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CONCEPTUAL FRAMEWORK FOR AUTOMATED CURRICULUM MAPPING IN OUTCOME-BASED EDUCATION USING SEMANTIC REASONING

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ABSTRACT

Higher education institutions globally are being mandated to implement Outcome-Based Education (OBE), placing curriculum mapping at the center of quality assurance. Yet mapping remains labour-intensive, subjective, and inadequate at scale. This paper proposes the Semantic-AI Curriculum Mapping (SACM) Framework—a conceptual architecture integrating ontologies, knowledge graphs, semantic reasoning, and Large Language Models (LLMs) to automate OBE-aligned curriculum mapping. A purposive synthesis of 30 peer-reviewed publications (2021–2026) is used to derive a six-category problem taxonomy and a six-layer framework, validated through a traceability matrix. No implementation is presented. Three original contributions are advanced: a problem taxonomy, the six-layer SACM framework, and a traceability matrix demonstrating comprehensive coverage of identified barriers. The framework's modular design is contextualized for Nigerian universities under NUC's Core Curriculum and Minimum Academic Standards (CCMAS, 2022).

Keywords: Automated Curriculum Mapping; Semantic Reasoning; Ontology; Knowledge Graph; Outcome-Based Education; Large Language Models; SACM Framework; NUC CCMAS; Curriculum Coherence.

1 INTRODUCTION

In the world, the higher education system is changing its paradigm to move from input-based teaching to competency-based teaching based on the competency demonstrated by graduates. The heart of this change is Outcome Based Education (OBE) as described by Spady [1] as "clearly focusing and organizing all aspects of an educational system around what is essential that all students can do successfully at the end of their learning experiences. OBE was first developed in the United States of America in the context of the mastery-learning tradition, and has subsequently been

adopted by accreditation bodies in Asia, Europe, Africa, and Oceania [2] and has been widely studied since the UN Sustainable Development Goal on quality education [3].

One of the most salient theoretical substantiations to OBE is the principle of 'triangulation' of Intended Learning Outcomes (ILOs), teaching and learning activities (TLAs), and assessment tasks (ATs) developed by Biggs and Tang [4]. The operational tool for ensuring this triangulation is delivered across the whole program, is curriculum mapping, which is used to systematically identify gaps, redundancies and misalignment in the assessment tasks and outcomes [5, 6].

This is reflected in the Nigerian law. In December 2022, the National Universities Commission (NUC) introduced Core Curriculum and Minimum Academic Standards (CCMAS) for 17 disciplines and 238 programs in the Nigerian University System which was to be implemented from the 2023/2024 academic session [7, 8]. The CCMAS integrates explicit program- and course-level learning outcomes for each discipline, and provides scale-level structural support for verification of alignment with the outcome-curriculum in each discipline in a manner manual processes would not be able to handle.

1.1 Statement of the Problem

Even though it is a known necessity, curriculum mapping in most of the institutions is still mostly manual, subjective, and labour-intensive. Faculty spend many hours trying to fit courses outcomes into program outcomes and often do this in ways that are idiosyncratic rather than formalized schemas [9, 10]. A study by [11] on a college of education in Nigeria revealed a total lack of alignment between the learning outcomes and the content of courses following a formal accreditation process – demonstrating the systemic danger of informal mapping approaches. In today's curriculum, particularly those for computing and AI, these methods have become structurally unfeasible for maintaining currency and coherence that OBE requires. The principled solution is provided by semantic technologies, such as ontologies and knowledge graphs, and SPARQL reasoning. However, a study by [12] found that in their systematic review of 4,510 studies, "ontology alignment and accurate curricula assessment seem to be the most substantial constraints to the use of widely distributed OSCMs." [13] also noted that the approaches currently in place are "predominantly post-hoc analysis rather than predictive forecasting or adaptive intervention. Large Language Models (LLMs) have introduced new opportunities [14] and integration with formal semantic architectures is still in its infancy [15].

1.3 Research Questions and Contributions This paper tackles four research questions: (RQ1) What are the main challenges in automated semantic curriculum mapping? (RQ2) What are ways to combine already existing approaches into a coherent taxonomy of problems? (RQ3) How can ontologies, knowledge graphs, semantic reasoning and LLMs be combined into a conceptual architecture that can overcome these challenges? (RQ4) What should the next wave of empirical research be based on? Three original contributions are introduced: (1) a problem taxonomy developed from 30 recent publications over the last 15 years, which uses six categories; (2) the six-layer conceptual framework of the SACM; and (3) a traceability matrix that validates the six-layer framework. The framework is modularly adapted to Nigerian Universities having to comply with the NUC's CCMAS requirements.

2 MATERIALS AND METHODS

2.1 Literature Search Strategy

The study used a purposive synthesis of 30 peer-reviewed publications (2021–2026) from the IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Frontiers and SAGE database. Theoretically relevant publications to the four research questions were chosen. The synthesis is not exhaustive; it is theory building.

2.2 Inclusion Criteria

The publications included were related to: (a) Semantic Technologies for Curriculum Mapping; (b) Knowledge Graph Applications in Education; (c) LLM Integration with Formal Semantic Architectures; or (d) Alignment of Outcome-Based Education to Education Alignment Frameworks.

2.2.1 Thematic Analysis

A thematic analysis was used to identify the common barriers in the selected literature. Six barrier categories were inductively derived and organized along three dimensions: severity, frequency of identification and technical versus institutional nature.

2.3 Framework Synthesis

The SACM framework was developed by combining the best practice elements found in the literature, which were chosen for their ability to demonstrate that they address at least one of the barrier categories. The framework is not

descriptive of any automated curriculum mapping system but is prescriptive and defines what an automated curriculum mapping system should do.

3 RESULTS

3.1 Literature Synthesis

Table 1 summarizes findings by theme from the 30 peer-reviewed publications.

Table 1: Literature Synthesis by Theme

Theme	No. of Studies (n)	Dominant Methods	Key Gap Identified	Selected References
Ontology-driven Mapping	7	OWL, Protégé, WordNet, SPARQL	Static, institution-specific implementations with limited interoperability	[9], [20], [21], [29]
Knowledge Graph Analysis	6	Neo4j, KeyBERT, Graph Convolutional Networks (GCN), Deep Learning	Lack of benchmark datasets and weak cross-curriculum semantic links	[14], [16], [17]
Semantic Reasoning and Validation	4	CORESE, OWL Full, Dual-Path SPARQL + LLM	No universally accepted standard for curriculum coherence validation	[22], [23]
Personalised Learning Paths	5	OWL 2 DL, SWRL, Knowledge-Augmented Generation (KAG), Large Language Models (LLMs) with Open Educational Resources (OER)	Real-time learner integration remains an unsolved challenge	[24], [15]
Interoperability and Emerging AI	5	Semantic MediaWiki, WASPEC, GARO-LLM	Existing studies focus mainly on post-hoc analysis rather than adaptive curriculum systems	[25], [13], [30]
Reviews and Research Agendas	3	Systematic Reviews, Bibliometric Analysis	Ontology alignment continues to be a major barrier to widespread adoption	[12], [16]

Cross-theme analysis reveals a clear evolutionary trajectory: from static ontologies (pre-2020) to hybrid LLM-knowledge graph systems (2024–2026). A convergent finding across all six themes is that existing approaches are predominantly descriptive and post-hoc, rather than predictive or adaptive. The most significant technical barrier consistently identified, as seen in [12], is Ontology alignment, while the most acute emerging gap represents limited AI-semantic integration [13].

3.2 Problem Taxonomy

Six categories of barriers were inductively derived from the literature synthesis and are presented in Table 2.

Barrier interdependencies. The six barriers are not standalone. P1 (manual processes) compounds P3 (heterogeneity) due to inconsistent human vocabularies.

Ontological alignment is harder. P3 in turn causes P4 (validation failure) since reasoning engines does not ensure consistency of coherence of schemas that are misaligned [22]. Data quality (P5) is a limitation on AI (P6).

Typical syllabi that are not well structured nor presented in a uniform format are unclearly understood by LLM models, which hinders their ability to extract useful structure from them (integration) [14]. So, it is important to work on P3 and P5 before P4 and P6, as these make them the highest-leverage points in the taxonomy.

Table 2: Six-category problem taxonomy for barriers to automated curriculum mapping

ID	Barrier Category	Severity	Frequency	Key Evidence	Nature
P1	Manual, subjective, and labour-intensive curriculum mapping processes	High	30/30	[9], [10], [11]	Institutional and Technical
P2	Static versus dynamic curriculum representations	High	25/30	[13], [24]	Technical
P3	Ontology alignment and semantic heterogeneity	High	28/30	[12], [16], [29]	Technical
P4	Absence of automated curriculum coherence validation	Medium	22/30	[22], [23]	Technical
P5	Data diversity, heterogeneity, and quality challenges	Medium	20/30	[16], [14]	Technical and Data
P6	Limited integration of Artificial Intelligence with semantic technologies	Emerging	15/30	[13], [15], [30]	Technical

3.3 The SACM Conceptual Framework

3.3.1 Design Rationale

The Semantic-AI Curriculum Mapping (SACM) Framework is a conceptual 6-layer framework Architecture synthesized from the best practice components identified from literature, each chosen because it can be clearly shown to address one or more barrier categories in Table 2. It's a prescriptive framework; it includes what an automated curriculum mapping system should look like. Not a description of any implementations.

3.3.2 Layer-by-Layer Description

3.3.2.1 Layer 1 - Data ingestion and pre-processing (Addresses: P1, P5).

3.3.2.1.1 Collects raw curriculum artefacts: syllabi, program specifications, NUC CCMAS

Assessment records of the school or institution, benchmark documents. An NLP pipeline—leveraging LLMs such as open-source Llama 3 or Mistral variants for cost-effectiveness in African Extracts and normalizes concepts, prerequisite statements and outcome from deployment contexts. The assessment uses the findings from unstructured text to make assertions [14]. The output is fed into a standardized feed for Layer 2.

3.3.2.2 Layer 2 — Ontology-based Knowledge Representation [Addresses: P2, P3]

All extracted curriculum concepts are formalized as an OWL 2 DL ontology, modelling courses, the learning outcomes are mapped to Bloom's taxonomy levels, competencies and prerequisites. Assessment techniques and program-level outcomes. The ontology is consistent with IEEE LOM, Dublin Core, European Qualifications Framework (EQF) and NUC CCMAS outcome structures [20, 24]. The institution-specific extension modules ensure interoperability with a shared core [21].

3.3.2.3 Layer 3 - Curriculum Knowledge Graphs Constructing [Addresses: P2, P3, P5]

Creates the ontology as a Curriculum Knowledge Graph (CKG) in a graph DB, as related to curriculum entities, with relationships (co-requisite, builds-on, assesses, maps-to) as typed edges [17, 26]. The CKG provides QL facilities to SPARQL queries to detect gaps and redundancies. This concept is built on analysis, and learning pathway visualization, and is constantly modifiable in relation to the curricula evolve—Overcome static representation barrier (P2).

3.3.2.4 Layer 4 — Semantic Reasoning and Validation Engine [Addresses: P3, P4]

Uses two complementary reasoning strategies: (a) rule-based SPARQL inference by the means of (b) pattern matching. The need for structural coherence checking (prerequisite) with engines like: CORESE or Apache Jena. All of the above coupled with ordering, outcome coverage, program well-formedness [22, 23], and (b) LLM-based. Content-level alignment validation using the semantic similarity scoring of course descriptions and benchmark outcomes [27]. The

dual-path approach deals with both formal logical and informal logical error consistency (SPARQL) and semantic meaning similarity (LLM).

3.3.2.5 Layer 5 - AI-enhanced Analysis and Optimization [Addresses: P2, P5, P6]

The Implements LLM and Graph Neural Networks (GNNs) for more advanced curriculum intelligence tasks: Knowing the unseen prerequisite relationships in course material, spotting emerging patterns, comparing CKG with external domain ontologies (Wiki data, ACM) to fill discipline gaps, building Recommendation Systems (Computing Classification System), and revising ranked curriculum recommendations [15, 14]. This layer moves the system from descriptive (post-hoc) to prescriptive to ensure it is (forward-looking) and addresses the static limitation of P2 directly.

3.3.2.6 Layer 6 — Personalization and Adaptive Output [Addresses: P1, P2]

Creates the outputs of the learners by using the 4-dimensional model of the learner (cognitive state, affective state, psychomotor state, and general state). Combined competencies with the CKG through (competency goals, learning preferences, prior experience), the SWRL rules and vector-based retrieval [24]. The outputs are: Personalized learning path students' competency gap reports and curriculum quality dashboards for Administration of faculty and compliance to NUC accreditation-ready audit trails CCMAS requirements [7].

3.3.3 Traceability Matrix

Table 3 maps each SACM layer to the six barrier categories, providing logical validation of framework completeness. A direct address (✓) indicates the layer's primary function targets the barrier; a partial address (○) indicates indirect or supporting contribution.

Table 3: SACM framework traceability matrix

SACM Layer	P1 Manual	P2 Static	P3 Heterogeneous	P4 Validation	P5 Data	P6 AI-gap
L1: Data Ingestion	✓	—	—	—	✓	○
L2: Ontology Representation	○	✓	✓	—	—	—
L3: Knowledge Graph	—	✓	✓	—	✓	—
L4: Reasoning & Validation	✓	—	○	✓	—	—
L5: AI-Enhanced Analysis	—	✓	—	○	○	✓
L6: Personalisation	✓	✓	—	—	—	○
All Barriers Addressed?	Yes	Yes	Yes	Yes	Yes	Yes

Legend: ✓ = Directly addresses the problem; ○ = Partially or indirectly addresses the problem; — = Not the primary scope of this layer; ✓ = direct address; ○ = partial/indirect; — = not primary scope of this layer

4 DISCUSSION

The nature and extent of the field.

The literature synthesis shows a field on a transitional inflection point. In the early days (before 2020), archetype-based ontologies were developed statically, using tools such as Protégé [10], and were specific to a single institution. In the years 2021-2023, a new development was the introduction of curriculum knowledge graphs, where moving from hierarchical taxonomies to dynamic, queryable networks emerged [17, 28]. Ontology-driven curriculum representation continued to mature in parallel over this period, with document-driven ontology construction pipelines demonstrating practical extraction of curriculum components from real institutional documents [29]. A third wave is combining LLMs with graph architectures, starting in 2024 [14, 15]. The SACM framework provides a synthesis of all three waves as a single pipeline, and is the logical next step from the current state of the art.

The student will place a review relative to other reviews. The student will locate one review relative to another review. Two major preceding reviews set the scholarship conversation. A study by [12] pointed out that the main challenge is the lack of ontology alignment, which is addressed directly by the SACM framework with the establishment of a common OWL schema and a common knowledge graph as the substrate for integration (Layers 2-3). Unlike the prevailing post-hoc description of the current systems, Layer 5's AI-enriched analysis is explicitly moving from post-hoc to a

prescriptive recommendation and gap modelling. The SACM framework is thus more than additive, but rather is architecturally responsive to the two most salient and important critiques in the literature.

The implications that emanate from this study for Nigerian and African Higher Education are highlighted below:

The NUC's mandate for CCMAS provides a regulatory mandate for curriculum intelligence tools in all the 170+ accredited universities in Nigeria [7]. The modular, 6-layer structure of the SACM framework, however, allows gradual implementation: Layers 1-2 (data ingestion and ontology) can be implemented with freely available open-source tools (Apache Jena, Neo4j Community Edition, open-source LLMs), while Layers 3-6 can be added as institutional capacity expands. This stage-wise approach is ideal for the resource and infrastructure needs of many African universities. Moreover, the pipeline's explicit integration with NUC CCMAS result-oriented structures in Layer 2 allows for direct generation of accreditation-ready audit trails (Layer 6), thereby decreasing the administrative burden of NUC accreditation exercises.

4.1.1 Limitations

Two restrictions should be highlighted. One important point is that the SACM framework is conceptual, so performance claims rely on the specific tools selected for each layer, and cannot be made without a testable demonstration. Secondly, the 30-papers were carefully chosen based on their theoretical importance, but are not necessarily exhaustive of papers of this type that may have been published in other non-English languages or in databases not searched.

5 CONCLUSION

Higher education curriculum mapping in the context of OBE is still underdeveloped due to the following reasons: (1) the lack of automated coherence validation, (2) the lack of automated tools for the AI integration of OBE curricula, (3) static representations of curricula, (4) semantic heterogeneity, and (5) manual processes. There is no existing framework that covers these barriers in a holistic manner in a single architecture.

The paper makes three new contributions. First, a six-category problem taxonomy (30 peer-reviewed publications (2021-2026)) that offers a structured characterization of the barrier landscape. Second, the L2 (ontological knowledge representation), L3 (curriculum knowledge graph construction), L4 (dual-path semantic reasoning), L5 (LLM-enhanced analysis), and L6 (adaptive personalization) layers are collectively integrated around a data ingestion core layer (L1) to form a SACM (Semantic Adaptive Curriculum Mapping) six-layer conceptual framework. Third, a traceability matrix that shows that the framework covers all six barrier categories.

The SACM framework will offer a principled architectural blueprint for researchers and developers of automated curriculum intelligence tools, whilst also offering a practical incremental adoption pathway to universities in Nigeria and Africa which have to comply with NUC CCMAS requirements. The three-horizon research agenda outlined below should be followed in future studies and transferred from the conceptual to the empirical phase.

5.1 Research Agenda

Three priority horizons are identified for future empirical work:

Short-term (0–2 years): Prototype evaluation of individual SACM layers as standalone modules, benchmarked against existing curriculum corpora (e.g., the AGH Computer Science curriculum used by Gacek and Adrian [14]). Develop and publish a shared OWL ontology for Nigerian HE curriculum mapping, aligned with NUC CCMAS, as an open educational resource. Benchmark open-source LLMs on concept extraction from Nigerian university syllabi.

Medium-term (2–4 years): Pilot a federated Curriculum Knowledge Graph across 3–5 Nigerian universities to enable cross-institutional gap analysis. Implement and evaluate the dual-path SPARQL + LLM coherence checker (Layer 4) and measure reduction in manual review time. Integrate real student performance data (with ethical approval) into Layer 6 personalization and evaluate recommendation quality.

Long-term (4+ years): Design self-auditing curricula that flag outdated content by comparing institutional CKGs against external domain knowledge graphs (Wikidata, ACM CCS). Integrate Explainable AI (XAI) methods—SHAP, LIME—into AI-generated curriculum recommendations to build faculty trust (cf. [25]). Extend towards a regional African curriculum intelligence network enabling semantically aligned, collaborative curriculum development across institutions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

There is no conflict of interest, financial or otherwise, related to this research.

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