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Digital Heuristics for Industrial Design: Operationalizing Tacit Sustainability Knowledge for Early-Stage Decision Making

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ABSTRACT:
Sustainability remains a largely under-investigated, particularly in early-stage industrial design, where significant decisions are often made with little readily available environmental information. This study puts forward and empirically tests a digital heuristic framework designed to translate tacit sustainability intuitions into cognitive specific decision supports. Situated within the SECI model and design cognition theory, this study investigates the role of a heuristic framework in facilitating practitioners to retrieve and operationalize experiential sustainability knowledge during ideation.
A mixed methodology was used, which included a thorough review and synthesis of the literature, a national survey that targeted 250 Saudi industrial designers across the country, expert validation and PLS-SEM. Results suggest that the sustainability orientation of early design outputs is boosted by making tacit knowledge explicit. Heuristic structuring was found to be a significant mediating variable ($\beta = 0.136$, $p < 0.001$), through which substantial compiling of complex trade-offs became possible. This phenomenon was even more obvious in the case of designers who were not equipped with proper digital tools for early-stage guidance. Qualitative findings also illuminated the cognitive function of heuristics in resolving trade-offs or tensions such as recyclability vs. durability that were typically encountered when considering materials and user behaviors.
The result is a validated digital archive converting tacit assumptions of environmental design, especially material action and human engagement, into accessible heuristic tools at point - of - use. Theoretically, this study bridges the gap between knowledge management and design cognition; practically, it provides a scalable, low-barrier solution for embedding sustainability reasoning in product innovation. Also, in line with Saudi Vision 2030, the guiding principles enable a shift from conservative reporting to anticipatory sustainability incorporation.

Keywords: Circular Economy Integration, Design Cognition, Digital Heuristics, Early-Stage Design Decision Making, Industrial Design, Sustainable Product Development, Tacit Sustainability Knowledge

1. Introduction

A new methodological framework of Partial Least Squares Structural Equation Modeling (PLS-SEM) that combines with qualitative practitioner validation to promote sustainability in industrial design is provided in this research. Based on design cognition and knowledge management theory, the study quantifies the impact of tacit knowledge and heuristic structuring on early decision-making in ways that are analytically rigorous yet grounded in practice.

Industrial design has become a strategic domain where environmental performance, commercial viability, and cultural acceptance must intersect. Climate

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requirements and circular economy regulations have further increased the demand for fundamental sustainability integration in early stages of product development (Lee *et al.*, 2023; van Dam *et al.*, 2019; König *et al.*, 2023). But the ongoing gap is not in the body of information about sustainability, but rather in how that information is integrated at the formative design decision making stage (Chatty *et al.*, 2022; Martínez *et al.*, 2017, Sun *et al.*, 2024, Ferreira *et al.,* 2025).

The research presented claims that sustainability of industrial design is not just a performance result to be measured at the end. The cause of sustainability is essentially an early-stage knowledge problem, as designers work under cognitive load and make commitment decisions committing to something long before designer can measure it (Ferreira et al., 2025). In such early stages, designers are generally guided by tacit experiential knowledge rather than explicit rules or data. In comparison, formal sustainability tools, including lifecycle assessment checklists or material scoring systems or even an environmental compliance matrix with preset criteria and quantifiable rules operate only on stable design parameters where the problem is already defined at early ideation. While tacit insights guide intuitive judgement under uncertainty, formal tools depend on structured inputs, making them difficult to employ when concepts are still fluid.

In these types of settings, knowledge about sustainability is tacit experiential, intuitive and context-specific which is very important (Nonaka and Takeuchi, 1995). Collected through material experience, user input and project memory such knowledge is not as often found in formalized systems but contains significant latent value (Ferreira *et al.,* 2025, McAdam *et al.*, 2007; Guo andAhn,2023; Frinch *et al.*, 2021). Implicit knowledge spans insights about material behavior in recycling streams and assumptions regarding how users repair or maintain products. But this set of information is passed on informally in design process through oral tradition, story and personal intuition-type frameworks (Ferreira *et al.,* 2025, Nonaka *et al.*, 1995; Sun *et al.*, 2024). *Tacit sustainability knowledge* within this context is defined as "the experiential environmental understanding that resides in individuals, which is embedded in intuition, personal judgement, and practice-based awareness, and is not formally codified in documents or explicit procedural rules" (Nonaka & Takeuchi, 1995).

The design cognition literature refers to heuristics as compact reasoning frameworks that facilitate complex decision making by structuring reasoning and reducing cognitive effort in the early stages of design (Yilmaz, Daly, Seifert & Gonzalez, 2014; Radford, 2014). In the sustainability field, heuristics can support trade-offs solutions (i.e., durability versus recyclability) when formal tools are not fit for purpose (Yilmaz *et al.*, 2010; del Campo, 2016). They can serve as cognitive tools, beyond prescriptive rules, that guide thinking and decision making (Seifert *et al.*, 2016; Watson *et al.*, 2023). In sustainability-oriented industrial design this is especially relevant, where deterministic analyses are applied in the early stages (JAWA and Hensen, 2015; Winandy-Bock and Hollberg-Kurpicz, 2022). Heuristics act as a mean that transforms complexity into a manageable decision support (Frinch *et al.*, 2021; Ibrahim *et al.*, 2024).

Knowledge management theory, in particular, the SECI model, suggests a process of transforming tacit knowledge into actionable forms through dynamic combination of tacit–explicit cycles (Nonaka and Takeuchi, 1995; Nonaka *et al.*, 2000). By structuring and digitizing sustainability heuristics knowledge become available at the idea creation stage connecting intuitive experience and collective practice (Nonaka and von Krogh, 2009; Jia, 2022).

Sustainability knowledge becomes more useful in Industrial design process through transformation of tacit to explicit knowledge to support design decision making. Therefore, this study frames the digital heuristic repository as an efficient means for integrating sustainability knowledge into early-stage decisions. The assumption is that heuristics as a method, located between abstract principles and concrete recipes, are well suited to the cognitive activities of designers (Ferreira *et al.,* 2025, Frinch *et al.*, 2021).

The application of this approach is contextualized within Saudi Vision 2030, encompassing the environmental stewardship and green economy imperatives. From this point of view, Saudi based enterprises should embrace design cultures that internalize sustainability by embedding it within the early decision-making process rather than compliance towards of the end. Circular design will not result from regulation alone, it requires designers to have practical environmental decision support knowledge (vanDam *et al.*,2019).

In order to position this study in relation to existing literature, Table 1 provides a structured matrix that aligns the key concept-based interventions related to tacit knowledge, design heuristics and knowledge externalization with their related empirical applications in sustainability-driven industrial design. This matrix illustrates how bridging theories from design cognition and knowledge management intersect in previous work, with both synergies and gaps informing the framework underpinning this study.

Table 1: Literature matrix connecting the relevant interventions

Author (Year)	**Focus Contribution**	**Key Finding Relevant to Introduction**	**Alignment to Argument in Introduction**
Lee et al., (2023)	Review of eco-design tools in product development	Found that many sustainability tools exist but usability in real design practice is weak	Supports claim that sustainability knowledge is abundant but not usable at decision time
Hunger (2025)	Integration of sustainability facets in early NPD	Identified gap in early phase sustainability alignment in product development teams	Confirms that early-stage sustainability integration remains inconsistent
Chatty et al., (2022)	Co-creating sustainable design frameworks	Demonstrated disconnect between sustainability frameworks and designer workflow	Validates the problem of non-usable sustainability knowledge
König et al., (2024)	Lightweighting and sustainability design integration	Proved environmental consequences are locked-in early	Justifies criticality of early design decisions
Yilmaz et al., (2010)	Design heuristics and ideation creativity	Empirically proved heuristics boost creativity and problem framing	Supports heuristics as cognitive scaffolds in early ideation
Watson et al., (2023)	Heuristics for complex decision networks	Showed heuristics reduce cognitive load in complex design ecosystems	Supports the role of heuristics in uncertainty management

Nonaka and Takeuchi (1995)	SECI knowledge conversion model	Explained tacit-to-explicit conversion pathway	Supports digital heuristic externalization of tacit insights
Nonaka and von Krogh (2009)	Updated model for tacit knowledge theory	Demonstrated importance of making tacit knowledge shareable	Validates need to formalize material + user behavior tacit knowledge
Swan et al., (1999)	Knowledge flows in innovation systems	Showed digital tools improve accessibility of knowledge assets	Supports argument for digital heuristic repository
van Dam et al., (2019)	Circular economy in industrial design research	Found circularity demands designer-side knowledge shifts	Connects introduction to the industrial design role in circular economies
Kuys (2021)	Sustainability priority among industrial designers	Found many designers value sustainability but do not operationalize it	Supports gap between sustainability interest vs sustainability execution
Siwiec et al., (2025)	Digital product lifecycle and sustainability	Found digitalization mostly applied post-concept rather than at ideation	Reinforces that current systems focus on evaluation not early concept
Vicente and Camacho (2023)	Evaluation of design for sustainability tools	Found tools exist but are rarely used in early ideation	Confirms need for ideation-scale tools, not evaluation-scale tools

These tensions reported in the above matrix can be systematized by using them to guide the study's constructs and methods. The contrast between tacit and formal knowledge aligns with the SECI model. The pressure experienced during early design decisions corresponds to principles in cognitive design theory, and the gap between cognitive load and available tools supports the inclusion of perceived tool limitations as a moderating construct. Together, these linkages provide a coherent theoretical basis for construct operationalization and methodological grounding. Subsequently, this paper constructs a conceptual framework that integrates cognitive design heuristics with sustainability knowledge-management. The model supports the implementation of sustainability thinking at designers' scales of understanding and action. The aim is to make knowledge about sustainability not bigger, but to make it more usable (Ferreira *et al.,* 2025).

2. Literature Review

2.1 Sustainability in Industrial Design Practice

With regard to industrial design, sustainability has gained attention and is increasingly seen as an essential part of the practice (van Dam *et al.,* 2019) where the focus on ecological, economic and social needs perspectives the product-development process(es). Industrial designers are confronted with increasing pressure related to product-resource scarcity, closed-loop economy demands for more sustainable design and the environmental impact of products over their lifecycle (Kuys, 2021). Empirical findings reveal that industrial designers tend to be unfamiliar with relevant sustainability frameworks and they still do not completely integrate sustainability into the very starting, conceptual stages of a design process (Kuys, 2021). In addition, literature reviewing the role of industrial design in circular economy transitions points out that although design contributions to circular economy are recognized (e.g., designing for reuse, remanufacturing and closed loops), current practice is often characterized by later-stage assessment rather than early directional selection (van Dam et al.,2019). In other words, sustainability orientation is added on to design process rather than being built-in a fundamental restraint for the actual transformation (Ferreira *et al.,* 2025).

This sustainable design perspective is taking on more visibility in the establishment of social architecture, shifting from end-of-pipe evaluation toward front-end integration: design for sustainability should take place early on in concept development, material choice, modularity and user behavior assumptions rather than applied late toward a prototyping phase or an evaluation stage (Basereh *et al.*, 2024). This shift is important because early decisions such as what material to use, how the product is architected, and the way in which services around the user are designed have long-term lock-in effects on the environment. So, what we can see then (as this section indicates), is that there are significant literatures in sustainability as considered within the industrial design practice sphere but, when it comes to a strategic level of sustainable implementation, there remains an ongoing "gap". Despite its strategic importance, sustainability often remains secondary in everyday design practice because cultural and organizational factors shape decision priorities. Design teams focus on speed, aesthetics, and market deadlines, which makes sustainability appear difficult to integrate early. Organizational routines, incentive structures, and limited interaction between sustainability experts and designers further weaken the use of formal frameworks. These barriers explain why sustainability knowledge is rarely activated at the right moment and underscore the need for heuristic supports that fit real design behavior.

2.2 Heuristics and Cognitive Scaffolding in Early Ideation

In design studies, much cognitive research has focused on heuristics mental shortcuts or rules of thumb used by designers to solve difficult, ill-de\ne problems (Yilmaz, 2010, Seifert *et al.,* 2014; Torrens *et al.,* 2025). For example, Yilmaz *et al.,* (2010), who concluded that when heuristic prompts were provided to novice designers, variety and creativity of ideation increased. Heuristics have been demonstrated by similar studies to act as cognitive 'scaffolding': that is, they reduce processing complexity and facilitate the rapid establishment of problem-space and divergent thinking in early-stage design (Yilmaz *et al.,* 2010). Recent efforts to approach heuristics as such (and thus as fluid rather than static entities) are also reflected in the novel approach of little work developed by Del Campo *et al.,* (2016), who proposes a "Heuristic Spectrum" along with dimensions of cognitive effort, intentionality, domain specificity and goal alignment, illustrating their potential for application.

In the field of sustainability-focused industrial design, such heuristics provide a potentially valuable bridge between complexity and decisions that can be acted upon. Creating a sustainable product involves trading off things (e.g., modularity versus manufacturability; bio-based material versus recyclability infrastructure). Pure evaluative models, or lifecycle tools at this stage may not support the kind of cognitive scale designers operate at in ideation; instead, heuristics provide simple, experience-driven prompts for early decision making. Much heuristic work has originated in engineering design or design education, but the potential of such approaches for sustainability-oriented industrial design is now also acknowledged (Ferreira *et al.,* 2025; Jin, 2021). However, such promise notwithstanding, the literature evidences a significant void in the form of that many heuristics in IND are hardly designed explicitly for sustainability decision-making at early stage.

2.3 Tacit Knowledge, the SECI Model and Sustainability Knowledge Flows

The knowledge management literature offers, in its body of works, a solid theoretical underpinning for converting tacit experiential knowledge into explicit shareable assets such as the (Nonaka Takeuchi, 1995) SECI (Socialization–Externalization Combination – Internalization) model. Based on this model, tacit knowledge (experience and intuition based) is externalized by processes like articulating heuristics or rules and combination by systematizing these, then internalized in individuals. Farnese (2019) provides an operationalization of the SECI model explaining how knowledge -creation processes could be estimated in organizations.

For design related tasks, implicit knowledge of sustainability is strongly relevant: professional designers frequently call on experience-based judgement (e.g., how a MA-performance behaves in real world supply chains; how users really repair or dispose of certain components) rather than on codified rules. The tacit nature of sustainability decision-making is thus a dormant resource that has to be orchestrated. In fact, McAdam, Mason and McCrory (2007) note that the subject of tacit knowing continues to be neglected within organizational studies and Setiono (2025) recently reviewed existing tacit-knowledge literature and found weaknesses in how organizations capture and transfer it effectively.

In the Industrial Design context, this implies sustainable knowledge management to be beyond providing frameworks and tools, by being able of capturing the tacit designer experience and then transforming it into explicit, retrievable heuristics or decision assets. However, the literature demonstrates sparse activity in this area: while sustainability assessment and lifecycle tools proliferate, knowledge flows and conversions of tacit sustainability reasoning within design teams are under-investigated (Ferreira *et al.,* 2025; Muthuveloo, 2017).

2.4 Gap Analysis: Existing Digital Tools Are Evaluation Oriented, Not Ideation Oriented

As a literature examining digital tools and frameworks for sustainability (e.g., LCA software, sustainability-assessment frameworks, business-model tools) grows rapidly some of it highlights they mainly serve as evaluative rather than ideational artefacts. For instance, Basereh *et al.*, (2024) reviewed sustainability assessment frameworks and concluded that many of the tools place utmost importance on evaluating outcomes than to help decision-backed concepts at early stages. Vicente and Camocho (2023) carried out a review of design-for-sustainability (DfS) tools, observing that many are available, but under-used in practice and that some categorization is more assessment-oriented than decision support from the front presentation end. Traditional digital sustainability tools lack cognitive usability, as they require fixed input and stable design parameters in early ideation that designers do not possess. For instance, LCA tools need detailed material descriptions or assumptions how products are manufactured and this decision supports that design has to be guessed or at least the sustainability perspective cannot be thought of only at a first phase of the process. Likewise, overly interface-heavy scoring systems can tax the cognitive budget by giving long lists of criteria that weren't how designers thought about problems in their daily lives. These discrepancies minimize or skew the extent of reasoning, nudging designers towards superficial compliance rather than deeper exploration of sustainability. Articulating these limitations as such helps to refine the rationale for heuristics that function on the more intuitive, resourceful scale defined by designers' activities.

Further, the literature on lifecycle of the digital product Cycle shows that sustainability digitalization tends to address such as manufacturing or use phase evaluation and not concept generation (Siwiec *et al.*, 2028). Calabretta (2025) notes in particular that while heuristics of sustainability may be recorded (e.g., through use of card decks), the way such are integrated into digital knowledge repositories for ideation is limited (Ferreira *et al.,* 2025).

In the domain of industrial design practice this has a straightforward consequence: Designers dispose of evaluation-oriented tools (e.g., LCA, simple carbon footprint calculators) but miss ideation-oriented, usable decision support systems that embed tacit sustainability knowledge in early decisions about form, material usage, architecture and user behavior assumptions. This sounds like a rich opportunity: that is, our digital heuristic repository could fill the missing link and as well support early-stage decisions instead of just post-concept evaluation.

Our review of the literature shows three intersecting trends and a hole. 1) (a) The established front end of sustainability for industrial design practice is acknowledged and growing yet still underexplored. 2: Heuristics and cognitive scaffolding are well supported with design research, and a promising link for bridging complexity and ideation. (3) Knowledge management theories, such as SECI theory, illustrate how tacit experience of designers can be organized and communicated. The missing link are digital tools which work tacit knowledge of sustainability for ideation, not exclusively evaluation. This is the void that coincides with the argument and thesis of this paper.

2.4 Development of Hypotheses

Silent sustainability expertise is that designers experientially, intuitively and practice-wise accumulate with the passage of time. Recent research suggests that such uncodified knowledge influences how designers perceive problems, choose materials, and arrive at ecologically responsible alternatives in the preliminary stages of design. Designers are used to referring to their internalized sustainability experience even when no formal support or advice were created yet, and this tacit reasoning has been demonstrated as a strong influence on early creative decisions in the context of sustainable product development (Diaz *et al.*, 2021; Guo and Ahn, 2023; Sun *et al.*, 2024; Ouldja *et al.*, 2024). Based on this evidence, the following hypothesis is proposed:

H1: Tacit sustainability knowledge has a positive direct effect on early-stage sustainability aligned design decisions.

Knowledge conversion processes, which involve converting tacit knowledge to explicit form are central in the facilitation of designers' more systematic use of sustainability knowledge. The literature on knowledge management and sustainable design shows that when tacit environmental insights are externalized through figurate metaphors, they become more easily shared, communicated, and applied in various stages of the design process (Nonaka and von Krogh, 2009; Yu *et al.*, 2022). This change is designed to support the wider design community in making more informed decisions around sustainability, by increasing clarity and consistency, alongside enabling organisational learning. Therefore, the following hypothesis is proposed:

H2: Knowledge conversion of tacit sustainability insights into explicit form will positively influence sustainability aligned decision making in the early stages of design.

Heuristics have long been recognized as aiding the designer in navigating complexity, particularly at early stages of ideation through lowering cognitive effort and providing truncated decision paths. The recent work in design cognition and sustainability literature asserts that structured heuristics may help designers process environmental information effectively, specify their focus, and generate feasible sustainable solutions efficiently during early product development phases (Yilmaz *et al.*, 2014; Jin, 2021; Sun *et al.*, 2024). This indicates that heuristics function as a channel of transferring converted sustainability knowledge to early design decisions. Therefore, the following hypothesis is proposed:

H3: Heuristic structuring will positively mediate the relationship between sustainability knowledge and early-stage sustainability decision making, because it reduces cognitive effort during ideation.

Digital support tools are relatively scarce in the early phases of sustainable design, and several works point out that limited digital software is available specifically to support environmental analysis, materials selection and sustainability trade-off assessment (Basereh *et al.*, 2024; Vicente and Camacho, 2023). The greater lack of fit for designers and more reliance on heuristics to fill the gap as perceived by designers indicates higher dependency when structured digital support is not sufficient. In this context, heuristics become more prominent in building early sustainability decisions. Based on this insight, the final hypothesis is proposed:

H4: The perceived digital tools gap will positively moderate the effect of heuristic structuring on early-stage sustainability decision making, where the effect will be stronger when designers perceive a higher absence of suitable digital sustainability tools.

Given the literature review, this paper presents a conceptual model (Figure 01) that combines knowledge conversion theory, design cognition research and digital sustainability tool literature to investigate how tacit sustainability knowledge becomes actionable during early phases of decision making. Tacit designer sustainability knowledge is embedded within experience, but unavailable during the ideation process unless it is externally articulated, codified and formalized (type of conversion occurring under the SECI model) (Nonaka and Takeuchi, 1995; Farnese *et al.*, 2019). Some forms of heuristics give a promising way to structure this search since it minimizes the cognitive load required and allows us to think quickly while in early ideation (Yilmaz *et al.*, 2010). In addition, as the majority of digital sustainability tools are evaluation-oriented and have low use in conceptual phases (Basereh *et al.*, 2024, 2022; Vicente and Camacho, 2023), the impact of heuristic-based knowledge structuring may well be enhanced if respondents experience a gap between desired and available digital support. Hence, the CFT places knowledge conversion as the driving force, heuristic structuring as a mediating process and perceived digital tools gap as the contingency factor influencing strength of impact on sustainability oriented early-stage design decisions.

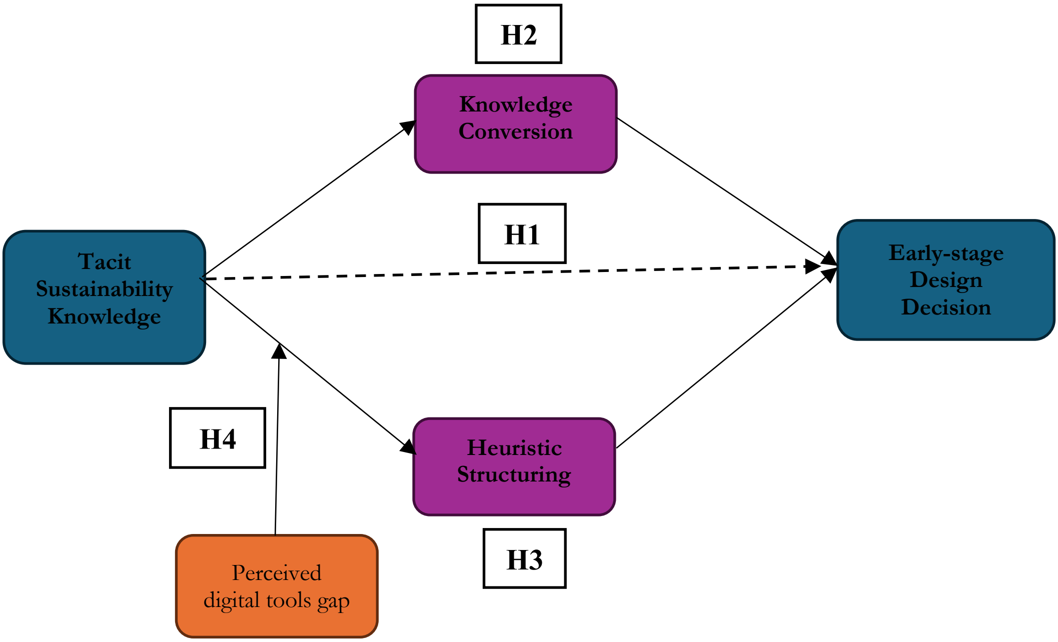

Figure 1: Conceptual framework

In order to further strengthen the proposed framework, it is important to specify the theoretical roots of each construct. Previous research underlines (compiled in Table 02) that sturdy frameworks need to display the theoretical ancestry with respect to each relationship (Whetten, 1989; Jaakkola, 2020). Researchers in the field of sustainability design have already used SECI processes to transform tacit environmental knowledge into explicit decision assets (Farnese *et al.*, 2019; Setiono *et al.*, 2025). Design cognition research also suggests that heuristics overcome cognitive load and direct preliminary thinking in sustainability challenges which are complex and unclear (Yilmaz *et al.*, 2014; Jin, 2021). Lastly, large databases are not used for design and development when information remains consistently at the archaeological scale rather than organized to task cognitive size (Vicente and Camacho, 2023; Calabretta *et al.*, 2025). Thus, the following theoretical anchor table is provided to show that every construct and path in the model is based on established theory and/or has published empirical support in the domain of sustainability design.

Table 2: Theoretical anchors matrix

Theory	Role in Framework
SECI Model (Nonaka and Takeuchi)	Explains how tacit sustainability knowledge is externalized into heuristics and shared
Design Heuristics Theory	Describes cognitive tools used by designers in ill-defined, early-stage contexts
Knowledge Usability Perspective	Highlights that accessibility and usability not availability of knowledge determines its value during design decisions

3. Methodology

This research adopts a mixed-methods approach, combining quantitative analysis with qualitative synthesis to develop the triangulated cohesive conceptual framework of digital sustainability heuristics in industrial design. This approach is methodologically appropriate with respect to the cognitive and experiential nature of the research focus, i.e. tacit knowledge of heuristics and early-stage design decisions.

Table 3 indicates the main construct measured in this work and their measurement items. These are tacit sustainability knowledge, heuristic structuring and early-stage decision influence, derived from interdisciplinary literature comprising the domains of design cognition, sustainability research and knowledge management. All constructs are related to theoretically validated measures applied in the SEM, who combine theoretical soundness with empirical measurability.

Table 3: Key constructs and variables

Variable	Description	Example Items	Key Literature Citation
Frequency of Use of Tacit Sustainability Insights	How often designers rely on informal, experience-based sustainability insights (rather than formal frameworks) in early design	(see questionnaire items below)	Tacit knowledge use in organizations (Li, 2020)
Sources of Tacit Insight	The origins of the tacit insights (project memories, peer conversations, past failures)	(see questionnaire items)	Tacit knowledge sharing / sources (Mahajan, Sharma and Soni, 2023)
Heuristic Form of Sustainability Insight	The cognitive structure or mental "rule-of-thumb" that designers apply for sustainability decisions (heuristics)	(see questionnaire items)	Heuristics in design cognition (Yilmaz et al., 2014)
Influence Strength on Decision Quality	How strongly these tacit sustainability heuristics influence early-stage design decisions	(see questionnaire items)	Decision-making in sustainable design (Cooper, 2023)
Perceived Digital Tool Gap at Ideation	Designers' perception that existing digital sustainability tools do *not* adequately support early-stage ideation (rather than later evaluation)	(see questionnaire items)	Gaps in tool orientation (Basereh *et al.*, 2024)

The research unfolds in four sequential phases, each contributing distinct data types and inferential strengths to enhance the overall validity and interpretability of findings.

3.1. Phase 1: Literature Synthesis

A specific search strategy for peer-reviewed literature retrieves conceptual patterns linked to (a) tacit sustainability knowledge, (b) cognitive heuristics and design ideation as well as c) early decision contexts in industrial design. A systematic review of the literature in the years 2010-2025 has been conducted in high impact design, sustainability and knowledge management journals. This process is inductive and thematic, to identify common sets of qualitative understanding which include dimensions related to material choice and user action assumptions both categories of tacit knowledge key to this study. It is upon these issues that the survey instrument and subsequent triangulation are built.

3.2. Phase 2: Quantitative Data Collection

A structured questionnaire is designed and distributed to a purposive sample of practicing industrial designers and advanced-level design students. The instrument measures:

- Frequency of tacit sustainability insight usage
- Methods of operationalization (e.g., heuristics, mental models, rules-of-thumb)
- Perceived influence of these insights on early-stage design quality

Likert-type scales and ranking questions are employed, and descriptive statistics, correlation analysis, and cluster mapping are used to identify patterns, relative impact, and contextual differences across respondents. This stage generates empirical grounding for the study's heuristic framework.

3.3. Phase 3: Cross-Source Triangulation

The quantitative survey data provide triangulation of the qualitative results from the review. Returning to overrepresented findings, and the discrepancies between what is reported as being done and what we know to be common patterns of use of knowledge. This represents an additional effort to increase construct validity, showing how practice is currently aligned (or not aligned) with conceptual models of tacit reasoning on sustainability.

3.4. Phase 4: Expert Validation

The authors present the combined results and draft heuristic model to a panel of subject experts in sustainability, senior industrial designers, and knowledge management academics. A standardized feedback tool is utilized to capture:

- Conceptual soundness
- Practical applicability
- Usability for early-stage decision-making

These heuristic elements are then refined and structured formally as a digital concept framework on the basis of their input, that is optimized for its retrieval and cognitive fit with designer's work process.

This 4-steps strategy provides methodological triangulation and a balance between empirical evidence and theoretical depth:

- Quantitative data reflecting patterns in the reasoning of current practitioners
- Qualitative synthesis provides interpretive depth without the requirement for primary interviews
- Expert validation serves to guarantee that the final framework is both epistemologically consistent and design applicable.

Taken collectively, this research design provides a credible and evidenced based approach to the operationalization of tacit sustainability knowledge into digital heuristic formats in support of real-time early-stage decision-making within an industrial designer context.

4. Data Analysis and Procedure

Integrated mixed methods combined quantitative modeling with qualitative validation to investigate the role of heuristic structuring in operationalizing tacit sustainability knowledge in early design.

Quantitative data were gathered through a structured online questionnaire, distributed to 250 industrial designers from multiple industries in Saudi Arabia. The instrument comprised validated Likert-scale measures of key constructs, such as the use of tacit knowledge, interaction formats that support conversion between knowledge types (conversion), heuristic structuring and problem-solving modes, perceived gaps in the digital tool when used to sup- port decision-making at an early stage in design preparation and qual- ity of decisions made early in design iterations. Data pre-processing Before the data was analyzed, it was checked for completeness, missing values and outliers. After cleaning, there was a final sample of 232 valid responses.

Analysis of measurement and structural models were conducted in SmartPLS 4.0, using the Partial Least Squares Structural Equation Modeling (PLS-SEM). Data analysis was split into two phases: the first phase involved a confirmatory factor analysis to measure construct reliability and convergent, and discriminant validity; in the second part of data analysis, path models were used to explore the hypothesized relationships (see Appendix 2) and mediation effects. The predictive relevance was examined on the basis of the model fit parameters, such as R^2 and Q^2.

To complete the quantitative results a large corpus of qualitative data was also collected using semi-structured interviews with seven master practitioners in sustainability focused industrial design. Thematically analysis of the interviews was conducted on NVivo after transcription. Inductive coding was also used to identify emerging themes about heuristic use, user-generated knowledge and digital tool limitation. Comparison between the quantitative and qualitative data risk triangulation with the results and put in context residents' experience.

The integrative nature of the process brought statistical generalization and experiential depth, underpinning the validation of the proposed model.

Table 4 shows an even distribution of respondents by experience, sector, and region. The majority of respondents have between 3 and 5 years or between 6 and 10 years of experience, which means that there is a good representation of early (middle) career professionals. Electronics, furniture, automotive and manufacturing are relatively equally divided by sector. Geographical participation is also quite wide, including all main geographical areas. All in all, this composition of the sample appears to be a representative one since it includes a variety of sectors related to manufacturing in the country.

Table 4: Demographic respondents' details

	Description	Frequency	Percentage
Experience	0–2 years	49	19.60
	3–5 years	72	28.80
	6–10 years	64	25.60
	11–15 years	37	14.80
	16+ years	28	11.20
Sector	Manufacturing	48	19.20
	Automotive	49	19.60
	Furniture	51	20.40
	Electronics	53	21.20
	General Industrial	49	19.60
Region	Central Region	41	16.40
	Western Region	48	19.20
	Eastern Region	54	21.60
	Northern Region	52	20.80
	Southern Region	55	22.00
	Total	**250**	**100**

5. Analysis and Discussion:

After collecting data, a step-wise quantitative approach was employed to test the measurement model and investigate relationships between study constructs. This stepwise method of analysis replicates similar empirical approaches that have been used in previous sustainability knowledge and design cognition studies (Yilmaz et al., 2016; Jin, 2021; Calabretta *et al.*, 2025).

5.1. Step 1: Data filtering and Preparation

Data was exported to SPSS (v28). If the proportion of missing responses was greater than 30 percent the case was excluded. Reverse-coded items were corrected. The data were subsequently checked for normality, outliers, and homoscedasticity in order to verify that the data was suitable for multivariate analysis with respect to recognized quantitative preparation procedures in design cognition research (Jain and Simon, 2023).

5.2. Step 2: Descriptive Statistical Profiling

Means, standard deviations and response distributions were computed. Demographic profiling was conducted to categorize respondents by experience, sector, and region.

Table 5: Descriptive statistics of constructs

Variables	Minimum	Maximum	Mean	S. D	Skewness	Kurtosis
Tacit Sustainability Knowledge	1	5	3.00	1.273	–0.020	–1.215
Knowledge Conversion	1	5	3.00	1.247	–0.071	–1.178
Heuristic Structuring	1	5	3.00	1.185	–0.015	–1.204
Perceived Digital Tools Gap	1	5	3.00	1.270	–0.030	–1.220
Early-stage Design Decision	1	5	3.00	1.186	–0.080	–1.132

Table 5 shows values of the means for all constructs to be close to 3.0, which suggests that moderate perceptions are on sustainability knowledge, knowledge conversion, heuristic structuring, digital tools gap and early-stage decision-making. Values for the standard deviation above 1.1 point to moderate variation. For skewness near zero, the distributions look balanced and when kurtosis is negative it means responses are not highly pooled. The distribution of data is acceptable to other statistics analysis.

5.2.1. Measurement Model

The selection of Smart PLS was motivated because this approach is appropriate for predictive modeling and theory generation in situations of complex conceptual models with mediating, moderating variables (Khan, 2025; Khan *et al.*, 2023; Ng *et al.*, 2024). It effectively handles non-normal data and is suitable for trends in medium-sized samples, while it is retained for analysis in this study. Furthermore, because it is an implementation of Partial Least Squares Structural Equation Modeling method, Smart PLS can be used in testing both measurement and structural models for exploratory and theory development research. This approach is advocated when maximizing the variance accounted for and analysis of causal paths between latent constructs (Hair *et al., 2019)* Before hypotheses involving structural relationships between constructs are tested, the measurement model should be evaluated to check if the constructs are reliable and valid as determined by factor loadings, internal consistency reliability, composite reliability and average variance extracted. This ensured convergent validity and reduced overlap of concepts. A proper measurement model is necessary, since structural findings are not meaningful unless constructs that sustain them are reliable and valid (Fornell and Larcker, 1981; Nunnally and Bernstein, 1994).

5.2.2. Reliability and Construct Validation

Cronbach's alpha was used to check the internal consistency reliability of the multi-item constructs, and for all factors $\alpha > 0.70$ (Nunnally and Bernstein, 1994). Exploratory Factor Analysis using principal axis factoring with Varimax rotation was applied to validate construct dimensionality. KMO and Bartlett's test confirmed factorability, consistent with similar validation approaches in sustainability design research (Farnese *et al.*, 2019; Jin, 2021; Khan, 2025). (presented in Table 06)

Table 6: Main constructs reliability and validity

Main Constructs	Loading	Cronbach's alpha	Composite reliability (rho_a)	Average variance extracted (AVE)
Early-stage design decision	0.837	0.893	0.894	0.701
	0.868			
	0.814			
	0.824			
	0.842			
Heuristic structuring	0.831	0.893	0.895	0.7
	0.834			
	0.819			
	0.858			
	0.84			
Knowledge Conversation	0.867	0.927	0.928	0.775
	0.893			
	0.88			
	0.872			
	0.889			
Perceived digital _tools gap	0.892	0.939	0.946	0.803
	0.888			
	0.905			
	0.893			
	0.902			
Tacit sustainability _Knowledge	0.908	0.94	0.942	0.806
	0.887			
	0.905			
	0.896			
	0.896			

All constructs present high values for their respective indicator loadings, being higher than 0.80 (Hair *et al.*, 2019) for reflective measurement model. This indicates that each item contributes to the construct that it represents. Cronbach's alpha for all constructs are between 0.893 and 0.940, showing high internal reliability. These lores exceed the 0.70 cutoff recommended by Nunnally and Bernstein (1994). Similarly, all composite reliability values are greater than 0.89, suggesting strong construct reliability and measure homogeneity. The values of the average variance extracted (AVE) extend from 0.70 to 0.81. They all surpass the 0.50 cut-off recommended by Fornell and Larcker

(1981) which shows enough convergent validity. Finally, credits are not given to Grade 2 because they only measure 57 and the gaps have witnessed.

5.2.3. Correlation Analysis

Pearson correlations were computed to identify linear associations among the constructs (Shown in Table 07). Significant positive correlations were observed between tacit sustainability insight usage, heuristic structuring and early design decision influence, confirming expected theoretical interplay reported in previous design cognition studies (Yilmaz *et al.*, 2010) (see figure (02)).

Table 7: Discriminant validity (HTMT)

Main Constructs	1	2	3	4	5
Early-stage design decision					
Heuristic structuring	0.514				
Knowledge Conversation	0.604	0.41			
Perceived digital _tools gap	0.069	0.266	0.047		
Tacit sustainability _Knowledge	0.495	0.53	0.729	0.081	

The results show that early-stage design decisions are moderately correlated with heuristic structuring (r = 0.514), knowledge conversion (r = 0.604), and tacit sustainability knowledge (r = 0.495).

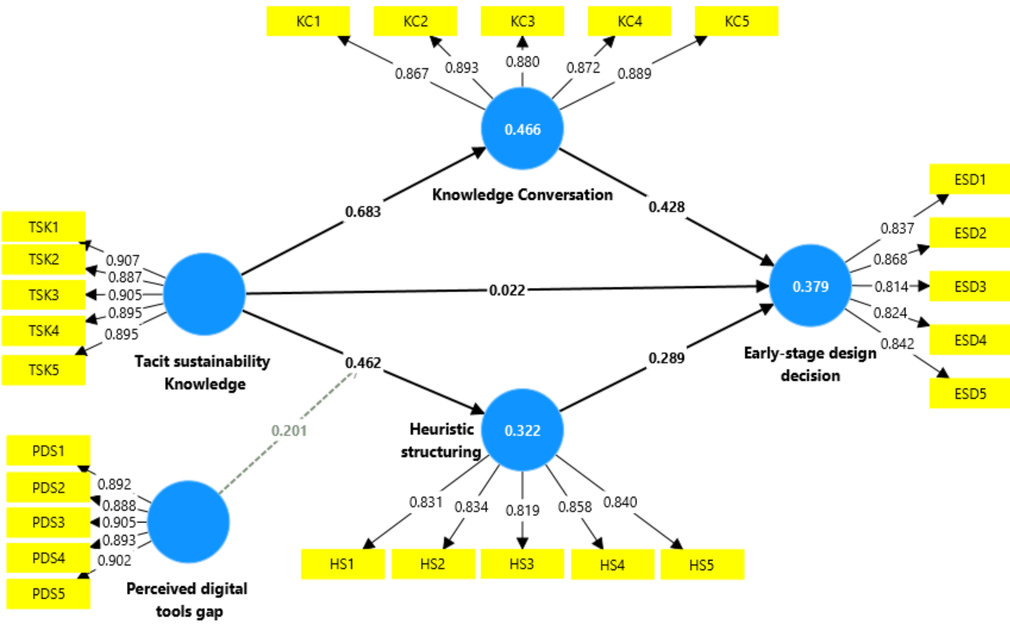

Figure 2 Measurement Model

This suggests that enhanced sustainability knowledge, stronger knowledge conversion, and structured heuristics are associated with improved early design decision-making. Tacit sustainability knowledge also has a strong correlation with knowledge conversion (0.729) and a moderate correlation with heuristic structuring (0.53), suggesting these constructs reinforce each other. The perceived digital tools gap has weak correlations with all constructs, indicating that it operates independently and does not strongly influence the other factors in this model.

5.2.4. Predictive Modelling

Multiple regression models were applied to test predictive pathways. Model 1 tested whether tacit insight usage and heuristic structuring predicted sustainability-aligned decision influence. Model 2 tested whether perceived digital tool gaps predicted reliance on heuristic structuring. Regression diagnostics confirmed acceptable VIF, linearity and homoscedasticity, consistent with recommended modelling standards (Calabretta *et al.*, 2025).

5.2.5. Integration and Theory–Data Convergence

Findings were then triangulated against the literature synthesis. Convergence was observed on the central claim that tacit sustainability insight is useful only when structured into cognitively usable form. Divergence was also noted: practitioners expressed stronger perceived tool gaps than reported in literature, which informed refinement of the conceptual model. Mixed interpretations in sustainability method studies are common and strengthen validity (Siwiec *et al.*, 2025).

5.3. Structural Model

This multi-tiered analysis process provided both statistical validation and conceptual insight, reinforcing the study's aim of operationalizing tacit sustainability knowledge through structural Model.

5.3.1. Hypothesis Testing

The direct influence of Tacit sustainability on Knowledge and Early-stage design decision is almost insignificant as the p-value is greater than 0.050 and t-value is less than 1.670 table 4.15 The indirect relationship between Quality of Tacit sustainability (relationship with customer) and early-stage design decisions are small, but significant in this study from Zero-order effect was zero to now However, these factors' effects are weakened in present theory with the existence of mediator. The indirect impact of tacit sustainability knowledge to the early-stage design decisions, mediated by knowledge conversion is significant (β= 0.301). This is consistent with the contention that articulating tacit knowledge facilitates better decisions, as research evidence is supported by Nonaka and Takeuchi's (1995) knowledge creation theory, which emphasizes the importance of knowing how to convert one type of knowledge into another in support of effective problem solving. The mediating effect through heuristic structuring is also significant (β = 0.136). This is also in line with the literature of design cognition, which demonstrates that heuristics can simplify complex sustainability information for designers and advise them to take better decisions at the early phase of the design process (Yilmaz and Seifert, 2011; Cross, 2011). Both paths indicate that tacit sustainability knowledge generates more robust early-phase decisions when combining it with structured knowledge processes and heuristics, which can be found in the detailed table (08).

Table 8: Indirect hypothesis results

Indirect Hypotheses	**β**	**(STDEV)**	**T statistics**	**P values**
Tacit sustainability _Knowledge -> Knowledge-> Early-stage design decision	0.022	0.074	0.291	0.386
Tacit sustainability _Knowledge -> Knowledge Conversation -> Early-stage design decision	0.301	0.046	6.548	0.000
Tacit sustainability _Knowledge -> Heuristic structuring -> Early-stage design decision	0.136	0.031	4.384	0.000

5.3.2. Moderation Direction

The other moderating impact of perception on digital tools gap and tacit sustainability knowledge, indirect through heuristic structuring (β = 0.059, p = 0.001). That is, when designers perceive a more significant void of digital tools, the degree of tacit sustainability cognition on heuristic structuring is higher to serve superior early design decisions. This is supported by study indicating that constraints force designers to rely more on heuristics and internal knowledge in problem solving (Bilda and Gero, 2007). It also implies that context has an influence on the facilitation or impeding of how tacit knowledge is managed in design reasoning and structured (Cross, 2011). Please refer to table (09) below for explanation.

Table 9: Moderation testing

Hypothesis	**β**	**(STDEV)**	**T statistics**	**P values**
Perceived digital _tools gap x Tacit sustainability _Knowledge -> Heuristic structuring -> Early-stage design decision	0.059	0.018	3.253	0.001

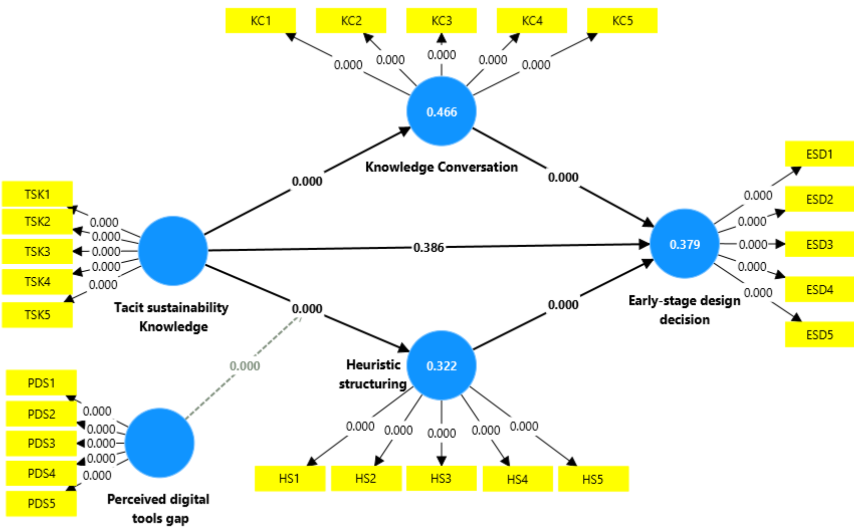

Figure 3: structural Model

5.3.3. Moderation Interception

The plot illustrates that the connection between tacit sustainability knowledge and heuristic structuring intensifies as the perceived gap in digital tools widens. When the gap is large (+1 SD), the slope becomes steepest, showing a more substantial positive influence. At the average level, the effect is moderate, and when the gap is small (–1 SD), the influence is weakest (see figure 4). This suggests that designers depend more on their tacit sustainability knowledge to organize heuristics when digital tools are scarce.

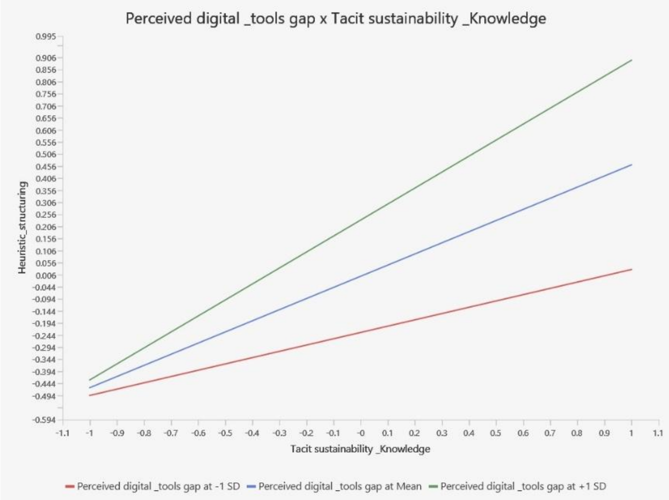

Figure 4: Moderation Interception Graph

5.4. Qualitative Insights from Expert Practitioners

In order to both illustrate and interpret the quantitative results, seven expert practitioners of industrial design with over a decade of long sustainable track records were recruited for semi-structured interviews. These interviews were intended to investigate the cognitive functions of tacit knowledge and the practical value of heuristic models on early design.

A thematic analysis approach was employed to post-process the qualitative data. Transcripts were inductively coded in the NVivo software to permit common themes to emerge without forcing them under predefined headings. Initial codes were regrouped to the higher-order themes that corresponded with the study's theoretical constructs: tacit knowledge activation, heuristic advantage, digital tool constraints and cognitive burdens when making decisions. They were cross-checked against survey data to look for similarities and differences between the two data sources.

Thematically: experience and intuition were ubiquitously acknowledged across both types of decision-making (particularly when navigating complex sustainability trade-offs). Nevertheless, such tacit knowledge was central to learning but difficult to share and carry over Identifying a need for the insights gained to be put into a form that can be more readily represented. Heuristic signals were considered as cognitive economy reminders to maintain creativity flow and integrate sustainable thinking. In addition, the majority of digital tools were criticized for being too data-heavy or not addressing real-time ideation needs, with similar themes surfacing in survey responses to perceived tool gaps. Overall, the interviews revealed that the framework is relevant and has potential for making lived experience knowledge actionable in a scalable and designer-friendly way.

5.5. Discussion

This paper aims to explore how tacit sustainability knowledge in industrial design can be rendered into practice during initial decision-making activities, through digital heuristic framing. The empirical findings provide strong support for the theoretical framework and show that conversion of knowledge and heuristic structuring significantly influence sustainability-related quality decision-making at an abstract phase.

The results support the core theoretical argument of the SECI model (Nonaka and Takeuchi, 1995) that tacit knowledge is only activated if it has been transformed into explicit form. Indirect effect of tacit knowledge on design decisions through knowledge conversion The substantial indirect impact of tacit knowledge (through knowledge conversion) on design decisions ($\beta=0.301$, $p<0.001$) confirms this mechanism as well as previous recommendations that sustainability insights embedded in individual experience need to be externalized in order to contribute to the shaping of design process effectively (Farnese, 2019; McAdam *et al.*, 2007).

Although the results are consistent with previous studies supporting the importance of heuristic-mediated reasoning in design (Yilmaz *et al.*, 2014; Cristofaro, 2025), they also point to important limitations. Empirical evidence also reveals that heuristics might reduce complex trade-offs in sustainability or lead to biased choices when assumptions change (Tversky & Kahneman, 1974; Gigerenzer & Gaissmaier, 2011). Moreover, eco-design investigations claim that formal tools such as LCA are better than intuition when detailed data appear (Baumann & Tillman, 2004; Bovea & Pérez-Belis, 2012). These counter perspectives situate the current model as being more of a smur in its cognitive supports, rather than a tool per se for formal assessments.

In addition, the research supports the mediating effect of heuristic structuring ($\beta = 0.136$, $p <0.001$) and provides empirical evidence for cognitive design theory: that heuristics decrease designers' cognitive loads and enhance trade-off reasoning in early stages of concept generation (Yilmaz *et al.*, 2014; Del Campo, 2016). This is consistent with previous work, which found that design heuristics enhance the quality and adaptability of ideation in the presence of uncertainty (Watson *et al.*, 2023). Importantly, by using heuristic structuring it was possible for designers to traverse tensions such as biobased material versus industrial recyclability infrastructure a key friction point identified in König *et al.*, (2017).

The moderating influence of perceived digital tool gaps ($\beta = 0.059$, $p = 0.001$) also reinforces that current digital sustainability tools are heavily focused on up-front evaluations and do little to support earlier-stage ideation (Basereh *et al.*, 2024; Vicente and Camacho, 2023). When designers feel a lack of tools (as these oncologists presumably do), they lean on structured tacit knowledge more heavily, supporting the importance of heuristics as decision assets for ideation. This result corresponds to that of Cross (2011) and Bilda and Gero (2007), who state that in the absence of strong digital guidance, designers rely more heavily on internalized and intuition-based modes of reasoning.

Taken together, these findings indicate that by operationalizing sustainability knowledge through digital heuristics one overcomes a long-lasting usability gap. In contrast to current sustainability tools which are complex, post-conceptual and data-heavy (Siwiec *et al.*, 2025), heuristic-driven tools operate at a cognitive scale of early-stage design, the level at which designers articulate problems and make conceptual decisions (Jia, 2022; Frinch *et al.*, 2021). This provides further evidence for the claim in the study that heuristics are an ideal "knowledge unit" for ideation insofar as they are neither too abstract nor too prescriptive.

6. Conclusion

This research has tackled an enduring issue for sustainable industrial design the difficulty in mobilizing and applying tacit environmental knowledge at the sketch ideation stage. By suggesting and confirming a model in which 'unconscious' sustainability knowledge is converted into digital heuristics, the contribution shows how to operate better ideation support for design decision-making. Results all confirm that heuristic structuring is a strong mediator to support the impact of tacit knowledge on sustainable design outcomes, and this effect is even enhanced especially in environments without digital tools at ideation stage.

Theoretical and applied implications of this study are presented. It contributes to knowledge translation and design cognition literatures- towards elaborating an overarching heuristic structuring as a critical mechanism for extracting tacit understandings. At the same time, it offers a practical approach for planners and decision-makers wishing to institutionalize sustainability at an early stage of design with particular emphasis on the aims of Vision 2030 together with broader circular economy principles.

Finally, the research highlights that digital heuristics are not simplified tools but wise knowledge interfaces intending to serve as mediators between meaningful thoughts and designing action. Add in ideation, by giving sustainability cognitive access in a place where it counts most, and you're no longer treating sustainability as an upstream constraint but seeing that its the best kind of upstream design catalyst. The accompanying guidance will be refined in line with advances in digital tool integration and the growth of heuristic libraries that will increasingly broaden the influence and impact of this framework.

6.1. Implications, limitations and future directions

The implications for the findings may also be relevant to design education ecosystem and national innovation strategies, within the ambit of Vision 2030. It is now up to countries like Saudi Arabia to lead the way in the circular economy culture, where sustainability thinking should be incorporated in a design mindset rather than retrofitted with regulations (van Dam *et al.*, 2019). By providing grotesque, caricatured images of a hellish future, digital heuristics make it possible in scalable terms to cultivate such shifts of mindset and place already accumulated sustainability knowledge readily at hand and cognitively available within the 'flow' of everyday life.

Overall, this research provides evidence that tacit sustainability knowledge integrated and encoded in digital heuristics enhances the ability of industrial design to have environmentally conscious decision-making. It not only extends theoretical understanding on the convergence of knowledge management and design cognition but provides a tangible localized toolkit for applying strategies of sustainability transformation from 'within' organizations. Future studies should consider discipline-specific sustainability heuristics and their potential inclusion in digital learning environments to inform real-time, practice-based decision-making. Although the present work demonstrates that heuristic libraries can be scaled, it remains to further develop adaptive interfaces that make use of situational prompts in a meaningful way. The approach could also be reinforced by a synergistic application of ethnographic and longitudinal empirical methods for actually tracking tacit-to-explicit knowledge conversion on an ongoing basis, with what is learned being used to refine the heuristic model over time and yield further insight into how designers come to internalize and leverage these cognitive supports on real projects.

The study validates the significance of tacit environmental heuristics in the early design phase and adds to a crosslink of design cognition, knowledge management and sustainability. It extends the SECI model by demonstrating that heuristic structuring is a distinct mediating process that translates tacit insights into cognitively articulated decision supports. It also provides evidence of the cognitive importance of heuristics as a fundamental processing source for sustainability reasoning in ideation and supports a conceptual platform where tools design, which promotes innovative sustainable development, could lay upon.

Pragmatically, the research delivers an empirically validated model for integrating sustainability understanding into early-stage design processes via digital heuristics. For designers, that means having access to sustainability prompts that aid quick intuitive thinking (not requiring bulky data applications). For tool builders and practitioners, it provides an opportunity to design lightweight ideation-stage tools that scale and align with designers' ways of working. Theoretically, at the policy level and within Vision 2030, it provides a tangible means of applying sustainability in product development environments.

Although the research has provided significant empirical support, it is conducted in the Saudi industrial design context, which may affect its generalizability. There may be respondent biases due to the self-report measures employed and although we have a strong model of explanation it could be enhanced by longitudinal or ethnographic studies. Table (1) is about the theoretical justification of each variable, while its limitation in the study is how those constructs measured at empirical level using self-report. As tacit sustainability thinking is hard to articulate explicitly, respondents' observations may not fully represent the underlying cognitive processes. This difference settles the range of the limitation and indicates the significance of complementary observational approaches in future endeavors. Future work should investigate domain-specific heuristic libraries, evaluate scenarios for real-time integration into digital design platforms and consider how the structuring of heuristics varies across differing design disciplines and cultures.

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