacting trajectories: deepening design capability and broadening design responsibility. Educationally, the map offers a conceptual lens for curriculum mapping, constructive alignment of learning outcomes and assessment, and integration of technical and human-oriented capabilities across design projects. These implications are propositions for curriculum design rather than empirically tested interventions. The framework complements established design processes and provides a basis for future educational validation.

Keywords: engineering design education; interdisciplinary learning; design cognition; creative ideation; human-centred design; curriculum development

INTRODUCTION

Engineering design is the organised transformation of needs and requirements into artefacts, systems, and solutions. Established methodologies formalised this activity through requirement clarification, conceptual design, embodiment, detailed design, evaluation, and implementation [1–6]. These approaches remain the technical backbone of engineering design because they make design activity explicit, teachable, traceable, and open to systematic evaluation.

Over time, the knowledge required for engineering design has expanded. Design research has examined how designers frame problems, reason, sketch, generate ideas, evaluate alternatives, and move iteratively between problem and solution [7–11]. Creativity research has introduced deliberate methods for enlarging and transforming solution spaces [12–21]. Human-centred approaches have strengthened attention to users, experience, context, participation, and stakeholder value [22–26], while sustainability and systems perspectives have extended design consideration towards life cycles, resource use, circularity, resilience, and socio-technical consequences [27–32].

This diversity creates an educational as well as a methodological problem. Engineering students may encounter systematic engineering design, Brainstorming, TRIZ, Design Thinking, user-centred design, life-cycle design, systems thinking, and reflective practice as isolated techniques. Learning the sequence of design stages does not

necessarily develop the reasoning, creativity, stakeholder awareness, and judgement needed to apply those techniques responsibly. An organising account of their distinct knowledge functions may help educators make intended capabilities explicit without treating a single method as sufficient for every design challenge.

This paper asks: What principal knowledge domains can be identified from established creative and design methodologies, and how might their distinct contributions inform interdisciplinary engineering design education? The focus is a domain-level account of design knowledge rather than a comparison of institutional curricula.

The objectives are to (1) review the evolution and diversity of major creative and design methodologies relevant to engineering design; (2) identify their principal knowledge domains; and (3) interpret how these domains may inform interdisciplinary engineering education. The contribution is an organising map for examining curriculum coverage, pedagogical integration, and assessment, rather than another prescribed design process.

Evolution of Engineering Design Knowledge

Engineering design knowledge has developed through successive and overlapping methodological traditions. Early work concentrated on formalising technical design activity. Later research examined cognition and creativity, followed by increasing attention to users, sustainability, and wider systems. These developments accumulated rather than simply replacing earlier approaches.

Traditional engineering design processes provide a useful baseline. Figure 1 summarises the general progression represented across established systematic methodologies [1–6].

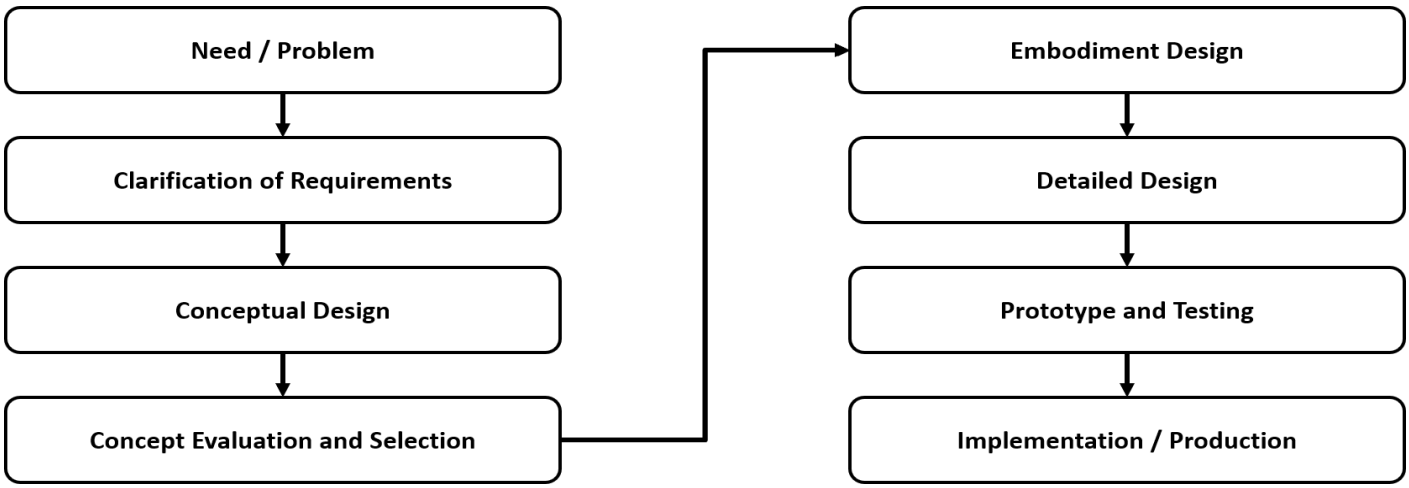

Figure 1. General form of traditional engineering design process. Iterative feedback may occur between successive stages.

Development of Systematic Engineering Design

Systematic engineering design became prominent during the twentieth century as researchers sought to make complex design activity more rational, repeatable, and communicable. Pahl and Beitz structured design around task clarification, conceptual design, embodiment design, and detail design [1]. Hubka and Eder similarly developed a systematic body of design knowledge centred on technical systems and design processes [2]. Pugh's Total Design connected market need, product design specification, conceptual design, detailed design, manufacture, and sales [3]. Later models by Ullman, Ulrich and Eppinger, and Cross further developed structured approaches to requirements, concept generation, evaluation, product architecture, embodiment, prototyping, and decision making [4–6].

These methodologies established a durable procedural foundation for engineering design. At the same time, their formalisation encouraged a further question: do prescribed stages fully represent how designers actually think and work? This question stimulated research into design cognition and the situated nature of design activity.

Emergence of Design Cognition and Creative Design Research

From the latter twentieth century, design researchers increasingly examined the cognitive processes occurring within design. Schön described professional practice as reflection-in-action, in which understanding develops through cycles of framing, action, and reflection [7]. Cross argued for distinctive 'designerly ways of knowing' [8], while Dorst and Cross described creative design as the co-evolution of problem and solution spaces [9]. Research on representation, sketching, and situated cognition further demonstrated that designers frequently reinterpret problems while developing solutions [10,11].

In parallel, creativity research made idea generation more explicit and teachable. Wallas described preparation, incubation, illumination, and verification [12], while Guilford established divergent production as a central construct in creativity research [13]. Osborn's Brainstorming promoted deferred judgement and quantity of ideas [14]; de Bono's Lateral Thinking encouraged deliberate disruption of habitual patterns [15]; and Zwicky's Morphological Analysis supported systematic combination of solution alternatives [16]. More structured engineering-oriented methods followed, including TRIZ [17], SCAMPER [18], C-Sketch [19], Design-by-Analogy and biomimetic design [20,21]. Collectively, these developments shifted creativity from an assumed personal talent towards a process that can be investigated and deliberately supported.

Rise of Human-Centred and Use-Oriented Design

Another major development concerned the relationship between engineered solutions and the people who use them. Human factors and ergonomics had long influenced engineering, but user-centred design increasingly emphasised usability, interaction, experience, and context throughout development. Norman highlighted affordances, feedback, mappings, constraints, and users' conceptual models [22]. ISO 9241-210 later formalised human-centred design as an iterative approach grounded in explicit understanding of users, tasks, and environments [23].

Participatory design and co-creation further positioned users and stakeholders as active contributors to design [24,25]. Design Thinking popularised iterative combinations of user understanding, problem framing, ideation, prototyping, and testing across engineering, business, and innovation contexts [26]. These developments expanded engineering requirements beyond technical specifications to include human capability, behaviour, experience, accessibility, and value.

Expansion Towards Sustainability and Systems Perspectives

From the late twentieth century, environmental concerns further expanded the scope of engineering design. Life-cycle approaches enabled impacts to be considered across material extraction, production, distribution, use, maintenance, and end-of-life [27]. Design for environmental sustainability brought these concerns into decisions on materials, energy, durability, disassembly, reuse, and disposal [28]. Cradle-to-cradle and circular-economy perspectives challenged linear models of production and waste by emphasising regenerative cycles, repair, reuse, remanufacture, and recovery [29,30].

Systems perspectives reinforced the need to consider relationships, feedback, interdependencies, boundaries, and emergent effects rather than treating an artefact in isolation. Contemporary sustainability frameworks increasingly connect products to broader socio-technical systems [31]. Industry 5.0 similarly frames technological development around sustainability, human-centricity, and resilience [32]. By the early twenty-first century, engineering design therefore encompassed not only technical performance but also cognition, creativity, users, life cycles, and wider system consequences.

Review and Synthesis Approach

This study adopted an integrative conceptual review to compare established methodologies and theoretical perspectives contributing to engineering design knowledge. Literature identification was informed primarily by the author’s existing disciplinary knowledge, prior reading, and familiarity with influential design traditions.

Accordingly, sources were selected purposively for conceptual synthesis rather than retrieved through a systematic database search [33–35].

The reviewed corpus comprises the 37 works cited in this manuscript, including foundational books, peer-reviewed articles, a technical standard, and policy-oriented publications, published between 1926 and 2021. Source selection emphasised relevance to engineering design, influential or distinctive contributions to design scholarship, and representation of methodological traditions in systematic engineering design, design cognition, creative ideation, human-centred design, systems and sustainable design, and design research. Earlier foundational publications were considered alongside subsequent works extending or formalising those perspectives. This date span describes the cited literature, not an a priori publication-year restriction. No database search strategy, record-screening totals, or reproducible search audit trail are claimed.

The synthesis followed three interpretive steps aligned with the research objectives (Table 1): (1) comparative examination of the purposes and historical contributions of selected approaches; (2) analysis of their dominant knowledge functions and iterative clustering into domains; and (3) cross-domain interpretation of complementary trajectories of deepening capability and broadening responsibility. Sources were interpreted in relation to the knowledge functions they illuminate rather than assigned exclusively to one domain. The purposive corpus does not establish literature saturation or exhaustive coverage.

Method 1, literature identification and comparative review, examined the development, purposes and contributions of the selected traditions. Method 2, knowledge-function analysis and conceptual clustering, asked what form of knowledge or capability an approach primarily contributes. Method 3, cross-domain interpretive synthesis, compared the resulting domains to identify higher-order patterns in the expansion of engineering design knowledge.

Because many methodologies span more than one function, the domains are analytical rather than mutually exclusive. Design Thinking, for example, combines human-centred inquiry, ideation, prototyping, and iteration [26]. TRIZ combines creative generation with systematic contradiction resolution [17]. Classification therefore reflects dominant contribution rather than exclusive membership.

Table 1. Alignment of research objectives, methods, and analytical outcomes.

Objective	**Method**	**Analytical outcome**
1. Review the evolution and diversity of major creative and design methodologies	Literature identification and comparative review	Historical and conceptual development of engineering design knowledge
2. Identify the principal knowledge domains	Knowledge-function analysis and conceptual clustering	Six principal knowledge domains
3. Interpret the contribution of the domains to contemporary engineering design	Cross-domain interpretive synthesis	Higher-order trajectories in the expansion of engineering design knowledge

The final interpretive stage compared the six domains at a higher level of abstraction. Rather than imposing a chronological sequence, the analysis examined whether each domain primarily increased the sophistication with which design activity is understood and performed, or expanded the range of actors, contexts, time horizons, and consequences considered in design. This comparison produced the broadening-deepening interpretation reported in Section 4.3.

Conceptual clustering was performed iteratively. Initial groupings were compared for overlap and explanatory distinctiveness, then consolidated where several approaches addressed substantially the same design concern. A domain was retained when it represented a recognisable body of design knowledge, could accommodate multiple established approaches, and could be distinguished by a central question not adequately represented by another domain. The resulting six-domain solution provided the most parsimonious representation of the reviewed traditions while retaining their major differences.

The unit of analysis was the methodology or theoretical perspective rather than individual empirical findings. For each approach, the review considered its stated purpose, the design activity it supports, the type of knowledge it makes explicit, and the level at which it acts. This distinction was important because methods with similar surface activities may serve different intellectual functions. Sketching, for example, may operate as an external representation for cognition, as a mechanism for collaborative ideation, or as a means of communicating an emerging engineering concept [10,19]. The analysis therefore focused on dominant knowledge function rather than terminology alone.

Results: Knowledge Domains of Contemporary Engineering Design

The analysis produced three results corresponding to the three objectives. First, the historical review showed progressive accumulation of methodological traditions rather than simple replacement of earlier approaches. Second, knowledge-function analysis produced six principal domains. Third, cross-domain synthesis revealed two complementary trajectories through which these domains have expanded contemporary engineering design knowledge.

Result 1: Progressive Accumulation of Engineering Design Knowledge

The comparative review shows that engineering design developed from a strong systematic and technical foundation [1–6] towards increasingly explicit knowledge of cognition and reflection [7–11], creative ideation [12–21], human-centred inquiry [22–26], and sustainability and systems concerns [27–32]. Newer perspectives generally supplement rather than invalidate established engineering design procedures. The result is a cumulative knowledge base in which different methodological traditions address different aspects of designing.

Result 2: Six Principal Knowledge Domains

Knowledge-function analysis and conceptual clustering identified six domains. Each domain is defined by a central question and a dominant contribution to design activity.

Design Cognition and Foundational Thinking

Design cognition concerns how designers perceive, frame, represent, reason about, and transform design problems. Key concepts include reflection-in-action, problem framing, visual reasoning, iteration, and problem-solution co-evolution [7–11]. Its contribution is explanatory: it provides knowledge of the reasoning mechanisms beneath observable design activities and clarifies why design expertise cannot be reduced to procedural knowledge alone.

Creative Ideation

Creative ideation concerns the deliberate generation and transformation of possible solutions. Methods range from relatively open techniques such as Brainstorming and Lateral Thinking to structured approaches including Morphological Analysis, TRIZ, SCAMPER, C-Sketch, Design-by-Analogy, and biomimetic design [14–21]. Their common contribution is to reduce fixation, enlarge solution spaces, and support recombination or transformation of ideas.

Systematic Engineering Design

Systematic engineering design provides the procedural and technical structure through which needs and requirements are transformed into feasible solutions. Functional decomposition, concept generation and selection, embodiment, detailed design, prototyping, verification, and implementation are recurring elements across established models [1–6]. Its principal contribution is disciplined technical development, including traceability, evaluation, manufacturability, reliability, and decision making.

Human-Centred Design

Human-centred design contributes knowledge of users, stakeholders, activities, experiences, and contexts.

Observation, user research, participatory methods, co-creation, prototyping, and usability evaluation help translate human needs into design requirements and evaluate whether proposed solutions create meaningful value [22–26]. Its contribution is to connect engineering decisions with the people and contexts affected by those decisions.

Systems and Sustainable Design

Systems and sustainable design extends the unit of analysis beyond the immediate artefact and user towards life cycles and wider systems. It addresses resource use, environmental impacts, durability, repair, reuse, circularity, system interactions, feedback, resilience, and long-term socio-technical consequences [27–32]. Its contribution is to situate engineering solutions in environmental, economic, social, and systemic contexts.

Design Research and Reflective Practice

Design research and reflective practice concern how knowledge about designing is generated, evaluated, and renewed. Reflective practice, empirical design studies, protocol analysis, conceptual research, and formal design research methodologies enable researchers to examine design behaviour, processes, methods, and outcomes [7,33–36]. This domain provides a feedback mechanism through which existing knowledge can be tested, refined, and extended.

The six domains are complementary rather than sequential. Figure 2 positions them as knowledge territories contributing to contemporary engineering design.

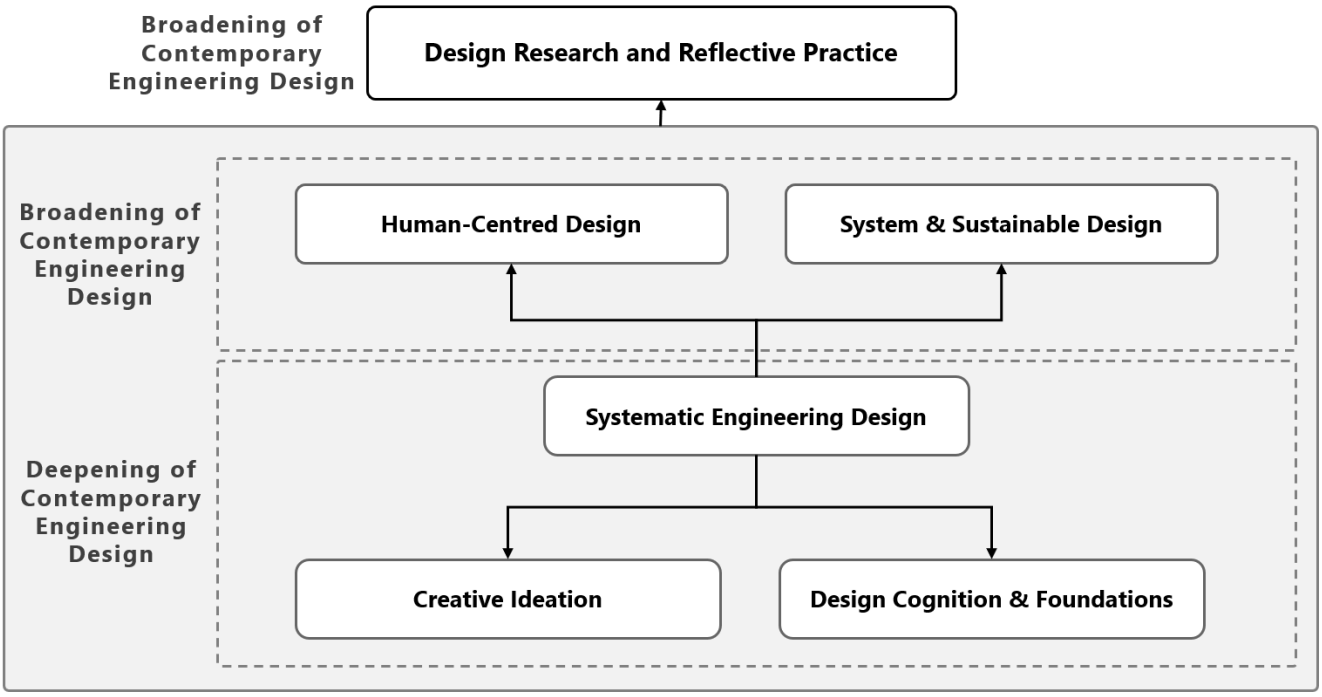

Figure 2. Major contributions of the knowledge domains to the expansion of contemporary engineering design.

Result 3: Broadening and Deepening as Complementary Trajectories

The first trajectory, deepening, denotes the increasing sophistication with which designers understand and enact framing, ideation, technical decision making, verification and reflection. The second, broadening, denotes the expansion of design concern beyond artefact functionality to users, stakeholders, life cycles, environments and interconnected systems. Table 2 gives the domain-level classification and central questions underlying this interpretation.

These trajectories are not successive stages. A single project may demand both: addressing the needs of an underserved user group can widen the design brief while requiring more rigorous observation, analysis and

testing. The broadening–deepening lens is therefore best used to interrogate the adequacy of design knowledge, rather than to rank domains or prescribe a fixed learning sequence.

Figure 2 provides a conceptual visualisation of relative emphases, whereas Table 2 identifies each domain's dominant trajectory and knowledge function. Neither representation implies exclusive membership, causal pathways, or a hierarchy of importance.

Table 2 summarises the six domains in terms of their guiding questions, dominant trajectories, and principal knowledge contributions.

Table 2. Knowledge domains and their dominant contributions.

Knowledge domain	Central question	Dominant trajectory	Primary contribution
Design cognition and foundational thinking	How do designers think?	Deepening	Framing, reasoning, representation, and cognitive transformation
Creative ideation	How are possibilities generated?	Deepening	Expansion and transformation of solution spaces
Systematic engineering design	How are solutions engineered?	Deepening	Structured technical development from requirements to verified solutions
Human-centred design	For whom are solutions created?	Broadening	Users, experience, values, capabilities, and context
Systems and sustainable design	How do solutions interact with wider systems?	Broadening	Life-cycle, environmental, social, and systemic consequences
Design research and reflective practice	How does design knowledge evolve?	Both	Generation, evaluation, and renewal of design knowledge

Accordingly, the map should not be read as six isolated categories. The boundaries are deliberately permeable. A biomimetic design activity, for example, may draw simultaneously on creative ideation, systematic engineering analysis, and sustainability considerations [21]. A participatory design activity may combine human-centred inquiry with creative ideation and reflective learning [24,25]. The value of the classification lies not in forcing each method into one exclusive category, but in making its principal knowledge contribution visible while preserving cross-domain interaction.

The mapping also reveals relationships among the domains. Design cognition provides explanatory knowledge relevant to activities across the design process, including framing, ideation, evaluation, and iteration [7-11]. Creative ideation is particularly prominent during concept generation but may also support reframing when alternative interpretations of a problem are needed [14-21]. Systematic engineering design provides the procedural structure through which concepts are developed, evaluated, and verified [1-6]. Human-centred and sustainable perspectives influence requirements, evaluation criteria, and design trade-offs throughout development rather than being confined to a single stage [22-32]. Design research and reflective practice operate across all domains by examining how such knowledge is produced and improved [7,33-36].

Discussion: Implications for Interdisciplinary Engineering Education

Interpreting the Knowledge-Domain Map

A knowledge-domain map complements process-based teaching by distinguishing completion of a design activity from the capability demonstrated within it. For example, reaching a concept-generation milestone is not

in itself evidence that students explored a sufficiently diverse range of ideas, and writing user requirements does not establish that these requirements were derived from stakeholder inquiry. Table 3 suggests learning activities and observable assessment evidence for each domain [37].

Curriculum mapping can therefore ask two questions in parallel: which design activities are provided, and what evidence shows that students have developed the corresponding knowledge functions? This distinction supports constructive alignment without requiring every module to assess all six domains equally.

Table 3. Illustrative curriculum and assessment applications of the six knowledge domains.

Knowledge domain	Possible learning activity	Illustrative assessment evidence
Design cognition and foundational thinking	Problem framing, sketch-based reasoning, reflective critique	Justified problem frames and documented reasoning
Creative ideation	Divergent ideation, analogy, concept combination	Range, originality and rationale of alternatives
Systematic engineering design	Requirements, concept selection, prototyping and verification	Traceable decisions and verified technical performance
Human-centred design	User observation, stakeholder engagement and usability testing	Evidence-based needs and usability evaluation
Systems and sustainable design	Life-cycle mapping and system-boundary analysis	Explicit trade-offs and life-cycle considerations
Design research and reflective practice	Design journals, evidence review and reflective evaluation	Critical reflection and justified methodological revision

Integrating Breadth and Depth in Design Learning

An illustrative application is a four-week module in a third-year mechanical engineering product-design course in which teams develop a manually operated device to support the safe handling of household items by older adults. In week 1, teams compare alternative problem framings and produce annotated reasoning sketches (design cognition), then conduct stakeholder observation or interviews and translate findings into user needs (human-centred design). In week 2, they use analogy, morphological analysis or another ideation method to generate multiple concepts and justify their selection (creative ideation). In week 3, students translate selected needs into engineering specifications, estimate loads, compare concepts, and build and test a low-fidelity prototype (systematic engineering design). In week 4, they consider materials, maintenance, repair and end-of-life implications (systems and sustainable design) and submit a design journal documenting evidence, changes in assumptions, and lessons for the next iteration (design research and reflective practice).

The assessment can combine a problem-framing rationale, evidence of stakeholder inquiry, a concept-diversity matrix, calculations and test data, a life-cycle trade-off note, and a reflective design journal. These artefacts correspond to Table 3 and allow instructors to identify strong technical work alongside gaps in user research, creativity, or reflective reasoning. This four-week example is a proposed teaching design, not a module implemented or evaluated in the present review.

Limitations and Future Research

Several limitations qualify the interpretation. First, the classification was developed through a single-author conceptual analysis; domain boundaries and the decision to retain six domains reflect interpretive judgement and were not independently coded or subjected to inter-rater agreement. Second, the framework has not been tested through curriculum implementation, student learning measurements, or comparative course evaluation. It therefore cannot support claims about improved educational outcomes. Third, the purposively assembled corpus is not an exhaustive survey and may privilege well-known, English-language and predominantly Western methodological traditions, underrepresenting local, Indigenous, non-English, and discipline-specific approaches. Fourth, the author-informed selection was not based on a documented database search or formal screening

protocol, limiting replicability. The trajectories in Figure 2 should accordingly be treated as heuristic interpretations rather than empirically demonstrated historical or causal relationships.

Future research could use multi-reviewer coding and a preregistered, multilingual search protocol to assess domain coverage and alternative groupings. Educator interviews and curriculum audits could examine interpretability across institutions and disciplines. Classroom studies could then investigate whether domain-aligned assessment improves students' demonstration of reasoning, ideation, technical verification, stakeholder awareness, systems judgement, and reflection. Digital design tools may be investigated as possible cross-domain enablers rather than presumed to constitute a separate knowledge domain [34,35].

CONCLUSION

This review organises established engineering design scholarship into six complementary knowledge domains: design cognition and foundational thinking, creative ideation, systematic engineering design, human-centred design, systems and sustainable design, and design research and reflective practice. By differentiating their knowledge functions, the map helps educators look beyond design-process milestones and identify the capabilities evidenced through student work. The accompanying curriculum example illustrates how one product-design module could develop and assess several domains within a shared project.

The conceptual distinction between deepening and broadening clarifies two interacting directions in engineering design knowledge: more sophisticated means of reasoning and developing solutions, and greater attention to people, life cycles, and systemic consequences. These directions remain complementary and context dependent.

The map offers an organising lens, not a new engineering design process. Its utility, transferability and completeness require further investigation across educational and disciplinary settings.

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