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ENVIRONMENTAL, SOCIAL AND GOVERNANCE (ESG)-ORIENTED DECISION SUPPORT IN OFF-SITE CONSTRUCTION: A LIFECYCLE-INTEGRATED ARCHITECTURE

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Abstract: Off-site construction (OSC) changes not only where construction activities are performed, but also how project decisions are distributed across the lifecycle. Decisions made during design and planning can shape manufacturing, logistics, on-site assembly, and operation, yet the knowledge needed to support these decisions is often dispersed across lifecycle stages, project teams, and information systems. This fragmentation becomes more critical when project teams are expected to consider environmental, social, and governance (ESG)-oriented value trade-offs, because such trade-offs are embedded in decision processes rather than confined to post-project performance evaluation. Existing decision support approaches in construction have advanced data integration, modelling, and analytical capability, but they remain limited in their ability to mobilise heterogeneous lifecycle and ESG-oriented knowledge in response to specific OSC decision contexts. This paper develops a lifecycle-integrated decision support system (DSS) architecture for supporting ESG-oriented decision-making in OSC projects. Adopting a problem-driven conceptual design approach informed by design science principles, the study proceeds through problem structuring, requirement derivation, and architecture synthesis. The main conceptual output is a lifecycle-integrated DSS architecture comprising three connected components: heterogeneous knowledge sources, a lifecycle-integrated knowledge base, and a retrieval-augmented generation (RAG)-enabled decision support engine. The architecture organises project knowledge around lifecycle stages, decision contexts, and knowledge domains, allowing ESG-oriented value trade-offs to be embedded within decision-relevant knowledge rather than treated as external evaluation criteria. The RAG-enabled decision support engine is designed to retrieve and synthesise relevant lifecycle, ESG-oriented, and project-context knowledge for specific decision situations. The study contributes by reframing ESG-oriented decision support in OSC as a problem of lifecycle knowledge structuring and context-specific knowledge integration. It provides a conceptual foundation for future prototype development, expert validation, and empirical testing.

Keywords: Off-site construction (OSC); Environmental, Social and Governance (ESG); Decision support system (DSS); Retrieval-augmented generation (RAG)

1 INTRODUCTION

Off-site construction (OSC) has reshaped how construction projects are planned and delivered by relocating substantial production and assembly activities from conventional on-site environments to factory-based and distributed delivery settings (e.g., Zhang et al. 2024; Kosbar et al. 2023). More fundamentally, OSC changes how project decisions are made. Many critical decisions are made during design and planning, while their consequences extend to manufacturing, logistics, on-site assembly, and operation. Recent OSC studies continue to emphasise the need to integrate design, production, logistics, and site operations, and to manage knowledge across project stages rather than treating OSC as a set of separated technical activities (Kosbar et al. 2023; Zhang et al. 2024; Tennakoon et al. 2023). Accordingly, decision-making in OSC needs to be understood as lifecycle-dependent, with strong interdependencies across stages. Early decisions can shape or constrain later actions, yet the knowledge needed to support those decisions is often dispersed across lifecycle stages, stakeholders, supply chain interfaces, and information sources. The result is a condition of decision fragmentation, where decision-making is distributed across the lifecycle but not effectively integrated (Tennakoon et al. 2023; Zhang et al. 2024).

At the same time, decisions in OSC projects involve more than technical and cost trade-offs. They require project teams to navigate broader environmental, social, and governance (ESG)-oriented value trade-offs that increasingly shape project planning, procurement, delivery, and reporting, including circular economy considerations in modular construction contexts (United Nations Environment Programme 2024; Senaratne, Saysanavongpheth, and Samaratunga 2025). These value implications cannot be fully captured through conventional project performance metrics alone, because they extend across lifecycle stages and include carbon, social impact, stakeholder, transparency, and governance considerations (Adewumi, Opoku, and Dangana 2024). ESG therefore provides a structured basis for organising broader value dimensions within OSC decision-making, particularly where project decisions involve trade-offs that extend beyond technical and cost considerations. For decision support, the key challenge is therefore not only to assess ESG performance after decisions are made, but to make ESG-oriented value trade-offs visible and usable within the decision-making process itself.

Although ESG was originally developed mainly at the organisational level, recent construction research has increasingly examined its relevance to projects through sustainability assessment, ESG target demonstration, and reporting-oriented frameworks (Adewumi, Opoku, and Dangana 2024). However, this body of work still provides limited guidance on how ESG-oriented value trade-offs can be incorporated into project-level decision-making processes, particularly in OSC projects where decisions are distributed across lifecycle stages and depend on heterogeneous sources of knowledge. Recent developments in BIM-enabled environments and digital twins have strengthened lifecycle information integration and data-driven decision support in construction (Omrany et al. 2023; Revolti et al. 2024), but they remain less explicit about how ESG-oriented value trade-offs are structured and mobilised within specific project decision contexts. This limitation points to the need for decision support approaches that can integrate lifecycle-related knowledge, ESG-oriented value trade-offs, and project-context knowledge in a structured way (Zhang et al. 2024).

To address this gap, this paper develops a conceptual architecture for a lifecycle-integrated decision support system (DSS) tailored to support ESG-oriented decision-making in OSC projects. The architecture structures knowledge around lifecycle stages, decision contexts, and knowledge domains. This decision-support problem requires more than a static knowledge repository or a predefined rule base, because ESG-oriented decision-making in OSC depends on heterogeneous and often unstructured knowledge, including lifecycle process knowledge, ESG-oriented value trade-offs, project constraints, stakeholder requirements, and prior project experience. These knowledge elements cannot be fully predefined as fixed decision rules because their relevance depends on the lifecycle stage and the specific decision context. Retrieval-augmented generation (RAG) is therefore incorporated as the mechanism for decision context-based knowledge retrieval and synthesis (Wu et al. 2025; Gao et al. 2023). RAG enables relevant knowledge to be retrieved from a structured knowledge base and synthesised into decision-support outputs for specific project situations. In this study, RAG is treated as the operational mechanism through which lifecycle, ESG-oriented, and project-context knowledge can be mobilised within the proposed DSS architecture. The proposed architecture provides a structured response to decision fragmentation in OSC and establishes a conceptual foundation for future RAG-enabled decision support tools.

2 LITERATURE REVIEW

2.1 Decision-making in Off-site Construction Projects

OSC has been widely recognised as a production-oriented approach that reorganises construction activities across design, manufacturing, logistics, and on-site assembly stages. Recent OSC research continues to emphasise that this reorganisation creates a delivery system in which design, production, supply chain, logistics, and site operations are closely connected rather than independently managed activities (e.g., Doan et al. 2025; Kosbar et al. 2023; Widanage and Kim 2024). In such a system, decisions made during design and planning can shape manufacturing efficiency, transportation feasibility, on-site assembly, and downstream operational outcomes. Decision-making in OSC therefore needs to be understood as lifecycle-dependent, with consequences that extend beyond the stage in which a decision is made.

A growing body of recent OSC literature has examined these interdependencies through coordination, knowledge management, supply chain integration, BIM–DfMA integration, project management capability, and external adoption barrier perspectives (e.g., Ginigaddara et al. 2024; Nesarnobari et al. 2025; Tennakoon et al. 2023; Zhang et al. 2024; Olayiwola et al. 2025). This literature shows that OSC performance depends not only on technical production efficiency, but also on the ability to coordinate project teams, integrate information, manage supply chain interfaces, and reuse knowledge across design, production, and delivery processes.

However, this literature still provides limited support for decision-making as an integrated lifecycle process. Existing studies offer valuable insights into coordination mechanisms, supply chain uncertainties, knowledge management requirements, digital integration, and capability needs, but they do not fully explain how decision-relevant knowledge should be structured and mobilised when project teams face specific decision situations. As a result, decision-making in OSC projects remains vulnerable to stage-based optimisation, where decisions are made within functional or lifecycle boundaries while their consequences extend across the project lifecycle. This limitation points to the need for decision support approaches that can connect lifecycle interdependencies, distributed knowledge, and project-specific decision contexts.

2.2 Decision Support Systems in Construction

DSS in construction have evolved from rule-based and model-driven approaches to more data-enabled, integrated, and AI-assisted environments (e.g., Baghdadi 2025; Omrany et al. 2023; Waqar 2024). Traditional DSS typically rely on predefined rules, optimisation models, simulation techniques, or structured datasets to support specific types of decisions, including scheduling, cost estimation, resource allocation, safety management, and sustainability assessment (e.g., Waqar 2024). These approaches remain useful where decision variables and evaluation criteria can be specified in advance, but they are less suited to decision situations that require the interpretation and integration of heterogeneous project knowledge across changing project contexts (e.g., Waqar 2024; Wu et al. 2025).

Recent developments in BIM-enabled environments, digital twins, and AI-supported decision systems have expanded the capacity of construction decision support by improving data integration, lifecycle information management, and dynamic monitoring. Digital twin research, for example, highlights the potential of integrating physical and digital information to support lifecycle-integrated monitoring, prediction, and decision-making in construction and asset management (e.g., Baghdadi 2025; Omrany et al. 2023; Revolti et al. 2024). Similarly, recent work on large language models, RAG, and hybrid search has shown growing interest in improving construction information retrieval, question answering, and access to domain-specific knowledge (e.g., Wu et al. 2025; He et al. 2025).

Despite these advances, a gap remains between data integration and decision-context-specific knowledge support. Many existing DSS and digital decision environments are stronger in representing structured data, models, and workflows than in retrieving, connecting, and synthesising heterogeneous and largely unstructured knowledge for specific project decision situations. This limitation is particularly important for OSC projects, where decision requirements vary according to lifecycle stage, project configuration, delivery strategy, stakeholder arrangement, and ESG-oriented value trade-offs. As a result, while DSS in construction have improved data integration and analytical capability, further work is needed to support decision-making that is lifecycle-sensitive, context-spedific, and capable of mobilising knowledge across technical, organisational, and value-related domains.

2.3 ESG in Project-level Decision-making

ESG-oriented value trade-offs are increasingly relevant to project-level decision-making in construction. Decisions made during design, procurement, and delivery planning often involve trade-offs between cost, time, technical feasibility, environmental performance, social impact, stakeholder expectations, and governance responsibilities. Recent sustainability and ESG research in construction shows growing attention to how environmental, social, and governance considerations are assessed, reported, and demonstrated within construction projects and organisations, while modular construction research has also begun to examine circular economy challenges and strategies in the Australian context (Hernandez Aros et al. 2025; Adewumi, Opoku, and Dangana 2024; Senaratne, Saysanavongpheth, and Samaratunga 2025). In OSC projects, these trade-offs are particularly important because decisions made in one lifecycle stage can influence value outcomes across design, manufacturing, logistics, on-site assembly, and operation.

Much of the recent construction ESG and sustainability literature remains oriented towards assessment, reporting, and performance demonstration. Sustainability assessment frameworks can support construction organisations in demonstrating ESG targets, but recent studies also show that such frameworks often provide uneven coverage of environmental, social, and governance dimensions, particularly in relation to governance considerations (Adewumi, Opoku, and Dangana 2024). Similarly, recent reviews of sustainability reporting in construction highlight the development of reporting models, metrics, and frameworks, including ESG-oriented approaches, while also showing that the field remains strongly focused on how sustainability information is disclosed, measured, and standardised (Hernandez Aros et al. 2025). These studies provide important insights into ESG performance, but they offer limited guidance on how ESG-oriented value trade-offs are structured within the decision-making process itself.

This creates an important gap for OSC decision support. In OSC projects, ESG-oriented value trade-offs are not simply final performance outcomes; they are shaped through decisions about design standardisation, procurement choices, manufacturing methods, logistics planning, assembly processes, information responsibilities, and stakeholder coordination. Recent work mapping ESG management indicators to construction activities suggests that ESG information is distributed across project activities, documents, and information sources (Gong et al. 2024). Without mechanisms to integrate ESG-oriented value trade-offs into decision support, these considerations risk remaining implicit, fragmented, or applied retrospectively. This limitation points to the need for decision support approaches that can incorporate ESG-oriented value trade-offs as part of the decision structure itself.

3 RESEARCH DESIGN

This study adopts a problem-driven conceptual design approach to develop a lifecycle-integrated DSS architecture for supporting ESG-oriented decision-making in OSC projects, following the principles of design science research (Gregor and Hevner 2013). The research design is shaped by the nature of the problem addressed in this paper: OSC decisions are distributed across lifecycle stages, while the knowledge required to support these decisions is fragmented across project teams, domains, and information sources. The aim is therefore to structure this lifecycle-distributed decision-support problem and translate it into a coherent system architecture.

The design process is informed by existing knowledge drawn primarily from peer-reviewed journal literature on OSC, lifecycle-integrated project organisation, construction decision support systems, ESG-oriented value trade-offs, and RAG. Relevant industry and practice-oriented documentary sources were also consulted to clarify contemporary OSC processes, decision situations, and knowledge contexts. The study adopts a conceptual synthesis approach to connect these bodies of knowledge and derive the architecture requirements needed to support lifecycle-integrated and ESG-oriented decision-making in OSC projects.

The architecture is developed through a three-stage design logic. First, problem structuring identifies the key features of OSC decision-making, emphasising that decisions are distributed across lifecycle stages while the knowledge required to support them is fragmented across stakeholders and domains. Second, requirement derivation translates these characteristics into system requirements, including the need to integrate lifecycle knowledge, decision context, and ESG-oriented value trade-offs within a unified decision support logic. Third, architecture synthesis organises these requirements into a system structure comprising integrated knowledge sources, a lifecycle-integrated knowledge base, and a RAG-enabled decision support engine.

The design logic of the proposed architecture is illustrated in Figure 1.

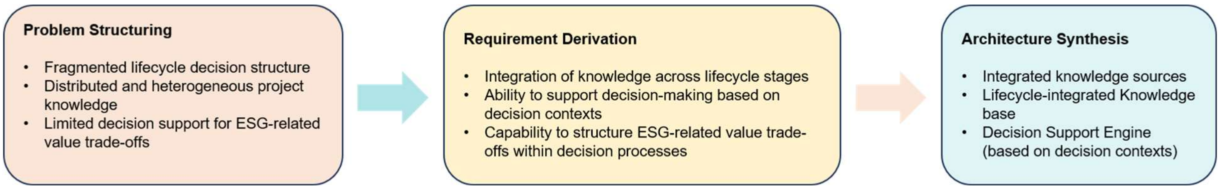

Figure 1 Design process of the Lifecycle-integrated DSS Architecture

4 Results and Analysis

4.1 Overview of the Lifecycle-integrated Architecture

This study develops a lifecycle-integrated DSS architecture for supporting ESG-oriented decision-making in OSC projects. As shown in Figure 2, the architecture is the main conceptual output of the study and translates the design logic of problem structuring, requirement derivation, and architecture synthesis into a system-level structure for organising and mobilising decision-relevant knowledge across OSC lifecycle stages.

The architecture consists of three connected components: knowledge sources, a lifecycle-integrated knowledge base, and a RAG-enabled decision support engine. The knowledge sources capture three types of decision-relevant knowledge: OSC project lifecycle knowledge, ESG-oriented knowledge, and decision context knowledge. OSC project lifecycle knowledge concerns stage-specific processes and cross-stage interdependencies across design, manufacturing, logistics, on-site assembly, and operation. ESG-oriented knowledge concerns value trade-offs associated with environmental performance, resource efficiency, social value, stakeholder impacts, transparency, responsibility allocation, and governance requirements. Decision context knowledge concerns project characteristics, constraints, delivery arrangements, stakeholder configurations, and available capabilities.

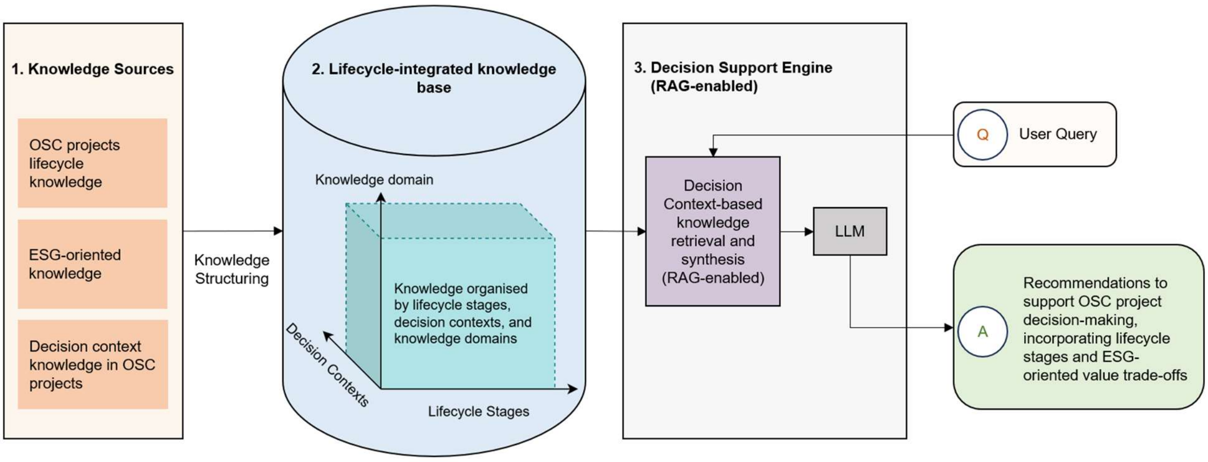

Figure 2 The Lifecycle-integrated Decision Support System Architecture

The lifecycle-integrated knowledge base organises these heterogeneous knowledge sources through lifecycle stages, decision contexts, and knowledge domains. Lifecycle stages locate knowledge within the temporal progression of OSC delivery, decision contexts define the situations in which decisions arise, and knowledge domains classify decision issues such as design coordination, manufacturing feasibility, logistics planning, assembly sequencing, information responsibility, risk management, and ESG-oriented value implications.

The RAG-enabled decision support engine retrieves and synthesises relevant knowledge from the lifecycle-integrated knowledge base in response to specific project decision situations. User queries are interpreted in relation to lifecycle stage and decision context, allowing the engine to generate decision-support outputs that are aligned with lifecycle implications, project-specific conditions, and ESG-oriented value trade-offs.

4.2 Integration Logic of the Proposed Architecture

The integration logic of the proposed architecture lies in how it connects lifecycle interdependencies, decision contexts, and ESG-oriented value trade-offs within a single decision-support structure. Rather than treating project decisions as isolated stage-based choices, the architecture positions each decision situation within a wider lifecycle and project context. This is important in OSC projects because decisions made in one stage often create consequences for later stages, stakeholders, and value outcomes.

First, the architecture integrates lifecycle knowledge by linking stage-specific information with cross-stage implications. A decision raised during the design stage, for example, can be connected to manufacturing repeatability, logistics feasibility, on-site assembly requirements, and operational consequences. This allows project teams to consider downstream implications at the point where decisions are formed, rather than after consequences have already emerged.

Second, the architecture integrates project context into decision support. The same type of decision can require different knowledge depending on project configuration, delivery strategy, stakeholder arrangement, supply chain condition, site constraint, and available capability. By structuring knowledge around decision contexts, the architecture avoids treating decision support as generic guidance and instead enables context-specific retrieval and synthesis.

Third, the architecture embeds ESG-oriented value trade-offs within decision-relevant knowledge. ESG-oriented knowledge is not added as a separate post-decision assessment layer. Instead, it is linked to lifecycle stages, decision contexts, and knowledge domains so that environmental, social, and governance implications can be considered as part of the decision-support process itself.

Through this integration logic, the RAG-enabled engine does not simply search for isolated information or calculate an optimal option. It retrieves and synthesises lifecycle, ESG-oriented, and project-context knowledge to make relevant trade-offs, risks, dependencies, and information requirements visible for project teams. The architecture therefore addresses decision fragmentation by transforming dispersed project knowledge into context-specific decision support.

4.3 Illustrating the Use of the Architecture

To illustrate the use of the proposed architecture, consider a typical OSC housing project in which the project team needs to decide whether to adopt a higher level of module design standardisation during the design stage. Although the decision is made early, it can affect manufacturing repeatability, logistics planning, on-site assembly, material use, rework risk, stakeholder requirements, and downstream information responsibilities. Within the proposed architecture, this query would be interpreted as a design-stage decision context. The RAG-enabled decision support engine would retrieve relevant knowledge from the lifecycle-integrated knowledge base, including design coordination requirements, manufacturing constraints, logistics considerations, assembly implications, and ESG-oriented value trade-offs such as material efficiency, waste reduction, site safety, stakeholder value, and governance responsibility. The synthesised output would not prescribe a single optimal option, but would identify relevant benefits, trade-offs, risks, and information requirements. For example, it may indicate that design standardisation can improve manufacturing repeatability and reduce material waste, while requiring earlier coordination with logistics and assembly teams and clearer responsibility for design changes across design, manufacturing, and site teams. This illustrative scenario shows how the architecture connects lifecycle implications, ESG-oriented value trade-offs, and project-context knowledge within a single decision-support process.

5 DISCUSSION

5.1 Implications for Decision-making in OSC projects

The proposed architecture has implications for how decision support in OSC projects is conceptualised. It shifts attention from supporting isolated decisions within individual project stages to supporting decision situations shaped by lifecycle consequences, project-specific conditions, and ESG-oriented value trade-offs. This responds to recent OSC research showing that OSC performance depends not only on production efficiency, but also on knowledge management, supply chain coordination, digital integration, and project management capabilities across the delivery process (e.g., Ginigaddara et al. 2024; Zhang et al. 2024; Nesarnobari et al. 2025).

The key implication is that lifecycle interdependencies should be treated as part of the decision-support structure. Recent OSC studies show that design, production, logistics, supply chain, and site operations are closely connected across project stages and organisational interfaces (e.g., Kosbar et al. 2023; Tennakoon et al. 2023; Zhang et al. 2024). In OSC projects, decisions are not only technical choices made within a single stage. They also create downstream consequences for production feasibility, supply chain coordination, logistics planning, assembly requirements, information responsibilities, and project value outcomes. By organising decision-relevant knowledge around lifecycle stages, decision contexts, and knowledge domains, the proposed architecture provides a way to make these cross-stage implications visible at the point of decision-making.

A second implication is that ESG-oriented value trade-offs need to be embedded within decision support rather than treated as external assessment criteria. Construction ESG and sustainability research remains strongly oriented towards assessment, reporting, and performance demonstration, with less attention to how ESG-oriented value trade-offs inform decision formation (e.g., Adewumi, Opoku, and Dangana 2024; Hernandez Aros et al. 2025). The proposed architecture takes a different position by linking ESG-oriented knowledge to lifecycle stages and decision contexts. This allows environmental, social, and governance implications to inform how decisions are framed, compared, and discussed before project actions are finalised.

A third implication concerns the project-specific nature of OSC decision support. OSC projects differ in their delivery strategies, stakeholder arrangements, supply chain conditions, site constraints, and available capabilities. As a result, generic decision guidance or fixed decision pathways are insufficient for many project situations. By positioning decision support as a problem of lifecycle knowledge structuring and context-specific knowledge integration, the proposed architecture provides a basis for more adaptive and project-sensitive decision support in OSC delivery.

5.2 Positioning within Existing Literature

This study contributes to three related bodies of literature: OSC project delivery, construction decision support systems, and ESG-oriented construction research. In relation to OSC literature, the study extends existing work on coordination, knowledge management, supply chain integration, BIM–DfMA integration, and project management capability by focusing on how decision-relevant knowledge can be structured and mobilised across lifecycle decision contexts (e.g., Ginigaddara et al. 2024; Widanage and Kim 2024). The contribution is not to identify another set of OSC success factors, but to propose an architecture through which dispersed lifecycle knowledge can be organised for decision support.

In relation to construction DSS literature, the study shifts attention from data integration and model-based analysis towards context-specific knowledge integration. Existing DSS, digital twin, and AI-assisted approaches have strengthened the ability to integrate data, monitor project conditions, and support analytical decision tasks (e.g., Omrany et al. 2023; Waqar 2024; Wu et al. 2025). However, OSC decision support also requires the retrieval and synthesis of heterogeneous and partly unstructured knowledge, including project constraints, stakeholder requirements, lifecycle implications, and ESG-oriented value trade-offs. The proposed RAG-enabled architecture addresses this gap by positioning retrieval and synthesis as a central mechanism of decision support.

In relation to ESG-oriented construction research, the study moves beyond assessment and reporting by positioning ESG-oriented value trade-offs as part of the decision-support structure. Rather than treating ESG as a set of indicators to be measured after decisions are made, the proposed architecture embeds ESG-oriented knowledge within lifecycle stages, decision contexts, and knowledge domains. This reframes ESG-oriented decision support in OSC as a problem of lifecycle knowledge structuring and context-specific knowledge integration.

6 CONCLUSION

This study proposed a lifecycle-integrated DSS architecture for supporting ESG-oriented decision-making in OSC projects. The study responded to the problem that decision-relevant knowledge in OSC is often fragmented across lifecycle stages, project teams, and knowledge domains, while ESG-oriented value trade-offs are often considered outside the decision-support process.

The proposed architecture integrates three elements: heterogeneous knowledge sources, a lifecycle-integrated knowledge base, and a RAG-enabled decision support engine. Its contribution lies in showing how lifecycle knowledge, project-context knowledge, and ESG-oriented knowledge can be structured and mobilised to support context-specific project decisions. In doing so, the study reframes ESG-oriented decision support in OSC as a problem of lifecycle knowledge structuring and context-specific knowledge integration.

Several limitations should be acknowledged. First, the study develops a conceptual architecture rather than a fully implemented DSS prototype. As a result, the architecture has not yet been empirically validated through case studies, expert evaluation, user testing, or system-based performance assessment. Second, the proposed knowledge structure is developed through conceptual synthesis of existing literature and documentary sources. Further work is therefore required to refine how lifecycle stages, decision contexts, knowledge domains, and ESG-oriented value trade-offs should be represented, classified, and connected in practice. Third, while the RAG-enabled decision support engine is proposed as a mechanism for decision context-based knowledge retrieval and synthesis, its technical implementation remains outside the scope of this study. Its retrieval quality, response reliability, usability, and fit with real OSC project workflows still need to be tested.

Future research can build on this work in several directions. First, the proposed architecture should be developed into a prototype system and evaluated through case studies, expert validation, and user testing with OSC project stakeholders. Second, further research is needed to examine how knowledge should be formalised and represented within such systems, particularly in relation to lifecycle stages, decision contexts, knowledge domains, and ESG-oriented value trade-offs. This includes exploring ontology development, structured knowledge modelling, metadata design, and integration of heterogeneous data and document sources. Third, future studies can investigate how the proposed architecture can be integrated with existing construction digital platforms, such as BIM-enabled environments and digital twins, to support practical deployment and industry adoption. Finally, empirical research is needed to understand how project teams interact with such systems and how decision support influences project outcomes, including coordination, rework, decision transparency, and project-level value.

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