Engineers' Perceptions of Sustainable Design Practices in Complex Engineering Systems

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Citation: Yeganeh, N. (2026). Engineers' Perceptions of Sustainable Design Practices in Complex Engineering Systems. *Multidisciplinary Engineering Science Open,* 3, 1-14.

Abstract

This study aimed to explore how engineers working in Tehran perceive, interpret, and implement sustainable design practices in complex engineering systems. A qualitative research design was employed to examine engineers' lived professional experiences of sustainable design in multidisciplinary engineering contexts. Twenty engineers from Tehran were recruited through purposive and snowball sampling. Participants had professional experience in civil, mechanical, electrical, industrial, software/systems, chemical, environmental, and infrastructure-related engineering fields. Data were collected exclusively through semi-structured interviews, each lasting approximately 45–75 minutes. Interview questions focused on participants' understanding of sustainability, design decision-making, trade-off management, organizational constraints, stakeholder expectations, use of sustainability tools, and perceived barriers to sustainable engineering practice. Interviews continued until theoretical saturation was reached. All interviews were transcribed verbatim and analyzed using thematic analysis with the support of NVivo software. Analysis generated five main categories: life-cycle and systems thinking, sustainability as a technical design criterion, trade-off management under complexity, organizational and project-level enablers, and tool/data limitations in sustainable engineering practice. Engineers generally perceived sustainable design as more than environmental protection, emphasizing long-term performance, resource efficiency, maintainability, risk reduction, social responsibility, and economic feasibility. However, participants reported that sustainability was often weakened by cost pressure, fragmented project governance, limited client commitment, insufficient local data, and late-stage integration into design processes. Sustainable design was most feasible when sustainability requirements were embedded early, supported by multidisciplinary collaboration, and translated into measurable engineering criteria. The findings suggest that engineers recognize sustainable design as a necessary professional responsibility in complex engineering systems, but its implementation depends on early systems-level integration, organizational support, credible assessment tools, and alignment between technical, economic, environmental, and social objectives.

Keywords: sustainable design; complex engineering systems; engineers' perceptions; qualitative research; life-cycle thinking; systems engineering; Tehran

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1. Introduction

Sustainable design has become an increasingly important concern in engineering because contemporary engineering systems are no longer evaluated only by technical efficiency, cost, reliability, or short-term functionality. They are also assessed according to their long-term environmental, social, economic, and systemic consequences. Engineering decisions shape infrastructure, energy systems, transportation networks, industrial processes, buildings, digital platforms, water systems, and manufacturing systems that interact with society and the natural environment over extended periods. As a result, engineers are increasingly expected to design systems that satisfy present needs while avoiding unacceptable burdens for future generations. This expectation reflects the broader concept of sustainability, which has commonly been framed around environmental protection, economic viability, and social well-being (Kuhlman & Farrington, 2010). In engineering contexts, however, sustainability is not an abstract value; it must be translated into specifications, materials, processes, design alternatives, maintenance strategies, risk assessments, and life-cycle decisions.

The increasing complexity of engineering systems has intensified the need for sustainable design. Complex engineering systems are characterized by multiple interacting components, uncertain operating conditions, distributed stakeholders, long life cycles, nonlinear effects, and interdependence between technical and social subsystems. A transportation system, for example, is not merely a collection of roads, vehicles, sensors, and control mechanisms; it is also connected to energy consumption, air quality, land use, economic mobility, user behavior, safety, maintenance, and public policy. Similarly, energy systems involve technical performance, environmental emissions, supply security, economic affordability, regulatory requirements, and social acceptance. These examples demonstrate that sustainable design in complex engineering systems requires systems thinking rather than isolated optimization. Engineers must understand how design decisions made at one level of the system may generate consequences elsewhere, sometimes across organizational, temporal, or geographic boundaries.

The literature on design for sustainability shows that sustainability-oriented design has evolved from a narrow focus on product-level environmental improvement toward broader system innovation and socio-technical transition. Ceschin and Gaziulusoy (2016) argued that design for sustainability has moved through different levels, including product innovation, product-service systems, spatial-social innovation, and socio-technical system transformation. This evolution is highly relevant for engineers working with complex systems because sustainability challenges often cannot be resolved by improving one component alone. Instead, engineers must consider how components interact, how users behave, how systems are governed, and how value is created and distributed across the system life cycle. Sustainable design therefore requires integration between engineering analysis, organizational strategy, environmental assessment, stakeholder engagement, and long-term planning.

Life-cycle thinking is one of the central foundations of sustainable engineering design. Life-cycle assessment provides a structured framework for evaluating environmental aspects and potential impacts across stages such as raw material acquisition, production, transportation, use, maintenance, and end-of-life treatment (International Organization for Standardization [ISO], 2006). This life-cycle perspective is particularly important because design choices can shift impacts from one stage to another. A material that reduces operational energy consumption may require high embodied energy during production. A system that is inexpensive to build may be expensive or environmentally damaging to maintain. A technology that improves efficiency may create new waste streams at the end of its service life. Thus, engineers must consider not only immediate design performance but also delayed, indirect, and cumulative impacts.

Ecodesign standards and environmental management frameworks also emphasize the need to embed sustainability into organizational design processes. ISO 14006 provides guidance for incorporating ecodesign into environmental management systems and highlights the importance of managing environmental considerations systematically rather than treating them as informal or optional concerns (ISO, 2020). Such standards are relevant because sustainable design often fails not due to lack of ethical awareness but because organizations lack procedures, incentives, decision criteria, or reliable tools for implementation. In many engineering projects, sustainability is discussed conceptually but is not converted into enforceable requirements, design review criteria, supplier specifications, or performance indicators. Consequently, the integration of sustainability depends on both individual engineers' professional judgment and the organizational systems within which they work.

Previous research has identified several challenges that limit sustainable design implementation. Boks (2006) emphasized the "soft side" of ecodesign, showing that organizational behavior, communication, cooperation, and implementation culture strongly influence whether environmental design principles are adopted in practice. Brones, de Carvalho, and de Senzi Zancul (2014) similarly argued that ecodesign is often insufficiently integrated into project management processes, creating a gap between sustainability intentions and operational project decisions. Pigosso, Rozenfeld, and McAloone (2013) proposed an ecodesign maturity model to support systematic implementation in manufacturing companies, indicating that organizations differ significantly in their ability to institutionalize ecodesign practices. These studies suggest that sustainable design is not only a technical issue but also a managerial and organizational challenge.

Engineers' perceptions are important because engineers act as key translators between sustainability goals and practical design decisions. While policy makers may define sustainability targets and organizations may announce sustainability strategies, engineers often determine how those goals are interpreted in real projects. They decide which materials are feasible, which alternatives are technically acceptable, which risks are tolerable, which performance indicators are measurable, and which trade-offs can be justified. Their perceptions influence whether sustainability is treated as a core design requirement, an additional constraint, a compliance issue, a client preference, or a professional responsibility. Understanding engineers' perceptions can therefore reveal the practical conditions under which sustainable design is either enabled or constrained.

The role of engineers is especially critical in complex engineering systems because such systems require negotiation between competing objectives. Sustainable design often involves trade-offs between cost and environmental performance, durability and material intensity, redundancy and resource efficiency, innovation and reliability, local feasibility and global standards, and short-term project delivery and long-term system value. Gagnon, Leduc, and Savard (2012) argued that sustainable engineering design differs from conventional engineering design because it requires broader criteria and greater attention to long-term and systemic impacts. Engineers must therefore move beyond narrow optimization and engage in multi-criteria reasoning that includes technical, economic, environmental, and social dimensions.

Despite the growing literature on sustainable design, there remains a need for qualitative studies that examine how practicing engineers understand sustainability within their actual professional contexts. Much of the sustainable design literature focuses on frameworks, tools, standards, or educational models, while fewer studies explore engineers' subjective interpretations, practical dilemmas, and organizational experiences. This gap is significant because frameworks alone do not explain how engineers make sense of sustainability under real project pressures. In contexts where economic constraints, regulatory uncertainty, client expectations, and limited environmental data affect engineering practice, engineers' perceptions may differ from formal sustainability models. Local qualitative evidence can therefore contribute to a more grounded understanding of sustainable design implementation.

Tehran provides a relevant context for studying engineers' perceptions of sustainable design. As a large metropolitan and industrial center, Tehran faces challenges related to urban development, infrastructure pressure, energy consumption, air pollution, water scarcity, transportation demand, construction growth, and technological modernization. Engineers working in Tehran are often involved in projects where sustainability concerns intersect with economic limitations, regulatory requirements, client demands, and technical complexity. These conditions make Tehran an appropriate setting for examining how engineers perceive sustainable design in complex engineering systems and how they describe the gap between sustainability ideals and implementation realities.

From a methodological perspective, qualitative inquiry is appropriate for this topic because engineers' perceptions involve meanings, experiences, interpretations, and context-dependent judgments. Semi-structured interviews allow participants to describe how sustainability is understood in their professional language, how decisions are made in practice, and how organizational and technical constraints affect design choices. Thematic analysis provides a flexible method for identifying patterns across participants while preserving the richness of individual accounts (Braun & Clarke, 2006). By focusing on engineers' experiences, this study seeks to generate practical insights that can inform engineering management, sustainability education, organizational policy, and future research on sustainable design in complex systems.

Therefore, the aim of this study was to explore engineers' perceptions of sustainable design practices in complex engineering systems, with particular attention to how engineers in Tehran understand sustainability, integrate it into design decisions, manage trade-offs, and experience organizational and technical barriers to implementation.

2. Methods and Materials

This study used a qualitative research design to explore engineers' perceptions of sustainable design practices in complex engineering systems. A qualitative approach was selected because the purpose of the study was not to measure predetermined variables but to understand how engineers interpret sustainability, how they describe design-related experiences, and how they make sense of barriers and enablers in professional practice. The study adopted an exploratory descriptive orientation, which was appropriate for producing a detailed account of participants' views while remaining close to their professional language and lived work experiences.

Participants were engineers working in Tehran who had direct experience with design, development, assessment, supervision, or management of complex engineering systems. Inclusion criteria were: having at least five years of engineering work experience, being currently employed or recently active in engineering projects in Tehran, having experience in design or project decision-making, and willingness to participate in an interview. Engineers from multiple disciplines were included to capture the multidisciplinary nature of complex systems.

A total of 20 engineers participated in the study. Participants were recruited using purposive sampling and then snowball sampling, whereby initial participants introduced other eligible engineers with relevant experience. The final sample included engineers from civil and infrastructure engineering, mechanical and energy systems, electrical and control systems, industrial and project systems, software and systems engineering, and chemical/environmental engineering. Theoretical saturation was reached after the eighteenth interview, when no substantially new codes or categories emerged. Two additional interviews were conducted to confirm the stability and completeness of the emerging categories.

Data were collected exclusively through semi-structured interviews. An interview guide was developed based on the study aim and the literature on sustainable design, systems engineering, life-cycle thinking, and ecodesign implementation. The guide included open-ended questions such as: "How do you define sustainable design in your engineering work?", "At what stage of the project is sustainability usually considered?", "What factors support or prevent sustainable design decisions?", "How do you manage trade-offs between cost, performance, safety, and environmental goals?", "What tools or standards do you use when evaluating sustainability?", and "What organizational changes would help engineers implement sustainable design more effectively?"

Each interview lasted between 45 and 75 minutes. Interviews were conducted in a private and convenient setting, either face-to-face or through secure online communication when necessary. With participants' permission, all interviews were audio-recorded and transcribed verbatim. Field notes were written after each interview to document contextual observations, preliminary analytic impressions, and emerging ideas. Data collection continued until theoretical saturation was achieved.

Data were analyzed using thematic analysis. The analysis began with repeated reading of transcripts to develop familiarity with the data. Initial codes were generated inductively from meaningful segments of the interviews. Coding focused on statements related to definitions of sustainability, design practices, decision-making processes, barriers, organizational conditions, tools, trade-offs, and professional responsibility. NVivo software was used to organize transcripts, manage codes, compare coded segments, and develop category structures.

After initial coding, related codes were grouped into subcategories and then into broader main categories. The research team reviewed the categories to ensure that they were internally coherent, conceptually distinct, and strongly supported by the interview data. Disagreements in coding interpretation were resolved through discussion and re-examination of the transcripts. Analytical memos were used throughout the process to document category development and researcher reflections. To enhance trustworthiness, the study used peer debriefing, member checking with selected participants, prolonged engagement with the data, and an audit trail of coding decisions. Credibility was supported by the use of direct quotations, while dependability was strengthened through systematic documentation of data collection and analysis procedures.

Participants were informed about the purpose of the study, the voluntary nature of participation, the right to withdraw at any time, and the confidential treatment of all information. Written informed consent was obtained from all participants before the interviews. Identifying information was removed from transcripts, and participants were assigned codes such as P1, P2, and P3. Audio files and transcripts were stored securely and used only for research purposes.

3. Findings

The study included 20 engineers working in Tehran. Fourteen participants were men (70%) and six were women (30%). Participants' ages ranged from 28 to 52 years, with most participants between 35 and 44 years old. Regarding education, four participants held a bachelor's degree (20%), twelve held a master's degree (60%), and four held a doctoral degree

(20%). In terms of engineering discipline, five participants were from civil and infrastructure engineering (25%), four from mechanical and energy systems (20%), four from electrical and control systems (20%), three from software and systems engineering (15%), two from chemical/environmental engineering (10%), and two from industrial/project systems engineering (10%). Professional experience ranged from 5 to 25 years: five participants had 5–9 years of experience (25%), seven had 10–14 years (35%), five had 15–19 years (25%), and three had 20 years or more (15%). Participants' roles included senior design engineer (n = 7, 35%), systems engineer (n = 4, 20%), project or technical manager (n = 5, 25%), and sustainability, quality, or HSE specialist (n = 4, 20%). Participants were employed in consulting and EPC firms (n = 7, 35%), energy and utilities (n = 5, 25%), manufacturing and process industries (n = 4, 20%), ICT and smart systems (n = 2, 10%), and transportation or infrastructure organizations (n = 2, 10%).

The first main category showed that engineers perceived sustainable design as a life-cycle and systems-level responsibility rather than a narrow environmental add-on. Participants emphasized that complex engineering systems must be evaluated from early conceptual design through construction, operation, maintenance, upgrading, and end-of-life stages. Many engineers argued that sustainability cannot be achieved if attention is limited to immediate project delivery or initial cost. Instead, they described sustainable design as the capacity to anticipate long-term effects, reduce waste, improve maintainability, and prevent the transfer of problems from one system stage to another. One participant explained, "For me, sustainable design means that I should not solve today's technical problem by creating tomorrow's maintenance problem" (P4). Another engineer stated, "In complex systems, every decision has a shadow. If you choose a cheaper component now, maybe you increase energy use, downtime, or replacement waste later" (P11). Participants also noted that sustainability requires attention to interdependencies between subsystems. For example, mechanical design decisions may affect energy demand, control system complexity, safety procedures, and user behavior. This category therefore indicates that engineers viewed sustainability as inseparable from systems thinking, especially in projects where technical components interact with social, economic, and environmental conditions.

The second category concerned the need to convert sustainability from a general value into measurable engineering criteria. Participants repeatedly stated that sustainability remains weak in projects when it is expressed only as a slogan or organizational commitment. Engineers reported that they can implement sustainability more effectively when it is translated into design specifications, performance indicators, material selection rules, energy targets, durability requirements, emission thresholds, risk criteria, or maintenance standards. One participant noted, "When the client says 'make it sustainable,' that is not enough. I need numbers, standards, priorities, and acceptance criteria" (P2). Another stated, "Engineers work with requirements. If sustainability is not in the requirements document, it becomes optional when the project becomes difficult" (P16). Participants described several ways of operationalizing sustainability, including reducing energy consumption, selecting recyclable or locally available materials, designing for modular maintenance, improving system efficiency, reducing emissions, increasing service life, and minimizing operational waste. However, they also reported that sustainability indicators are often added late in the design process, after major architectural and technical decisions have already been made. As a result, sustainability becomes a corrective measure rather than a guiding design logic. This category demonstrates that engineers perceived sustainable design as feasible only when sustainability is embedded early and formally in design requirements.

The third category reflected engineers' experiences with trade-offs among sustainability, cost, safety, reliability, schedule, and performance. Participants did not describe sustainable design as a simple choice between "green" and "non-green" alternatives. Instead, they emphasized that sustainable design in complex systems often requires difficult prioritization under uncertainty. For example, a more environmentally efficient technology may have higher initial costs, limited supplier support, uncertain maintenance requirements, or insufficient local expertise. One engineer stated, "Sometimes the sustainable option is technically better, but the project budget sees only the purchase price, not the life-cycle cost" (P7). Another participant explained, "We are always balancing. If I reduce material too much, maybe I reduce embodied carbon, but I may also reduce safety margin or durability. Sustainability is not just using less; it is using intelligently" (P13). Participants also reported that decision-makers often prioritize initial cost and project delivery time over life-cycle value. This creates tension for engineers who understand long-term consequences but have limited authority to change procurement or budget decisions. Some participants indicated that sustainable design requires multi-criteria decision-making, where environmental, economic, technical, and social factors are evaluated together. The category shows that engineers perceived trade-off management as one of the most important competencies for sustainable design in complex engineering systems.

The fourth category showed that sustainable design depends strongly on organizational and project governance. Participants stated that individual engineers may support sustainability, but their influence is limited if organizational procedures, project contracts, leadership priorities, and client expectations do not support sustainable choices. Engineers described several organizational barriers, including fragmented communication between disciplines, weak sustainability leadership, lack of incentives, short-term budgeting, inadequate design review processes, and procurement rules focused mainly on lowest initial cost. One participant explained, "The engineer may believe in sustainability, but the project structure may punish sustainable decisions because they take time, require coordination, or cost more at the beginning" (P5). Another stated, "If sustainability is not supported by management, it becomes personal interest, not project policy" (P18). Participants also identified enabling conditions, including early involvement of sustainability experts, cross-disciplinary design meetings, client commitment, clear sustainability responsibilities, and integration of sustainability into project milestones. Engineers working in organizations with environmental management systems or stronger quality procedures reported more systematic attention to sustainability. This category suggests that sustainable design is not only a matter of individual awareness but also a function of governance structures that shape engineering decisions.

The fifth category concerned the availability and usability of sustainability tools and data. Participants were aware of tools such as life-cycle assessment, environmental impact assessment, energy modeling, risk assessment, simulation, and design standards, but they reported uneven use in practice. Some engineers stated that these tools are valuable but time-consuming, data-intensive, or poorly integrated into routine design workflows. Others emphasized the shortage of reliable local data on materials, energy profiles, emissions, supplier practices, maintenance conditions, and end-of-life pathways. One participant noted, "We can use international databases, but sometimes they do not reflect our local materials, energy mix, or construction methods" (P9). Another engineer said, "The problem is not that engineers reject tools; the problem is that tools are not always connected to the speed and pressure of real projects" (P20). Participants also reported that standards can support sustainable design, but standards alone are insufficient unless engineers understand how to apply them in context. This category indicates that sustainable design in Tehran-based engineering projects requires better access to localized data, practical tools, training, and decision-support systems that fit real project conditions.

4. Discussion

The first major finding was that engineers perceived sustainable design as a life-cycle and systems-thinking responsibility. This finding aligns with the broader sustainable design literature, which argues that sustainability cannot be reduced to isolated product improvements but must be understood across system levels and life-cycle stages. ISO 14040 defines life-cycle assessment as a framework for examining environmental aspects and potential impacts across the life cycle of products and systems (ISO, 2006). Similarly, Ceschin and Gaziulusoy (2016) showed that design for sustainability has evolved toward systemic and socio-technical approaches. The engineers in the present study reflected this shift by emphasizing long-term maintenance, operational performance, interdependence among subsystems, and downstream consequences of early design choices. Their accounts suggest that complex engineering systems require a broader design logic in which sustainability is not treated as a final-stage evaluation but as an organizing principle from the conceptual stage. This result also supports the argument that engineering design must adapt to sustainability challenges by integrating technical, environmental, economic, and social reasoning into system architecture and decision-making (Isaksson & Eckert, 2022). The participants' emphasis on unintended consequences is especially important because complex systems often generate indirect effects that are not visible when engineers focus only on individual components.

The second finding showed that engineers require sustainability to be translated into technical design criteria before it can meaningfully influence practice. This result is consistent with ecodesign implementation research, which shows that sustainability goals must be embedded into product development processes, project routines, and design requirements (Brones et al., 2014; Pigosso et al., 2013). Participants did not reject sustainability; rather, they expressed frustration with vague sustainability language that lacks measurable requirements. This indicates a practical gap between strategic sustainability discourse and engineering implementation. In engineering work, decisions are typically made through specifications, constraints, tolerances, calculations, standards, drawings, procurement documents, and verification procedures. If sustainability is absent from these formal artifacts, it becomes vulnerable to omission when time, cost, or technical pressures increase. This finding supports the view that sustainable design should be integrated into requirement engineering, design reviews, and performance evaluation rather than treated as an optional ethical preference. It also suggests that organizations should develop sustainability indicators that are specific enough for engineers to use but flexible enough to accommodate project-specific complexity.

The third finding concerned trade-off management. Engineers described sustainable design as a multi-objective decision process involving cost, performance, safety, reliability, durability, schedule, resource efficiency, emissions, and long-term value. This finding aligns with Gagnon et al. (2012), who argued that sustainable engineering design differs from conventional engineering design because it requires broader evaluation criteria and attention to long-term consequences. It also reflects the general sustainability literature, which recognizes the need to balance environmental, economic, and social dimensions (Kuhlman & Farrington, 2010). In the present study, participants emphasized that sustainable options are not always obviously superior in every dimension. A material may reduce environmental impact but increase cost; a technology may improve efficiency but require specialized maintenance; a design may reduce resource use but create reliability concerns. These findings suggest that engineers need structured methods for multi-criteria decision-making and life-cycle costing. The results also show that sustainability cannot be achieved merely through moral commitment. Engineers need authority, data, and decision frameworks that allow them to justify sustainable alternatives when initial cost comparisons are unfavorable.

The fourth finding indicated that organizational and project governance strongly shape sustainable design implementation. This finding is consistent with Boks (2006), who emphasized that organizational behavior, cooperation, and cultural factors play a central role in ecodesign adoption. Participants in this study reported that engineers may personally value sustainability but remain constrained by procurement systems, client expectations, fragmented project structures, short-term budgets, and weak managerial support. This finding is important because it challenges individualistic explanations of sustainability failure. The problem is not simply that engineers lack knowledge or motivation. Rather, sustainable design requires organizational conditions that support early integration, cross-disciplinary coordination, accountability, and life-cycle-oriented decision-making. Brones et al. (2014) argued that ecodesign and project management are often insufficiently connected, and the present findings confirm this concern in the context of complex engineering systems. When sustainability is not embedded in project governance, it becomes dependent on individual initiative and is easily displaced by schedule or cost pressure. Therefore, organizations need to institutionalize sustainability through design gates, formal responsibilities, procurement criteria, and leadership commitment.

The fifth finding showed that engineers experience limitations in sustainability tools, data, standards, and local adaptation. This finding aligns with prior research showing that although sustainable design methods and tools exist, practitioners often struggle to select, adapt, and apply them in real projects (Chatty et al., 2022; Dekoninck et al., 2016). Participants reported that life-cycle tools, environmental databases, simulations, and standards can support sustainable design, but their usefulness depends on data quality, usability, time availability, and contextual relevance. The shortage of local data was particularly important in the Tehran context. International databases may not accurately reflect local material production, energy systems, construction practices, supplier behavior, maintenance conditions, or end-of-life infrastructure. This result suggests that sustainable design capacity depends not only on individual competence but also on knowledge infrastructure. Engineers need localized databases, practical toolkits, training, and integrated software environments that connect sustainability assessment with routine engineering workflows. Standards such as ISO 14006 can guide ecodesign integration into environmental management systems (ISO, 2020), but standards require organizational translation into practical procedures. Without this translation, standards may remain symbolic rather than operational.

The findings collectively suggest that engineers in Tehran understand sustainable design as a necessary but difficult practice in complex engineering systems. Their perceptions were not limited to environmental protection; they included life-cycle value, maintainability, energy performance, safety, resource efficiency, social responsibility, and economic feasibility. This broad understanding is consistent with the evolution of sustainability from a narrow environmental concept to a multidimensional systems-oriented framework (Ceschin & Gaziulusoy, 2016; Kuhlman & Farrington, 2010). However, the study also shows that awareness is not sufficient. Sustainable design requires early integration, measurable criteria, organizational support, credible data, appropriate tools, and decision authority. The gap between sustainability intention and implementation appears to be produced by the interaction of technical uncertainty, economic pressure, weak governance, and insufficient knowledge infrastructure. Therefore, sustainable design should be understood as a socio-technical capability rather than a purely technical method.

This study has several limitations. First, the sample was limited to 20 engineers working in Tehran, which may restrict transferability to other regions, industries, or national contexts. Second, the study relied only on semi-structured interviews, and no observational data, document analysis, or project case analysis was used. As a result, the findings represent participants' perceptions and self-reported experiences rather than direct observation of design practices. Third, although the sample included engineers from different disciplines, some sectors were represented by only a small number of participants. Fourth, the study did not compare perceptions across organizational types, project sizes, or levels of sustainability maturity. Finally, because sustainability is a socially desirable topic, some participants may have emphasized positive attitudes more strongly than actual practice.

Future research should examine sustainable design practices across multiple cities, industries, and project types to compare contextual differences in engineering decision-making. Mixed-methods studies could combine interviews with document analysis, design review observations, project performance indicators, and case studies of completed engineering systems. Future studies may also compare the perceptions of engineers, project managers, clients, regulators, and end users to better understand stakeholder conflicts in sustainable design. Longitudinal research would be valuable for examining how sustainability decisions made during early design stages affect construction, operation, maintenance, and end-of-life outcomes. Further research should also develop and test localized sustainability assessment tools and databases that reflect regional materials, energy systems, climate conditions, and regulatory environments.

Engineering organizations should integrate sustainability into the earliest stages of project definition and requirement development. Sustainability criteria should be written into design briefs, procurement documents, technical specifications, and design review checklists. Project managers should support engineers by allowing time and resources for life-cycle analysis, multi-criteria decision-making, and cross-disciplinary coordination. Organizations should also provide training in life-cycle thinking, sustainable materials, systems modeling, environmental standards, and trade-off analysis. Local databases should be developed to help engineers evaluate environmental and life-cycle impacts under realistic regional conditions. Finally, clients and senior managers should recognize that sustainable design may increase initial investment but can reduce long-term costs, operational risks, maintenance burdens, and environmental impacts.

5. Conclusion

This qualitative study explored engineers' perceptions of sustainable design practices in complex engineering systems in Tehran. The findings showed that engineers understand sustainable design as a broad and multidimensional responsibility involving life-cycle thinking, systems integration, technical performance, environmental protection, resource efficiency, maintainability, social responsibility, and economic feasibility. Participants emphasized that sustainable design must be embedded early in the project life cycle and translated into measurable engineering requirements. They also described sustainability as a trade-off-intensive practice that requires balancing cost, safety, reliability, schedule, efficiency, and long-term value.

The study further revealed that organizational and project governance plays a decisive role in enabling or constraining sustainable design. Engineers may value sustainability, but their ability to implement it depends on management support, client commitment, procurement systems, interdisciplinary collaboration, and formal design procedures. The findings also highlighted limitations related to sustainability tools, local data, standards implementation, and practical training. These limitations reduce engineers' capacity to justify and operationalize sustainable alternatives in real projects.

Overall, the study suggests that sustainable design in complex engineering systems should be treated as a socio-technical capability. It requires not only knowledgeable engineers but also supportive organizations, reliable data, life-cycle-oriented decision frameworks, and governance systems that align sustainability with engineering practice. Strengthening these conditions can help engineering organizations move from symbolic sustainability commitments toward practical and measurable sustainable design implementation.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all who helped us through this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

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