Domain ontology for mapping competency development in higher education engineering programs

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Abstract

This manuscript outlines an ongoing master's research project focused on the development of a domain ontology to support the mapping and monitoring of competencies acquired by students throughout their academic programs. The methodology combines the Realism-Based Ontology Engineering Methodology (ReBORM), the Basic Formal Ontology (BFO), and the competencies outlined in the Conceive–Design–Implement–Operate (CDIO) framework. In contrast to existing approaches, this integration enables semantic traceability between courses, content, and competencies, supporting curriculum analysis and alignment with labor market expectations. The ontology supports terminological standardization, ensures interoperability across curricular structures, and provides a foundation for the automatic assessment of competencies and identify gaps in program design. Although initially applied to a computer engineering program, the ontology is designed to be extensible to other educational programs. This paper details the research context, methodology, and preliminary modeling results, with the empirical validation using actual curricular data planned for the subsequent research phase.

Keywords

ontology, competencies, computer engineering, CDIO, high education curriculum

1. Introduction

In a society accelerated by the rise of artificial intelligence, the systematization of knowledge becomes imperative. Within competency-based academic education [1], this systematization is instrumental for evaluating the curricular structures of educational institutions and aligning graduate profiles with labor market expectations [2].

Despite numerous definitions, a competency can be understood as the ability to mobilize knowledge, personal skills, and socio-methodological competencies to solve problems in educational or professional contexts [3, 4]. In engineering, for example, high-level competencies combine technical-scientific mastery with the capacity for innovation and adaptation to complex scenarios [5]. Several efforts to map the competencies acquired by students throughout the curricular structure can be found in the literature [6].

In line with this perspective, the notion of mobilizing knowledge related to competencies is also a cornerstone of contemporary discussions on information literacy, a concept widely discussed in the literature, and often defined as the ability to locate, evaluate, and use information effectively [7]. A critical approach to this concept, critical information literacy, expands this definition to include the capacity to mobilize knowledge and use it to act upon complex problems and question the power structures embedded in the production and dissemination of information.

Proceedings of the 18th Seminar on Ontology Research in Brazil (ONTOBRAS 2025) and 9th Doctoral and Masters Consortium on Ontologies (WTDO 2025), São José dos Campos (SP), Brazil, September 29 – October 02, 2025.
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The systematization of competencies in the field of engineering has spurred the proposition of various theoretical and methodological models [8]. It is important to note, however, that competencies are not restricted to technical or engineering domains. They also encompass interpersonal abilities such as conflict mediation, synthesis of perspectives, and consensus building. Prominent among these initiatives is the CDIO (Conceive, Design, Implement, Operate) model, which is internationally established as a reference for the integration of technical and transversal skills throughout the lifecycle of engineering projects, from conception to operation [9].

However, despite these efforts, current approaches still reveal important limitations. Pedagogical frameworks such as CDIO offer structured competency guidelines but lack formal semantic representations to ensure interoperability and traceability, while ontological initiatives in education often remain disconnected from pedagogical foundations, which restricts their applicability in practice. As a result, there is still no systematic, semantically rigorous, and pedagogically grounded model capable of effectively supporting the monitoring of student learning outcomes. This gap is particularly critical in undergraduate education, where, in addition to technical expertise, transversal competencies such as teamwork, leadership, creativity, and information literacy must be systematically developed and assessed to align graduate profiles with societal and labor market demands.

In this context, ontologies emerge as a tool capable of addressing the need for terminological standardization and semantic relationships in the management of graduate attributes [3]. The development of specialized ontologies can unify competency frameworks and mitigate conceptual ambiguities, thereby promoting greater interoperability in the integration of educational systems and models.

The objective of this work is to develop an ontological representation that enables the tracking of competencies acquired by students throughout the educational path defined in the curricular structures of higher education programs. Although initially applied to a computer engineering program, the proposed model seeks sufficient generality and flexibility to be adapted to different knowledge areas and academic contexts. This allows for the analysis and monitoring of educational development in programs of diverse natures and complexity levels.

Thus, the central question the ontology seeks to address is how the competencies of an undergraduate program are distributed across its curricular structure. To achieve this objective and answer this question, the Realism-Based Ontology Engineering Methodology (ReBORM) and the Basic Formal Ontology (BFO) will be employed, in conjunction with the competencies delineated in the Conceive-Design-Implement-Operate (CDIO) framework. To support the development and validation of the proposed ontology, this research also adopts the Design Science Research (DSR) [10] methodology, which provides a structured framework for the creation and evaluation of innovative artifacts.

This article is structured as follows: Section 2 presents the theoretical background, covering concepts of ontologies and competency mapping based on the CDIO model. Section 3 reviews related works that contextualize this research. Section 4 describes the adopted methodology. Section 5 presents the ontology modeling and discusses the results obtained. Finally, Section 6 provides the final considerations.

2. Theoretical background

2.1. Ontologies

An ontology, in the context of computer science and the field of knowledge representation, is defined as an explicit, formal specification of a shared conceptualization[11]. As a representational artifact, an ontology's primary characteristics are: (1) formalization, which entails the use of logic and standardized languages to ensure precision; (2) conceptualization, which organizes domains into concepts, relations, and axioms; (3) sharedness, as it reflects a consensus on a domain among agents or communities; and (4) reusability, allowing its application across different contexts [12]. These characteristics underpin its utility in knowledge modeling, systems interoperability, and semantic inference.

Ontology reuse is an essential practice to ensure consistency, interoperability, and efficiency in knowledge representation, thereby avoiding redundant effort in the construction of new models [13]. In this work, the Basic Formal Ontology (BFO) is adopted as a reference ontology due to its fundamental

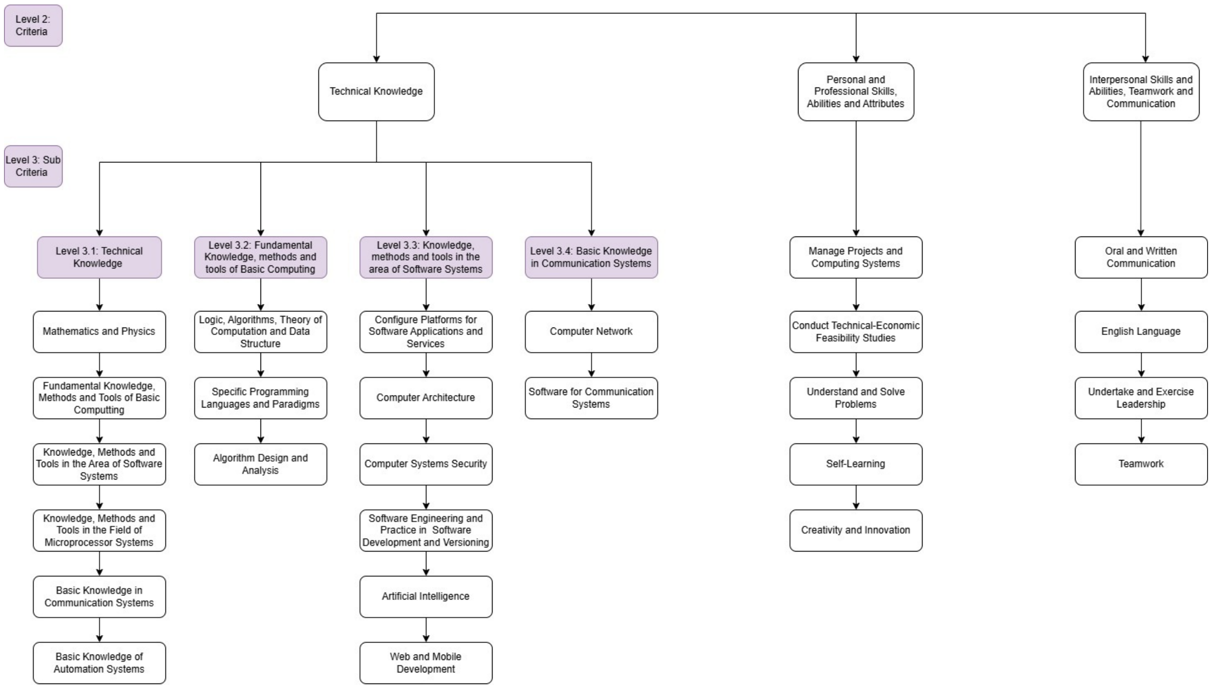

Figure 1: Expected competencies for graduates of the computer engineering program at the Federal University of Itajubá – Itabira Campus. Image by P. A. C. Santos, G. B. Vitor, R. A. d. S. Braga, A. C. O. Santos [2]

characteristics: (1) philosophical rigor [14]; (2) broad recognition [15]; and (3) interoperability [16]. BFO was selected for its capacity to provide a top-level framework that supports the coherent organization of entities across diverse domains, facilitating both modeling and reuse.

To operationalize the structured integration and reuse of ontologies, Farinelli et al. (2017) [17, 18] propose the ReBORM (Realism-Based Ontology engineering Methodology), which combines principles of ontological realism [19] with practices from the NeOn methodology [20]. According to Farinelli et al. (2017), ontological realism aligns with the philosophical rigor of BFO by emphasizing the precise demarcation of the domain and the correspondence between ontological entities and reality. The NeOn methodology, in turn, provides an iterative-incremental cycle organized into phases—such as conceptualization, inception, design, implementation, and delivery—ensuring that the developed ontology remains aligned with scientific principles and engineering praxis [18].

2.2. CDIO and competency mapping

The CDIO is an educational framework widely adopted in engineering education around the world, focusing on the development and planning of competency- and outcome-based curricula [21]. The CDIO Syllabus [21] outlines a set of knowledge, skills, and attitudes considered desirable for students, and it is flexible enough to be adapted by any engineering education institution.

At the university under study, version 2.0 of the CDIO Syllabus is adopted. Figure 1 presents the competencies defined in the course's pedagogical project, in accordance with the principles established by CDIO 2.0.

3. Related work

To address the gap between the qualifications offered by vocational education and the competencies required by the labor market, [3] details the development of job-Know. This is an ontology designed to forge an explicit link between the knowledge, skills, and abilities (KSAs) developed in vocational education and training (VET) and the competency prerequisites of job positions. The conceptual basis for this ontology is a three-dimensional semantic framework (TCK 3-D), which models the interrelationships among task, competence, and knowledge. Thus, job-know provides a formal and computationally processable representation of the work and education domains, enabling systematic analysis and alignment between what is taught and what is required.

To overcome the challenges of hierarchical alignment between macro-level educational objectives and micro-competencies in outcome-based education (OBE) curricula, [5] proposes OBC-ONTO, an ontology that models vertical (program $\rightarrow$ course) and horizontal (interdisciplinary) coherence in higher education. This framework formalizes the relationship among program educational objectives (PEOs), program learning outcomes (PLOs), and course learning outcomes (CLOs), utilizing a learning experience matrix that links each PLO to specific pedagogical activities, content, technologies, and assessments. Unlike previous models, which omitted the representation of program-level outcomes, this ontology offers critical support for curriculum reviewers and accreditation processes, ensuring that declared competencies are traceable, measurable, and aligned with industry demands.

Meanwhile, [22] proposes a new paradigm for engineering education, centered on the integration of projects and competencies. Its objective is to establish an ontology-based knowledge representation model, formally mapping professional domains to curricular structures. To this end, it defines hierarchical competency models (bachelor's, master's, doctorate), where declarative knowledge is decomposed into detailed ontologies — encompassing core concepts, identifiers, and concretizers — which serve as a basis for curriculum construction.

Considering the related works presented, this manuscript addresses a gap in the literature: the lack of interaction between pedagogical frameworks and ontologies for mapping and assessing competencies in Engineering programs. Specifically, no ontological representation integrated with the CDIO framework was found. Thus, this manuscript proposes to fill this gap by means of an ontology implemented in Protégé, which: (i) structures technical, personal, and interpersonal competencies aligned with the CDIO framework; (ii) employs inference rules for the automatic assessment of acquired skills; and (iii) is validated using real data from the program at the Federal University of Itajubá (Unifei), Itabira campus.

4. Methodology

As mentioned in Section 2.1, this work adopts the ReBORM methodology for ontology design, structured into five phases: 1) concept, 2) inception, 3) design, 4) implementation, and 5) delivery. Therefore, the competency mapping for the computer engineering program, based on the CDIO framework[2] and presented in Fig. 1, will be represented in the BFO ontology following the phases defined by the ReBORM methodology.

This research adopts the Design Science Research (DSR) methodology [10], a paradigm suited for the development and validation of innovative artifacts designed to solve identified problems. The DSR cycle guides this work through three core iterative phases: (i) problem identification, which motivates the need for the artifact; (ii) artifact development, which encompasses the design and construction of the solution; and (iii) evaluation, which assesses the artifact's utility and efficacy in addressing the problem.

As a result of phases 1 and 2, the Ontology Requirements Specification Document (OSRD) is available at [23].

The competencies identified in Fig. 1 were decomposed into terms[24]. Subsequently, by applying steps (3) and (4) of the ReBORN methodology, a hierarchy was constructed based on the Basic Formal Ontology (BFO). The final ontology file, corresponding to phase 5, is available at [25]. Section 5 presents the results and a discussion of the ontology.

5. Ontology modeling and discussion

The ontology proposed in this study, hereafter referred to as CompOnt, is partially illustrated in Fig. 2. A consolidated summary of all competencies as ontological entities, along with their respective classifications, can be found in [24].

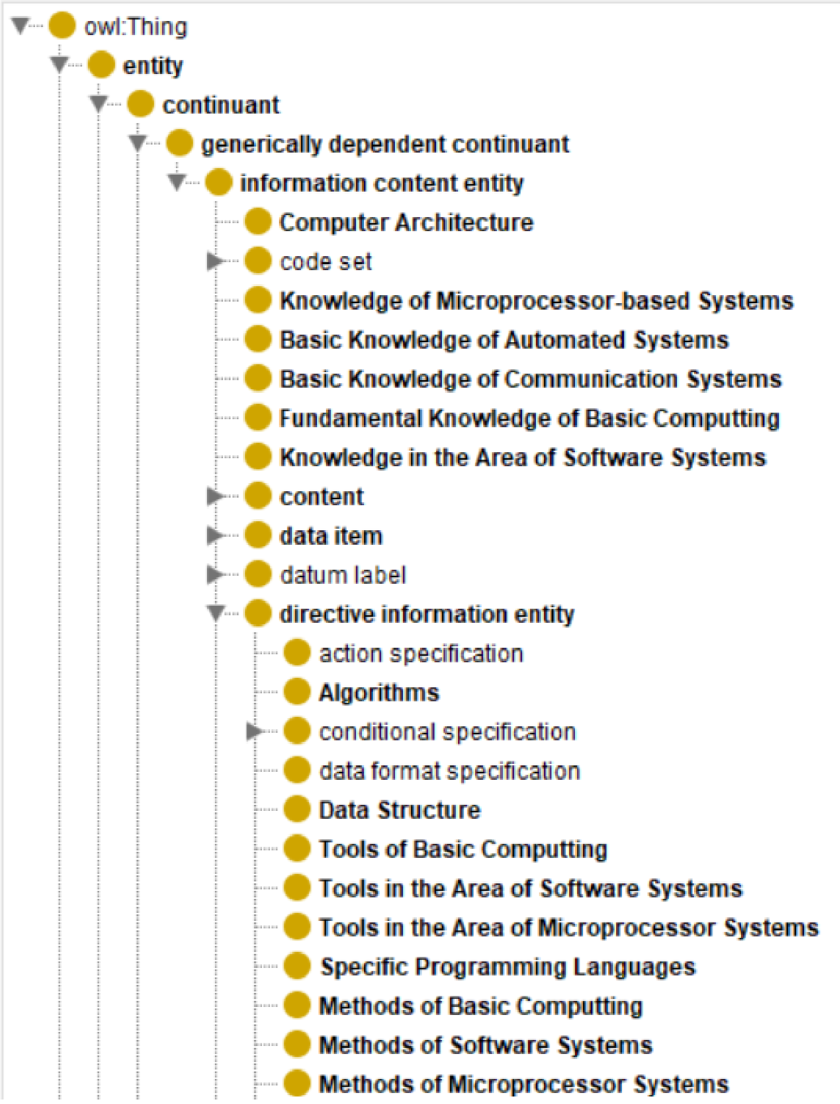

Figure 2: Section of CompOnt as represented in Protégé. Image by Authors [25]

In contrast, informational artifacts that serve as a plan or set of instructions to guide a process were categorized as directive information entity (**continuant - generically dependent continuant - directive information entity**). Such entities have a prescriptive nature. This group includes **algorithms**, **data structure**, **specific programming languages**, **programming paradigms**, **softwares for communication systems**, as well as the **methods** and **tools** associated with **basic computting** and the **area of software systems** and **microprocessor**.

Activities and actions that unfold over time and are executed according to a plan, method, or design were mapped to the planned process class, located in the **ocurrent - process** branch. This category encompasses complex processes such as **understand e solve problems**, **conduct technical economic feasibility**, **algorithms analysis and design**, and **software development**—including its **web** and **mobile** specializations. Also classified in this category were operational processes such as **configure platforms for software applications**, the execution of **software services**, and **software versioning**.

Transversal competencies and abilities intrinsic to an agent (e.g., a student or professional) were classified as quality (**continuant - specifically dependant continuant - quality**). Such entities are inherent in and dependent on a specific bearer for their existence. Examples include **self-learning**, **creativity** e **innovation**, **oral and written communication**, **leadership**, and **teamwork**.

Finally, entities that represent material objects and physical systems, which exist independently in spacetime, were categorized as object aggregate (**continuant - independent continuant - material**

entity - object aggregate). The concepts of **computer network** and **computer systems** were allocated to this class, as they represent tangible sets of hardware components.

6. Final considerations

This work presented an ongoing research effort toward the development of a domain ontology for mapping competencies in higher education programs. The proposed model integrates ReBORM, BFO, and CDIO, and has been preliminarily applied to the computer engineering program at UNIFEI. The results demonstrate the feasibility of formally representing both technical and transversal competencies, enabling interoperability and potential reuse across different educational contexts.

The proposed ontology differs from existing solutions by providing a unified semantic framework that bridges pedagogical foundations (CDIO) with ontological rigor (BFO/ReBORM). This integration allows for precise competency tracing across curricular components, supporting gap analysis and alignment with labor market requirements. By enabling automated assessment and curriculum evaluation, the ontology offers a practical approach to developing professional profiles that better meet societal and industry needs.

However, the research is still in progress. The empirical validation of the ontology, through its application to real curricular data and stakeholder evaluation, remains a future stage. This will be crucial for confirming its effectiveness as a tool for curriculum mapping, competency assessment, and support for pedagogical decision-making.

By systematically integrating pedagogical frameworks and reference ontologies, the proposed approach contributes to overcoming current limitations in competency-based education. The primary technological contribution is the CompOnt ontology, which provides a reusable and extensible semantic framework for diverse academic areas. This extensibility ensures the ontology can evolve to incorporate new courses, institutions, and curricular structures, thereby advancing the state of the practice in competency mapping.

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