

OntoKSD: A Semantic Model for Competence Traceability in Computing Education

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Abstract. *Competence-based Computing Education requires mechanisms capable of connecting curricular specifications, instructional tasks, assessment participation, and learning evidence. However, these elements are often represented in isolation, limiting competence traceability. This paper presents OntoKSD, an ontology-based model that represents competences through Knowledge–Skill–Disposition (K–S–D) structures and connects competence specifications to instructional tasks, evidence artifacts, and proficiency interpretations. An evaluation conducted across undergraduate and integrated secondary-level Computing Education scenarios indicates that OntoKSD supports the reconstruction of competence–task–evidence relations and comparisons between curricular expectations and proficiency interpretations.*

1. Introduction

Competence-based education (CBE) has become a central orientation in Computing Education because it seeks to align curricular structures, learning outcomes, assessment practices, and professional expectations around what students are expected to know and perform in authentic contexts [Gervais 2016, Curry and Docherty 2017]. This orientation is reflected in recent Computing Education curricular frameworks, particularly Computing Curricula 2020 (CC2020), CS2023, and IS2020, which describe competences as combinations of knowledge, skills, and dispositions (K–S–D) mobilized in task performance [Force 2020, Kumar et al. 2024, Force et al. 2021]. Brazilian initiatives, including the Computing Education Reference Guidelines, the revised National Curricular Guidelines for Computing, and the Computing complement to the BNCC, similarly reinforce competence-oriented curriculum organization and assessment [Sociedade Brasileira de Computação 2017, Conselho Nacional de Educação 2023, Sociedade Brasileira de Computação 2022].

Operationalizing these principles remains challenging. Competence specifications, instructional tasks, learner participation, assessment records, evidence, and proficiency interpretations are commonly distributed across pedagogical projects, course plans, rubrics, reports, and learning management systems. Studies in Brazilian Computing Education likewise report difficulties in consistently relating competences to curricular structures, instructional tasks, and assessment practices [Romeiro et al. 2025, Ferreira et al. 2024]. This fragmentation creates a *traceability gap*: the difficulty of explicitly reconstructing how competences are defined, activated, evidenced, and interpreted across instructional and assessment contexts.

This problem is particularly relevant in Computing Education, where competence demonstration may involve heterogeneous artifacts such as source code, formal models, simulations, and technical reports. Learning tasks may also activate multiple competences and produce shared evidence while requiring learner-specific proficiency interpretations.

Ontology-based approaches have supported competence modeling, management, interoperability, learner profiling, and proficiency description across learning and professional ecosystems [Miranda et al. 2016, Paquette et al. 2021, Calhau et al. 2024]. However, most remain domain-independent or oriented toward organizational settings and provide limited integrated support for instructional activation, learner participation, assessment evidence, and competence-related trace reconstruction in Computing Education.

The research question guiding this work is:

How can competence structures, instructional tasks, assessment evidence, and learner participation in Computing Education be semantically connected to support the explicit reconstruction and querying of competence-related educational traces?

To address this question, this paper presents and evaluates OntoKSD, a competence-centered semantic model that integrates competence specifications, instructional contexts, learner participation, educational evidence, and proficiency interpretations. The evaluation examines whether these relations can be coherently represented, retrieved, and reconstructed in realistic Computing Education scenarios. It focuses on representational adequacy and semantic retrieval rather than educational effectiveness, automated competence assessment, or learning diagnosis.

2. Related Work

Research related to OntoKSD can be organized into three areas: (i) computational approaches for competence representation, (ii) computing curriculum and competence frameworks, and (iii) evidence-oriented educational traceability. Existing approaches provide important foundations for competence-based educational modeling, but typically address competence representation, curriculum guidance, and educational evidence separately or only partially, offering limited support for integrated semantic traceability in Computing Education.

2.1. Computational Approaches for Competence Representation

Ontology-based approaches have been employed to represent competences in educational and organizational contexts, supporting learner modeling, personalization, interoperability, and competence management. Paquette [Paquette et al. 2021] explored ontology-based competence modeling for learning and knowledge management environments, whereas Miranda et al. [Miranda et al. 2016] proposed a semantic model focused on organizational competence management, interoperability, and competence gap analysis.

More recently, Core-O introduced explicit ontological distinctions among competence, capability, manifestation, proficiency, and evidence, providing a foundational, domain-independent semantic framework for competence representation across professional and learning ecosystems [Calhau et al. 2021, Calhau et al. 2023, Calhau et al. 2024].

2.2. Computing Curriculum and Competence Frameworks

Computing curriculum frameworks provide the normative basis for competence specification. CC2020 defines competence as the integration of knowledge, skills, and dispositions, while IS2020 and CS2023 relate competence-oriented structures to knowledge areas, learning outcomes, cognitive expectations, and task-centered design [Force 2020, Force et al. 2021, Kumar et al. 2024]. Bloom’s revised taxonomy and Computing-specific adaptations further characterize the cognitive expectations associated with learning and assessment activities [Anderson et al. 2001, ACM CCECC 2023, Thompson et al. 2008]. Although these frameworks provide essential curricular guidance, they do not formally represent relations among competences, learning activities, evidence, and proficiency.

2.3. Evidence and Educational Traceability

Competence-based education requires competences to be demonstrated through observable performance rather than treated merely as curricular statements [Gervais 2016, Mulder 2017]. Accordingly, recent approaches increasingly represent evidence, manifestation, and proficiency [Calhau et al. 2024], but still provide only partial support for integrating competence specification, contextual activation, learner participation, evidence production, and proficiency interpretation, particularly in Computing Education scenarios involving heterogeneous artifacts and collaborative activities.

Taken together, these approaches provide complementary foundations for curriculum specification, evidence representation, and proficiency modeling. However, they offer limited integrated support for reconstructing the relations among competences, instructional activation, learner participation, evidence, and proficiency in Computing Education. OntoKSD addresses this traceability problem by combining these dimensions within a unified semantic model.

Table 1 compares only the explicit representational scope reported in the primary publications. *Explicit* denotes a first-class construct; *Partial*, incomplete support or the need for extensions; *Conceptual*, a non-computational curricular or conceptual description; and *Not Explicit*, no identified explicit representation. The comparison does not assess implementation quality, completeness, or overall superiority.

Table 1. Comparison of the explicit representational capabilities reported by related approaches and OntoKSD

Representational Feature	Paquette	Miranda	Core-O	CC2020/CS2023	OntoKSD
Structured representation	Explicit	Explicit	Explicit	Conceptual	Explicit
K–S–D decomposition	Partial	Partial	Partial	Conceptual	Explicit
Bloom-aligned KS relation	Partial	Not Explicit	Not Explicit	Conceptual	Explicit
Computing Education alignment	Not Explicit	Not Explicit	Not Explicit	Conceptual	Explicit
Task-centered activation	Partial	Partial	Partial	Conceptual	Explicit
Assessment participation	Not Explicit	Partial	Partial	Not Explicit	Explicit
Evidence representation	Partial	Partial	Explicit	Not Explicit	Explicit
Proficiency interpretation	Partial	Partial	Explicit	Not Explicit	Explicit
Competence–task–evidence reconstruction	Not Explicit	Partial	Partial	Not Explicit	Explicit

3. Method

This study follows a Design Science Research (DSR) approach, in which a scientific artifact is designed and evaluated in response to a relevant problem [Hevner et al. 2004,

Peffers et al. 2007]. The artifact investigated in this paper is OntoKSD, a semantic model for competence traceability in Computing Education. Its development was informed by the NeOn methodology [Suárez-Figueroa et al. 2012], particularly for requirements elicitation, vocabulary reuse, and iterative refinement.

The research comprised three stages: requirements derivation, model construction, and evaluation. Ontology requirements were derived from three complementary sources: (i) a Systematic Mapping Study on competence ontologies and semantic representations, (ii) Computing curricular frameworks such as CC2020, CS2023, and IS2020, and (iii) iterative analysis of competence specifications, instructional tasks, assessment situations, and educational artifacts from undergraduate and secondary Computing Education. Together, these sources informed the ontology requirements for competence structure, instructional activation, evidence, proficiency, and traceability. These requirements guided the conceptual design of OntoKSD and were subsequently formalized as ontology classes, properties, and semantic relations.

OntoKSD was developed through conceptual modeling and OWL 2 implementation in Protégé [Musen 2015]. Its design formalized requirements for K–S–D competence structures, cognitive expectations, instructional activation, assessment participation, evidence, and proficiency. gUFO [Almeida et al. 2020] informed the conceptual modeling, while SKOS [W3C 2009] supported controlled vocabularies and curricular classifications.

The evaluation comprised three complementary activities: logical verification, educational scenario instantiation, and retrieval-based analysis. Logical verification examined ontology consistency before and after the instantiation of educational scenarios. The instantiated ontology was subsequently evaluated through Competency Questions (CQs), which specify the information an ontology should be able to retrieve [Grüninger and Fox 1995, Suárez-Figueroa et al. 2012]. These CQs were operationalized as SPARQL queries to assess whether OntoKSD could consistently reconstruct the semantic relations required for competence traceability across instructional and assessment contexts.

4. OntoKSD: A Model for Competence Traceability

In this paper, competence traceability refers to the semantic reconstruction of relations among competence specifications, learning tasks, learner participation, educational evidence, and proficiency information. Rather than merely retrieving linked records, it relies on the explicit semantic representation of competence-related entities and their roles across instructional and assessment contexts.

OntoKSD provides this shared semantic layer by distinguishing competence specification, contextual activation, evidence production, and proficiency attribution within a coherent computational model. Figure 1 presents the minimal semantic subset of OntoKSD required to reconstruct competence–task–evidence relations in the instantiated educational scenarios.

OntoKSD distinguishes abstract competence specifications from their contextual activation, evidence, and proficiency interpretations. Competences are organized through K–S–D structures and Knowledge–Skill relations, which associate knowledge elements with expected cognitive processes, including Bloom-aligned expectations.

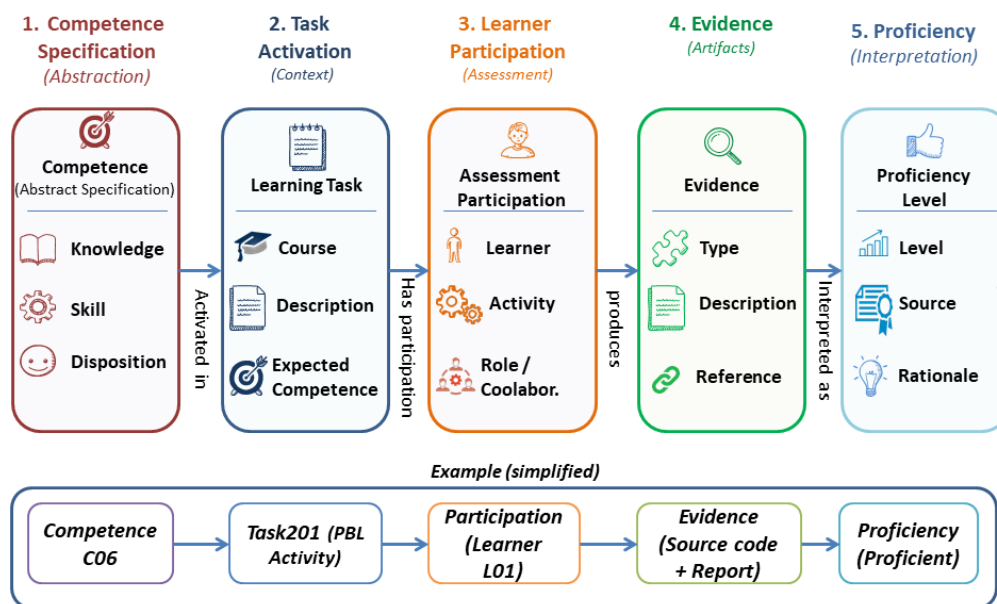


Figure 1. Minimal semantic subset of OntoKSD for competence traceability.

CompetenceActivation connects competences to learning tasks and assessment situations in which they are expected or required, preserving the distinction between curricular competence expectations and their contextual activation. Competence demonstration is represented through learner-specific *AssessmentParticipation* relations, which connect assessment situations to generated evidence and proficiency interpretations. Evidence may include artifacts such as source code, formal models, diagrams, proofs, reports, and written explanations produced during task execution.

5. Ontology Evaluation and Results

This section evaluates OntoKSD as an ontology engineering artifact, examining its representational adequacy, semantic consistency, and retrieval capability through educational scenario instantiation and Competency Question execution. The evaluation investigates whether the ontology can coherently represent and reconstruct competence-related educational traces involving competence structures, Knowledge–Skill relations, learning tasks, learner participation, evidence, and proficiency information. It does not assess learning effectiveness, assessment validity, teacher adoption, or educational decision-making.

5.1. Educational Context and Scenario

The study was conducted across two Computing Education contexts: an undergraduate Theory of Computation course involving three instructors and four teaching assistants, and integrated secondary-level courses in Algorithms and Programming Languages involving five instructors.

The evaluated scenarios combined prospective and retrospective uses of OntoKSD. Two Theory of Computation offerings were explicitly organized using competence-oriented structures derived from the ontology, whereas the remaining cases reconstructed competence specifications and activation relations from authentic instructional artifacts. To reduce dependence on post-hoc assumptions, these reconstructions were iteratively discussed with instructors from the evaluated contexts.

The instantiated dataset comprised approximately **57** competences, **168** Knowledge–Skill relations, **19** learning tasks, **124** participation records, and **100** evidence items, including automaton diagrams, JFLAP simulation files, formal proofs, source code, technical reports, and assessment submissions. Collaborative activities produced shared evidence while preserving learner-specific proficiency attribution.

Competence specifications instantiated in the evaluated scenarios were previously produced through the Competency Specification Process (CSP), an iterative task-centered process for eliciting and refining competence specifications from authentic instructional activities. CSP combines instructional task analysis, collaborative review, iterative refinement, and cross-task consolidation to improve competence consistency and reuse.

During CSP application, preliminary competence specifications were reviewed by instructors and Computing Education researchers. The review focused on competence boundaries, knowledge granularity, Bloom-aligned cognitive expectations, action-verb selection, and opportunities for competence reuse or specialization. Divergences were resolved through successive refinement cycles until consensus was achieved.

Because CSP emphasizes collaborative refinement rather than independent coding, formal inter-rater agreement measures were not computed. Instead, competence specifications were iteratively discussed and revised until consensus was reached among the participants.

Accordingly, the collaboratively validated competence specifications served as input for ontology instantiation and evaluation, whereas OntoKSD remained the artifact under investigation.

The instantiated ontology comprised **133** classes, **240** object and data properties, and more than **89,000** RDF triples, including schema-level structures and scenario-specific educational records. All educational records were anonymized prior to analysis and used exclusively for artifact evaluation. Figure 2 illustrates how OntoKSD reconstructs an instantiated competence trace from the *Task201 – Drone Monitoring* scenario.

To strengthen ecological validity, OntoKSD was operationalized in a real Moodle environment for a Theory of Computation course. Competence specifications were imported through Moodle’s competency framework, associated with the course, and linked to assessment activities whose submissions (e.g., technical reports and JFLAP simulation files) served as evidence artifacts. Moodle provided the operational environment, whereas OntoKSD supplied the semantic layer connecting competence specifications, instructional tasks, learner participation, evidence, and proficiency. Rather than replacing Moodle’s competency framework, OntoKSD complements it with explicit semantic relations supporting competence traceability and ontology-based querying.

This operationalization also revealed representational limitations of Moodle’s competency framework. Although Moodle supports competence catalogs, activity associations, competence assessment, and proficiency assignment, it does not explicitly represent K–S–D structures, Bloom-aligned Knowledge–Skill relations, competence activation by instructional tasks, assessment participation, or fine-grained evidence and proficiency attribution for individual competence constituents. Consequently, the Moodle implementation should be viewed as an operational approximation rather than a complete realization of OntoKSD.

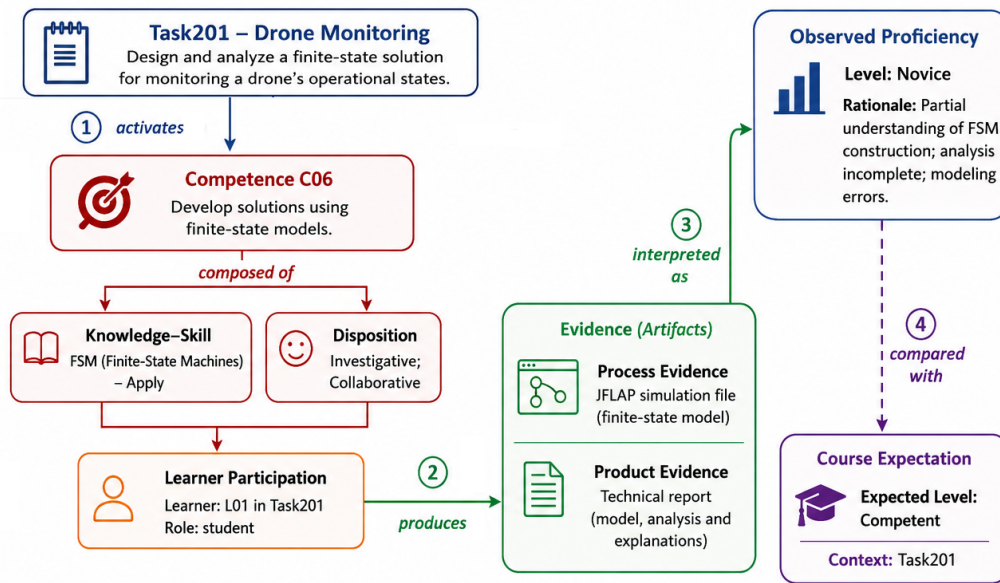


Figure 2. Instantiated competence reconstruction linking competence specification, K–S–D constituents, participation, evidence, and proficiency interpretation in the *Task201 – Drone Monitoring* scenario.

5.2. Evaluation Procedures

The complete evaluation framework comprised 42 Competency Questions implemented through 58 SPARQL queries. All queries successfully answered their corresponding Competency Questions, reconstructing the targeted relations and returning results consistent with the instantiated educational records without logical inconsistencies after reasoning. The evaluation covered competence structure, Knowledge–Skill relations, activation mechanisms, assessment participation, evidence provenance, proficiency interpretation, learner profiles, curricular alignment, and competence gap analysis. Due to space limitations, this paper reports a representative subset focused on the traceability capabilities most directly related to the research question. Table 2 summarizes five representative CQ categories from this evaluation framework.

Table 2. Representative subset of Competency Questions used in the evaluation

CQ	Dimension	Query verifies	Observed result
CQ1	Composition	K–S–D components associated with a competence.	Knowledge, skill, and disposition elements identified for the selected competence.
CQ2	Knowledge–Skill	Knowledge–Skill relations associated with a competence.	Knowledge elements connected to Bloom-aligned cognitive expectations and action verbs.
CQ3	Activation	Learning tasks that activate a competence.	Learning tasks identified through competence activation relations.
CQ4	Evidence	Evidence associated with competence demonstration.	Evidence items and learner participation records associated with competence demonstration.
CQ5	Traceability	Integrated competence traceability.	Connected retrieval involving competence structure, Knowledge–Skill relations, task activation, learner participation, evidence, and proficiency information.

The instantiated scenarios preserved the assessment structures originally adopted in the evaluated educational contexts, maintaining the relation between instructional tasks,

learner participation, and educational evidence. This choice favored realistic competence-based educational situations instead of artificially isolated competence measurements.

5.3. Traceability Results

The instantiated scenarios supported all reconstruction procedures defined by the Competency Questions. Figure 2, derived from the *Task201 – Drone Monitoring* scenario in the Theory of Computation course, illustrates an instantiated competence reconstruction involving process- and product-oriented assessment artifacts.

Table 3 summarizes the corresponding reconstructed competence record, illustrating how competence specifications, learner participation, evidence, and proficiency attribution are connected within a single semantic structure.

Table 3. Concrete instantiated competence reconstruction from Task201

Element	Instantiated value
Competence	C06 – Develop problem-solving solutions using finite-state machines
Knowledge	Finite-state machines
Bloom expectation	Apply
Learning task	Task201 – Drone Monitoring
Participation	Task201_G02_L01_OfficialParticipation
Evidence	Task201 G01 ProcessEvidence and Task201 G01 ProductEvidence
Score	4.50
Proficiency interpretation	Novice Level

Beyond competence reconstruction, the instantiated scenarios supported comparisons between course-level proficiency requirements and learner performance derived from participation records and assessment evidence. Figure 3 illustrates a SPARQL CONSTRUCT query reconstructing a proficiency mismatch by connecting the course competence specification, learner profile, evidenced competence, and the corresponding required and observed proficiency levels. In the illustrated scenario, the required *Competent* level contrasts with the evidenced *Novice* level.

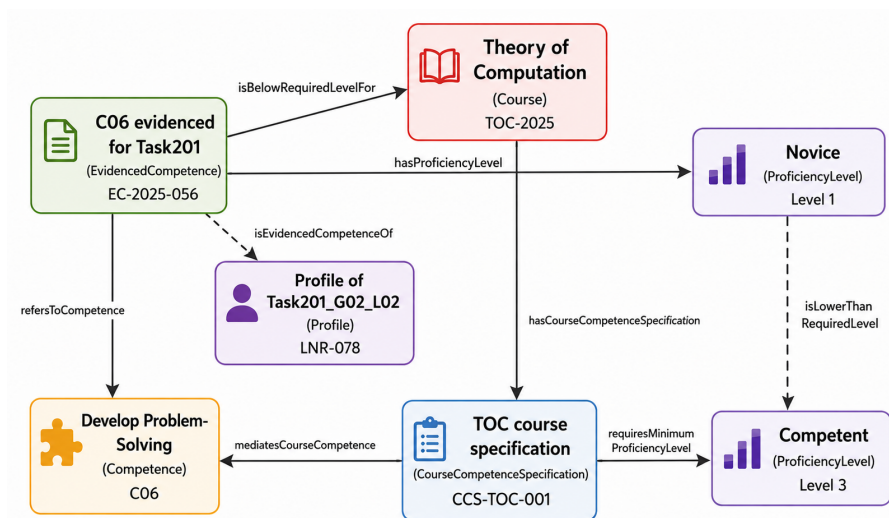


Figure 3. Proficiency-level mismatch reconstruction obtained from a SPARQL CONSTRUCT query.

The ontology also supported evidence-centered reconstruction by connecting evidenced competences, supporting artifacts, evidence types, and assessment occurrences. Figure 4 illustrates this reconstruction for the Task201 scenario, where process- and product-oriented evidence jointly support the same learner-specific competence record.

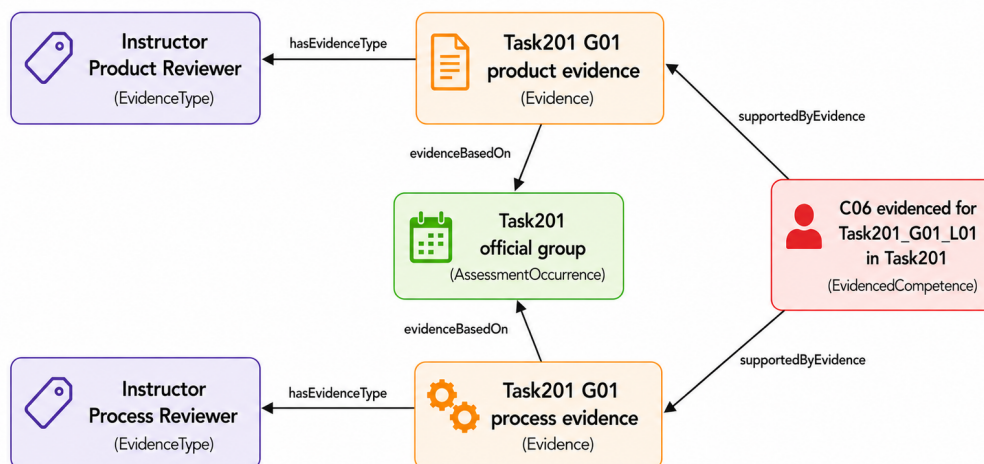


Figure 4. Evidence-centered reconstruction graph for Task201.

These results demonstrate that OntoKSD supports the reconstruction of competence structures, instructional activation, evidence provenance, proficiency attribution, and proficiency gaps across instructional and assessment contexts, providing the semantic foundation for competence-oriented educational traceability in Computing Education.

5.4. Educational Implications

The instantiated scenarios suggest that OntoKSD can support curriculum mapping, assessment alignment, and evidence organization in competence-oriented educational environments by preserving the distinction between abstract competence specifications and contextualized evidence derived from instructional and assessment activities. This separation is particularly valuable in scenarios involving competence reuse, collaborative activities, and multiple assessment contexts, where the same competence may be activated across different educational situations while preserving learner-specific proficiency attribution.

The proposed model also provides practical support for different educational stakeholders. Teachers can consistently specify competences, relate instructional tasks to expected competence development, and organize assessment evidence. Course coordinators can analyze competence coverage, identify curricular gaps, and improve curricular coherence. Curriculum designers can trace alignments among competence frameworks, learning activities, assessments, and program outcomes to support curriculum planning and revision. Students may benefit from explicit competence traceability by understanding which competences are addressed by learning tasks, what evidence supports their development, and how proficiency is interpreted across learning experiences.

More broadly, OntoKSD serves as a semantic reference model for competence-oriented educational planning and analysis rather than an automated assessment system. By explicitly connecting competence specifications, instructional tasks, learner participation, evidence, and proficiency, the ontology supports ontology-based retrieval of

competence-related information that would otherwise remain fragmented across educational artifacts.

6. Discussion and Threats to Validity

The evaluation indicates that OntoKSD can reconstruct competence-related educational traces across heterogeneous instructional contexts while preserving the semantic distinctions among activation, participation, evidence, and proficiency interpretation.

Table 1 compares explicit representational scope rather than implementation quality or overall superiority. Its classifications therefore refer only to constructs explicitly documented in the primary publications of each approach.

Core-O explicitly represents competences, manifestations, evidence, and proficiency as part of a domain-independent competence reference ontology. However, constructs central to this study's Competency Questions—including Bloom-aligned Knowledge–Skill relations, instructional task activation, assessment participation, and integrated competence–task–evidence traceability—are not explicitly covered by its primary modeling scope and would require educational extensions. OntoKSD represents these structures directly.

OntoKSD is compatible with Core-O's conceptual foundations, but its contribution is not limited to adding Computing Education terminology. It integrates competence specifications, Bloom-qualified Knowledge–Skill relations, task activation, learner participation, evidence, proficiency interpretation, and curricular alignments within a unified traceability architecture. These constructs were designed to operate jointly and emerged from both competence ontology literature and empirical requirements elicited through the CSP. OntoKSD therefore addresses educational traceability requirements that lie beyond the primary representational objectives originally targeted by Core-O.

A central advantage of OntoKSD does not lie in replacing relational storage systems or enabling reasoning unavailable in traditional databases. Rather, it provides a declarative and interoperable semantic layer in which competence specifications, assessment participation, evidence production, and proficiency interpretation are represented as interconnected but semantically distinct elements. This explicit ontological commitment supports contextual traceability and semantic reuse without relying on application-specific procedural logic.

The evaluation scenarios were intentionally selected to provide heterogeneous instructional and evidential conditions. Theory of Computation involved formal and abstract artifacts, whereas Algorithms and Programming emphasized executable artifacts and structured task sequences. This diversity reduced dependence on a single evidence structure and strengthened the retrieval procedures across distinct educational situations.

The Moodle operationalization suggests that OntoKSD can support competence-centered LMS organization even without native OWL support. It also exposed representational limitations in current LMS environments, which remain centered on course- and grade-level abstractions and provide limited support for fine-grained evidence and constituent-level proficiency attribution.

OntoKSD also complements Evidence-Centered Design (ECD) [Mislevy et al. 2003]. Whereas ECD provides a conceptual framework for design-

ning assessments through evidentiary reasoning, OntoKSD explicitly represents and traces the relations among competence specifications, assessment tasks, learner participation, evidence artifacts, and proficiency interpretations. It can therefore serve as a semantic layer for information produced by ECD-informed assessment processes while preserving traceability among these entities.

OntoKSD intentionally distinguishes evidence from proficiency interpretation. Evidence artifacts, such as technical reports, source code, simulation files, and assessment records, document learner performance, whereas proficiency levels are pedagogical interpretations derived through rubrics, institutional schemes, or instructor judgments. The ontology represents the relation between evidence and proficiency without prescribing how the latter should be inferred. Because interpretation remains external to the ontology, different assessment models and institutional criteria can be adopted while preserving a consistent semantic representation.

The instantiation process revealed recurrent modeling difficulties among instructors, particularly regarding knowledge granularity and Bloom-aligned cognitive expectations during competence specification. These observations support the explicit representation of Knowledge–Skill relations together with Bloom-oriented justification verbs and controlled curricular vocabularies. Instructors also found it easier to associate competences from existing catalogs with learning tasks than to create new competence specifications, highlighting the importance of reusable competence repositories.

These observations should be interpreted in light of the provenance of the instantiated competence specifications. Because they had already been collaboratively refined through successive CSP review cycles before ontology instantiation, the evaluation focused on OntoKSD's representational adequacy and traceability capabilities rather than on the competence elicitation process.

Several threats to validity should nevertheless be considered. Internal validity may be influenced by modeling choices involving contextualization, competence granularity, and evidence interpretation. Construct validity is limited because the selected Competency Questions do not necessarily encompass all educational traceability requirements. External validity remains limited to Computing Education scenarios, particularly Theory of Computation and integrated secondary-level courses, which were intentionally selected to provide heterogeneous instructional and evidential conditions. Operational validity depends on the quality and completeness of the educational artifacts used for ontology instantiation, retrieval, and reconstruction.

The evaluation was intentionally designed as an ontology engineering evaluation focused on representational adequacy, semantic consistency, ontology instantiation, and Competency Question execution. Accordingly, the reported results demonstrate that OntoKSD can consistently represent, relate, and retrieve the educational information it was designed to capture. They should not be interpreted as evidence of improved learning, assessment validity, educational decision-making, or overall superiority over alternative representations. These questions require complementary comparative, large-scale, and user-centered evaluations.

OntoKSD represents competence specifications produced by external elicitation processes. In this study, these specifications were obtained through the Competency Spe-

cification Process (CSP); therefore, the semantic quality of the instantiated knowledge depends on the quality of the underlying competence specifications. Part of the evaluation relied on the retrospective reconstruction of educational scenarios from authentic instructional artifacts. Although these reconstructions were reviewed with the participating instructors, some post-hoc interpretation bias cannot be completely excluded, particularly regarding contextual relations and competence activation pathways. This limitation affects the interpretation of specific scenarios rather than OntoKSD's representational capabilities.

7. Conclusion

This paper presented and evaluated OntoKSD as a semantic model for competence traceability in Computing Education. The evaluation provided evidence that OntoKSD can explicitly represent, retrieve, and reconstruct competence-related educational relations through ontology instantiation and Competency Question execution. This evaluation should therefore be interpreted as an ontology engineering evaluation focused on representational adequacy, semantic consistency, and retrieval capability. It does not provide evidence regarding educational effectiveness, assessment quality, teacher adoption, or improvements in instructional decision-making, which remain important directions for future work.

By distinguishing abstract competence specifications from contextualized evidence, participation records, and proficiency attributions, OntoKSD supports the reconstruction of competence-related educational traces while preserving reusable semantic structures across instructional and assessment contexts. The evaluated scenarios showed that the model can connect competence structures, task activation, assessment participation, evidence provenance, and proficiency interpretation within a unified computational representation.

The evaluation also suggests that OntoKSD can serve as a semantic reference model for competence-oriented educational ecosystems, supporting the integration of curricular expectations, instructional activities, assessment records, and educational evidence. By providing a shared semantic layer for these elements, OntoKSD provides a basis for addressing the fragmentation that commonly characterizes competence-related educational information in Computing Education and for enabling more explicit forms of educational traceability.

Future work will extend the evaluation to additional Computing Education domains, including Software Engineering, Data Science, and interdisciplinary computing courses, together with longitudinal LMS-integrated scenarios involving broader educational data ecosystems. It will also investigate comparative evaluations against alternative competence representations, systematic quantitative analyses of the results obtained from the complete set of Competency Questions, and user-centered studies involving instructors, curriculum designers, teaching assistants, and students to assess the perceived usefulness of ontology-supported competence traceability and its contribution to competence-oriented educational planning, assessment, and curriculum management in authentic educational settings.

Declaration on the Use of Artificial Intelligence

Grammarly and ChatGPT were used solely as writing-support tools to assist with English language revision and improve textual clarity. These tools were not used to generate research questions, collect or analyze data, develop the proposed process, interpret findings, or formulate conclusions. All scientific contributions, methodological decisions, results, and interpretations presented in this paper are the sole responsibility of the authors.

Artifact Availability

A replication package is available for review purposes at <https://github.com/eduknowgpt/OntoKSD>. The package contains the OntoKSD ontology, supporting vocabularies, SPARQL queries implementing the Competency Questions, and a representative instantiated dataset used in the evaluation. Together, these artifacts enable inspection of the semantic model, execution of the reported queries, and reproduction of the evaluation results presented in this paper.

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