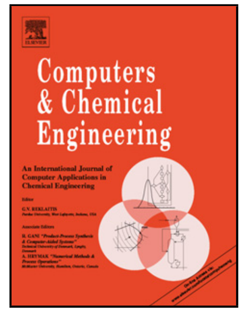

Title: An Ontological Approach to Chemical Engineering Curriculum Development

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<AT>An Ontological Approach to Chemical Engineering Curriculum Development

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<ABS-HEAD>Highlights► An ontology (ChEEdO) was developed to model the chemical engineering curriculum. ► ChEEdO models taught modules, learning outcomes and topics in the curriculum. ► The object, context and levels of the learning outcomes specified learning. ► The functionality of semantic reasoning via the ontology was demonstrated. ► The ontology was used for curriculum development and learning integration.

<ABS-HEAD>Abstract
<ABS-P>Continuous reflection and evolution of curricula in chemical engineering is beneficial for adaptation to evolving industries and technologies and for improving student experience. To this end it was necessary to develop a method to enable a holistic reflection on the curriculum and to examine potential areas of improvement and change. The curriculum was modelled using knowledge modelling through the development of an ontology, Chemical Engineering Education Ontology (ChEEdO) in the Protégé 3.5 environment. ChEEdO models topics, taught modules and the learning outcomes of the modules within the domain of chemical engineering. The learning outcomes were related to the topics using verb properties from Bloom's taxonomy and the context of each learning outcome. The functionality of semantic reasoning via the ontology was demonstrated with a case study. The modelling results showed that the ontology could be successfully utilised for curriculum development, horizontal and vertical integration and to identify appropriate pre-requisite learning.

<KWD>Keywords: Knowledge modelling; Curriculum development; Ontology; Chemical engineering; Education.

<H1>1. Introduction: Knowledge Modelling in Education

Knowledge modelling features in curriculum development historically in the form of ontologies, as well as concept maps. Conceptual curriculum mapping was used as a tool to develop and validate engineering curricula based on the program outcomes (Morsi et al., 2007) with proven benefits of facilitating validation, enabling student and teacher conceptualisation of the course, and improving quality and alignment. Similarly, concept maps were used for curricula in school education, which encouraged alignment, integration and communication amongst teachers and are still used in the UK high school education (Koppang 2004; BBC 2015). Whilst concept mapping is a valid tool for knowledge modelling for curricula, we argue that the additional use of properties, restrictions and inferences in ontology engineering provides more scope to probe and interrogate the curriculum structure.

The term ontology originates from philosophy and it is the explanation (λόγος - logos) of being (ον - on); today it is used in computer science and knowledge engineering. The most common definition in literature has been coined by Struder et al., (Struder et al., 1998) which builds on previous definitions by Uschold and Gruninger (Uschold & Gruninger 1996) and Gruber (Gruber 1993), among others, who define ontology as ``*a formal explicit specification of a shared conceptualisation*". Formal means that it is machine readable. Explicit specification refers to the explicitly defined concepts, properties, restrictions and instances of the ontology. The term shared acknowledges that the described knowledge must be commonly accepted by a group of people. Finally, the term conceptualisation is by definition an abstract model of some phenomenon. In simpler terms, an ontology is a knowledge model that contains a group of concepts/terms that describe a specific domain, and more importantly, which is machine processable (Trokanas et al., 2014). These concepts are organised in a taxonomy associated through class-subclass relations (*isA*), and characterised by properties and domain specific relations among them. Relationships and properties are restricted using axioms which allow for inference capabilities (Raafat et al., 2013). An ontology is completed with the use of instances which represent specific entities of the domain.

Within high school curricula in the UK, an ontology for the description of the terminology was developed and enables organisation of learning resources and content discovery (BBC 2015). Ontology engineering in higher education curricula has been used for various applications such as managing complexity (Dexter & Davies 2009), curriculum development (Cassel et al., 2008), improving resources (Gašević & Hatala 2006), curriculum review (Ronchetti & Sant 2007), and content sequencing (Chi 2009). Some capabilities of knowledge systems in the domain of curricula are: discovery and separation/extraction of foundation material from more complex material, validation of a program, assessment alignment and validation, change management / curriculum development, supporting consultation and collaboration, a decision making tool, and relationship inferences such as horizontal and vertical alignment. This paper aims to demonstrate the viability of knowledge based modelling to support decisions related to the development and review of chemical engineering curricula based on the curriculum for Chemical Engineering at the University of Surrey. As at present and without intention to limit the scope, the functionality of the ontology is demonstrated in reference to identifying: horizontal integration, and the potential for inter-module assessments; evaluation of vertical integration, and appropriate pre-requisite learning; contextualisation of material, with respect to later learning; and, assisting with decisions about developing new material in the curricula.

<H1>2. Methodology: Development of ChEEdO

<H2>2.1 Curriculum development strategy

Chemical engineering is an applied discipline that brings together different scientific concepts under the same context. Generally, chemical engineering curricula follow a modular structure with progression from either year to year or from semester to semester. Each module comes with a set of learning outcomes, which have to be achieved for the module to be passed. As a student progresses through their chemical engineering degree there are core concepts that are expected to be covered by industry and to achieve accreditation (Gomes et al., 2006; IChemE 2011). Core and specialist streams within chemical engineering require a progression-like education, i.e. the sequence of topics in chemical engineering is important as fundamental concepts learnt in earlier years are built upon in later years. To this end, students benefit from obvious vertical integration within their curriculum that is a clear link between current and prior learning (Gomes et al., 2006).

In addition to vertical integration, horizontal integration in the curricula is beneficial to the student learning experience. Due to the modularised nature of the degree, students are often unable to see the connections between different topics and, consequently, the curriculum lacks integration throughout the degree program. In order to exemplify these connections, horizontal integration has been suggested as a technique to alter the student perception (Abbas & Romagnoli 2007). In its simplest form this can be done by setting a single piece of coursework that relates to two or more concurrent modules. In addition, staff engagement effort can be reduced by concomitantly reduced assessment using single assessment pieces across modules. Hence, horizontal integration is able to reduce staff workload and create a deeper student learning experience which, in turn, is beneficial in curriculum development (Abbas & Romagnoli 2007).

As evident (Byrne 2006), chemical engineering graduates can now be found in highly specialist areas such as molecular engineering, nanotechnology and microelectronics. To further develop the curriculum, introduction of concepts at higher levels within the degree program or addition of specialisation is becoming ever more desirable. Specialisation options are often geo-specific and may be reflected in the expertise and research interests of the staff teaching the degree (Gomes et al., 2006). In terms of teaching efficacy it is often best to align teachers with fields of expertise in order to maintain enthusiasm, which assists in student motivation (Patrick et al., 2000). Developing material at a modular level, however, requires an in depth knowledge of the content within a curriculum across the degree program. New material should then be placed in the context of prior learning to enable constructive learning. Over the years chemical engineering has changed from the traditional core concepts to the inclusion of a broader range of concepts. Nowadays, chemical engineers are expected to acquire a certain skill set related to the profession (Rugarcia et al., 2000) as reflected in the accreditation requirements (IChemE 2011). In addition, constant evolution of industry and technology require alternative skill sets to the traditional chemical engineering degree program. However, the program still requires core material to be embedded within the curriculum. In order to reflect and develop a curriculum, core material should be identifiable and learning material and skills placed in the context of later application.

Constant evolution of teaching methods, industry, technology and graduate requirements mean that curricula are continuously evolving. In order to develop a curriculum to meet these changes an in-depth knowledge of the current curriculum is required. Horizontal and vertical integration requires knowledge of the learning topics and contexts in other modules in the degree program. Then, the addition of new material in later years requires knowledge of prior learning in previous semesters and years. Similarly, the student should be able to place their current learning in the context of application or later learning and core learning material should be identifiable. The knowledge required on the curriculum is vast and it is not practical for teachers to retain as the curricula is also evolving. Therefore, a knowledge model in the form of an ontology is proposed to reflect the curriculum and to assist in decision making regarding curriculum development. A modelling approach allows for facile integration and contextualisation of learning and provides a tool to inform learners and teachers about curriculum content. To this end, ontology is designed to model the knowledge contained within the curriculum for chemical engineering.

The knowledge about the curriculum structure, taught modules, topics of learning and learning outcomes are modelled using the module descriptors. The module descriptors contain learning outcomes which utilise Bloom's taxonomy (Bloom 1956) and follow the structure as defined by Biggs (Biggs & Tang 2011). This means that each learning outcome has a learning verb that defines the learning level reflected in the six learning levels defined by Bloom, namely: knowledge, comprehension, application, evaluation and synthesis. Then, the learning outcomes consist of learning topic and context, which, together with the learning level, formulate the specification of learning. Learning outcomes are designed such that assessment reflects the achievement of these outcomes. Hence, they form a basis of the prescribed learning within the degree program and are subsequently chosen as the basis of knowledge modelling in the ontology formulation. The context and topic of learning exist within a taxonomy of topics that are also modelled. The topics are related to each other in consideration of prerequisite learning and subsections of larger topics.

<H2>2.2 Ontology implementation

The three high level classes or concepts of the ontology are: *Module* containing instances $\{s_i^M\}_{i=1}^{n_M}$ representing modules*, LearningOutcome* containing instances $\{s_i^L\}_{i=1}^{n_L}$ representing learning outcomes and *Topic* containing instances $\{s_i^M\}_{i=1}^{n_M}$ representing topics, as shown in Figure 1. For a full explanation of the ontology formulation, please refer to Appendix A. Here and further in this paper, names of classes and data and object properties are self-explanatory. The domain of the demonstration model is developed based on module descriptors from the reaction engineering branch of the Bachelor's degree programme of chemical engineering including the whole first year curriculum at the University of Surrey. This consists of eleven modules, each having a set of learning outcomes. The learning outcomes have learning subjects classified further as subclasses of the class *Topic*. The logical associations between learning outcomes and topics is established by two object properties *hasLearningOf* and, *hasContextOf*, as demonstrated in Figure 1 and Table 1. Here, the topics were modelled on an as-needed basis, and subsequently classified into classes and subclasses based on knowledge of chemical engineering.

<H3>2.2.1 Topic conceptualisation and modelling

In addition to subsumption *isA* relationships, the topic concepts related to chemical engineering were modelled by additional two object properties: mereology property *isPartOf* and functional<xps:span class="xps_endnote">1</xps:span> property *Uses*, as previously applied in the development of a computing educational ontology (Cassel et al., 2008). The topics were firstly categorised into classes and subclasses using parent topics as guidance. For example, some of the key parent topics related to chemical engineering are *Mathematics, ScientificFundamentals, Thermofluids, ReactionEngineering* and *Measurement*. Then, each parent topic has subclasses, which are considered to be subsets of the parent topic. e.g. *Engineering* has subclasses *ChemicalEngineering, MechanicalEngineering, BioSystemsEngineering*. As defined by eq. (3), (Appendix A) the subclasses inherit all the properties and restrictions on these properties from their superclasses. In order to link a topic that was considered as prerequisite learning for another topic, the object property *Uses* is defined to imply that a specific topic should be learnt prior to another topic. For example, relation *ReactionEngineering Uses Chemistry* implies that the topic Chemistry has to be learnt prior to the topic Reaction Engineering, as shown in Figure 2. By the same token the topic *ReactorKinetics* uses theory covered in *ChemicalReaction* and *ChemicalReactionEquation.*
The object property *isPartOf* implies that one topic, i.e. topic A, is a constituent part of another topic, i.e. topic B, and hence that topic A contributes toward the learning of topic B. An example of this is presented in Figure 3, where the mereology of *ProcessAnalysis* and *ReactionEngineering* are shown, and the transitive<xps:span class="xps_endnote">2</xps:span> object property *isPartOf* demonstrated. The transitive nature of the property means that, if *ProcessAnalysis isPartOf ReactionEngineering* meaning that the Process Analysis topic is the part of Reaction Engineering and *ReactionEngineering isPartOf ProcessPlant,* which means that Reaction Engineering is a part of the topic Process Plant, then by the virtue of transitive property it can be inferred that *ProcessAnalysis isPartOf ProcessPlant* meaning that the topic Process Analysis is also a part of the topic Process Plant. The functional property, *Uses* is also transitive, hence for simplicity these links are not visualised in Figure 3. Figure 4 shows module and topic classifications where indentation refers to the level in ontology subsumption. Each topic and learning outcome is governed by a set of restrictions, (determined by definition) which allows for semantic reasoning.
The restrictions of the presented ontology are listed in Table 2, observing the notation of Appendix A where a restriction is defined by the domain class S_i^J, the property $\mathrm{dom}\left(R_i^C\right)$ and a range that varies from a range class (S_j^R), to a natural number (n) (representing cardinality) or a value (v) (representing an ontology literal). For example, the *ObjectDifferentiationLO* (S_j^R) class is defined as a *LearningOutcome* (S_i^I) that is linked to at least one instance of topic *Differentiation* (S_j^R), through the *hasLearningOf* $\left(R_i^C\right)$ property. This example is also presented in Figure 5, where ∃ represents an existential restriction, = represent a necessary condition and ≡ represent a necessary and sufficient condition.

<H3>2.2.2 Learning outcome taxonomy and modelling

Each learning outcome has a learning verb that defines the learning level reflected in the six learning levels defined by Bloom (Bloom 1956). Associated with each learning verb are lists of verbs that define learning levels, e.g. verbs such as identify, recognize, describe and name are all knowledge verbs. Then, the learning verb relates to a learning object and context, which defines the scope and topic of learning. In the ontology learning outcomes presented by the high level concept *LearningOutcome* were linked to the context represented by a high level concept *Topic* (Figure 1) by the object property *hasContext.* In addition and to reflect learning verbs from Bloom, the superproperty *hasLearningOf* is used, which has five subproperties based upon the levels of learning, as defined in Bloom's taxonomy which inherit the domain and range from the superproperty (Table 1). In order to facilitate reasoning, the learning verb properties and their inverse properties were modelled as transitive properties. A list of the learning verb object properties and their inverse are given in Table 3.

The object and the context in the learning outcomes were found in the topic mereology. Thus, each learning outcome *hasLearningOf TopicX* and the learning outcome *hasContext TopicY.* The topic mereology, by construction, identifies prior learning, sub-topics and constituent topics which facilitates the functionality of the ontology reasoning. As topics are introduced by fixed learning outcomes, this approach minimises subjectivity effects of classification decisions. An example of how this was constructed is given in Figure 6 where two learning outcomes are featured from a first year module, Scientific Fundamentals (SCFU). The construction of the semantic model begins with the learning outcomes as described in the module descriptor, and the identification of the key learning verb, learning object and context. Each learning outcome is linked to a module, which in turn belongs to a year level. The learning verbs are classified into one of the learning levels as listed in Table 3. The learning object and learning context are taken from the learning outcome statement as shown in Table 4. In some cases the context of the learning outcome is not clear and requires some inference or additional knowledge of the subject. This information is normally found within the module aims on the module descriptor, if not already known. A full list of classified learning outcomes is given in Appendix B.

<H1>3. Results and Discussion

Once the ontology model was constructed, semantic reasoning was used to reclassify the knowledge of the model in ways which were meaningful to the user. The classification used the Pellet 1.5.2 reasoner which allowed for consistency checking, concept satisfiability, classification of classes and subclasses and realisation of which classes an instance belongs to, all according to the defined relationships within the ontology. This can be used for many different scenarios; however to demonstrate the functionality four case studies are chosen, i.e. horizontal integration, vertical integration, curriculum development through contextualisation of learning, and curriculum development through inclusion of new material.

<H2>3.1 Horizontal Integration in the First Year of Study

Horizontal integration aims to conceptually connect two co-current modules either through co-teaching or co-assessment. In order to probe the ontology for potential horizontal integration cases we use semantic reasoning to discover which contexts and learning objects are overlapped within two or more learning outcomes. Each learning outcome is attached to a module, which is taught at a specific level, within a specific semester and overlapping modules can be identified. Therefore, a specified class of learning outcomes is defined to find two or more modules with related learning via the learning outcomes. For example, considering the parent topic of *Measurement* we create two new classes asserted as subclasses of *LearningOutcome* and defined by the two following restrictions, *hasLearningOf some Measurement* and *hasContext some Measurement*, respectively. This leads to the reclassification, based on semantic reasoning, of any learning outcome which has any learning of the parent topic *Measurement* or learning of any subclass of *Measurement* as defined in the topic taxonomy into the class *ObjectMeasurmentLO*. Similarly, any learning outcome that has context of the parent topic *Measurement* or any subclass of *Measurement* is reclassified under *ContextMeasurmentLO* class. The ontology is reclassified to incorporate the new classes with the results displayed as in Figure 7, which demonstrates that within learning outcomes MAEB1, 3 (Mass and Energy Balances Module), TSLS2, 3 (Transferrable Skills and Laboratory Skills), MAT27 (Maths2) and CTLS4 (Chemical thermodynamics and Laboratory Safety) there are learning or contexts related to the parent topic *Measurement*. The learning outcomes were defined in the construction of the model, inclusive of restrictions relating to learning object and context, and restricted to their specific modules which facilitates reclassification and discovery. Once the modules are discovered, the user can see (by definition within the ontology) when the modules are taught, to further narrow down learning outcomes from the same semester. This discounts CTLS as this is done in second year while the other modules are done in first year, second semester. Hence three modules are identified by the user for potential horizontal integration, through the reclassification and navigation within the ontology using the Protégé interface. Then, from these results the actual keywords of the learning outcomes are discovered; as well as the required learning level (Table 5). The user can then use this new information to decide on new horizontal integration assessment relating to the outcomes within these modules.

Without a knowledge model, the search for horizontal alignment involves either expert knowledge of the curriculum at a certain year level and semester, or for the educator to research module descriptors and content to learn which concepts are presented that may overlap. Often the deliverer may not be a chemical engineering curriculum expert, such as a mathematics professor who delivers first year maths or a laboratory coordinator in first year and the review of content poses an arduous task. Moreover for the development of a standalone laboratory module, horizontal alignment can be used to ensure laboratory tasks are aligned with learning, either in the same semester or from past modules. Some learning outcomes are obviously linked, such as the learning outcomes, MAEB1, TSLS2,TSLS3, TSLS5 and MAT27 are obviously linked to measurement. However learning outcome MAEB3 has no obvious link to measurement and may not have been discovered through a non-expert review of module descriptors and content. Therefore the use of the knowledge model aids in decision making regarding horizontal alignment for both expert and non-expert users.

<H2>3.2 Vertical Integration: Identification of Prior Learning

The order of learning in chemical engineering is important as concepts learnt in earlier years are built upon in later years and students benefit from obvious vertical integration (Gomes et al., 2006). Here, the curriculum ontology is used to identify topics that were covered in previous modules, their level and their context. Considering the key skill of differentiation, which is applied in a third year module, the ontology is reclassified to identify the modules that offer differentiation as a learning outcome i.e. have learning of differentiation or have a learning outcome with the learning object of differentiation. The results displayed in Figure 8 demonstrate that differentiation Maths 1 module and Maths 2 modules both have learning of differentiation. In a similar manner to previously described, the individual learning outcomes with learning of differentiation are also discovered via reclassification, namely MAT14, MAT15 and MAT21, MAT22, MAT24.

By selecting a learning outcome, the various contexts of the differentiation are displayed for each learning outcome. In Figure 9, the learning outcome MAT21 is displayed and the context is *Engineering*. It is also useful to note that the development of the application of *Differentiation* is also evident. The context widens from *Mathematics*, to *MechanicalBehaviour* to *Engineering*. Then the application of differentiation delves into subclasses of differentiation (differentiation, ordinary differential equations, and partial differential equations) which demonstrate increased depth of the coverage of the topic.

In this case, differentiation was covered across two modules, within five different learning outcomes in various contexts and so would be covered to a sufficient level. Information on the number of learning outcomes relating to a key concept within a module can easily be extracted from the ontology. In this case differentiation was applied under two/six learning outcomes in Mathematics 1 and three/eight learning outcomes in Mathematics two. In addition, the context of *Differentiation* can be probed using reclassification, which discovers that an additional Learning Outcome, MAT26, with objects *Eigenvalues* and *Eigenvectors hasContextOf Differentiation*. This demonstrates some additional depth of learning within the context of differentiation. Hence, the breadth and depth of the coverage of core techniques within the curriculum can be discovered using the reclassification within ChEEdO.

The information about prior learning is useful when students demonstrate a lack of knowledge in what is considered a core or fundamental area at higher levels of the degree program. The educator who realises the lack of knowledge uses the ontology to check where and when related content was taught. If there is a gap in the curriculum, this can be identified and rectified, correspondingly if there is no gap then the teaching content likely requires improvement. The current alternative is a manual review of past modules and related content to firstly realise if and when relevant topics are covered, prior to the review of content for the purpose of vertical integration. In this way, the ontology model serves as a course management tool to identify gaps, overlaps and synergies (Ronchetti & Sant 2007). The course management, and related decisions regarding curriculum devepment are facilitated with reduced complexity and the consideration of competencies in multiple locations is enabled (Dexter & Davies 2009).

<H2>3.3 Curriculum Development: Contextualisation

In order to improve the student experience and ensure that subject content is relevant, curricula are constantly updated and evolving in time with technology enhancement. Often students are displeased with some areas of fundamental sciences and do not see their use in later years. The topics modelled within the ontology can demonstrate which other areas of chemical engineering relate to fundamental learning topics. This can also aid in the identification of core and non-core areas of the curriculum. For example, if the ontology is reclassified to group which concepts *Uses* the topic of *Differentiation* the results will include all of the concepts in the topic taxonomy which have been defined as using differentiation. Figure 10 shows the results of two reclassifications, one in relation to which topic *Use*s *Sustainability* and *Uses Differentiation*.

If a wider, or more ‘core’ topic areas are considered, then more hits are generated such as in Figure 11 where the reclassification was related to the use of Chemistry and Mass Balance. It should be noted that *MassBalance* is classified within the *UsesChemistry* classification as the concept of mass balance does indeed utilise chemistry principles. These results also demonstrate the transitive nature of the verbs where if a subclass of chemistry is used, this is included within the reclassification.

In this manner non-experts such as students and tutors are able to interact with the learning curriculum. Non-experts are likely to interact with the material in the way it is presented, i.e. within the modular structure that is taught. By facilitating an easy discovery of the wider context students gain appreciation of taught material and become more aware of the holistic nature of the curriculum. Similarly, non-expert tutors are able to contextualise the learning beyond that of the module which increases relevance and subsequent student interest. In this manner the ontology tool is able to present knowledge to those who were unlikely to engage in the curriculum in a wider context facilitating a more autonomous approach to learning and teaching.

<H2>3.4 Curriculum Development: Introducing New Material

When additional areas of learning are considered, the curriculum needs to be evaluated to consider what learning has been done in certain contexts in previous years. For example, we consider the development of additional learning about chemical and physical analysis at a third year level in the context of reaction engineering. It is known that the learning of these additional concepts requires knowledge of *MolecularPhysicalChemisty* to understand the mechanisms behind the analytical techniques. Hence the specific topic of *MolecularPhysicalChemisty* is added to the topic taxonomy, as a subclass of *PhysicalChemistry*. Firstly, the learning and context of Physical Chemistry is explored, via reclassification of the ontology under the subclasses, *PhysicalChemistryLO* and *ContextPhysicalChemistryLO.* However, no learning outcomes or modules are reclassified under these classes, hence physical chemistry was not a context nor a learning object of any of the modelled learning outcomes. Then, the user can consider the wider context that includes the class of *Physics* and *Chemistry* to understand the wider context of the prior learning. Hence four subclasses are created to probe where students were exposed to physics and chemistry, and their subclasses, namely: *ObjectPhysicsLO, ObjectChemistryLO, ContextChemistryLO* and *ContextPhysicsLO.* The results of this reclassification are shown in Figure 12. Where it is apparent that the prior learning material related to two modules, Scientific Fundementals (SCFU) and Chemical Thermodynamics and Laboratory Safety (CTLS) in three and four learning outcomes respectively. Therefore, when introducing the new concept of molecular physical chemistry, the academic can structure the new material to further develop the students' level with respect to prior learning.

In addition to the prior learning, contextualisation of the new material with old is desired. The additional learning of chemical and physical analysis was in the context of reaction engineering. Hence in order to assist the development of new material, identification of topics that contribute to reaction engineering is required. This can be done through the reclassification of topics that relate to the topic *ReactionEngineering* via the object property *isPartOf*. A reclassification is performed to identify these topics as shown in Figure 13. Here we can see related topics that could contribute toward contextualisation of the new material. Then, as previously demonstrated additional reclassification can identify where these topics were learnt and in which context.

Contextualisation with respect to prior knowledge allows for a constructivist approach for the learning of new material in the curriculum. The educator can identify prior learning and place the new material into context which is of benefit to the student. Current methods of development require the educator to review the curriculum content manually to identify linked topics which requires broad expert knowledge of the domain. In later years of study, new material may be introduced by specialists in parallel fields who do not have an in-depth knowledge of the chemical engineering curriculum. The knowledge model facilitates the introduction of the specialist knowledge in a familiar context for the students and enables the specialist to appreciate what learning material is appropriate. In a wider context decision making regarding the use of specialist knowledge and/or new material for curriculum development is assisted. Educators can identify if the required learning has been achieved and the likely relevance of a new topic to studied topics.

<H1>4. Implications

Here, an alternative to traditional curriculum development methodology has been presented for which functionality has been demonstrated for integration and contextualisation of learning as well as for introducing new material. Traditional methods of curriculum development require a high level of expert knowledge in the area, normally with several years of educational experience. However the use of a knowledge model facilitates curriculum development and review for non-experts such as new academics, learning administrators and students. This has applications in wider contexts such as degree accreditation, student transfer and exchange, and multi-disciplinary integration. Accreditation for chemical engineering involves demonstration of learning of specified concepts throughout the degree program. The ontology is easily able to be reclassified according to these concepts and the timing, context and level of learning discovered, assisting in the accreditation process. Hence the curriculum can be aligned or demonstrated to be aligned to accreditation requirements using the ontology tool. Similarly for curriculum development between accreditations, educators can use the ontology tool to ensure that accreditation will be maintained (Dexter & Davies 2009). In a similar manner student exchange or student transfer can be facilitated. Learning done at the home institution can be easily matched to learning within the presented degree program through the reclassification techniques demonstrated above. This can advise where a transfer student should enter a degree program, if additional prior learning is required and can advise which modules an exchange student should enrol in to meet home degree requirements. Further development of the ontology to include information such as European Credit Transfer and Accumulation System (ECTS) points and assessment details (exam, coursework, practical etc) to further facilitate exchange, transfer or accreditation. In addition, when the ontology is developed at an institutional or faculty level, integration of degree programs can be enabled allowing increased autonomy for students and facilitating multi-disciplinary degree programs. The holistic modelling of a program can determine the students' learning outcomes achieved which enables identification of possible breadth modules in later years, based on prior learning, increasing the pool of module available to students without requiring additional resources. In fact the ontology can become a tool to enable student-centred curriculum development as described previously (Cassel et al., 2008).

However one of the remaining challenges with the construction of such an ontology is semantic consistency within and across disciplines. Here, fixed module descriptors were used which enabled the development of the model from known data. In general degree programs include such module descriptors, constructed by the module leaders which must reflect the content and learning outcomes of the module. Therefore the initial development from learning outcomes or competency indicators is an effective way to commence the construction of the ontology, as previously described (Cassel et al., 2008, Chi 2009). However there remains a certain degree of subjectivity in the development of relationships within the topic taxonomy which must be agreed upon by users of the ontology and allow for flexibility for reclassification. The relationships of *isA, Uses* and *isPartOf* relates topics, which, in addition to learning levels are the key elements that define reclassification. Once reclassified, related topics are either automatically identified or can easily be navigated to (depending on the reclassification). Hence if the semantic relations in the model differ slightly from how the user may define them, wider relations are still identified through reclassification. In addition semantic differences or slight changes in language are able to be overcome using synonym identification within the construction of the model. Whilst differences may still exist, a careful, systematic approach to the construction of the model can minimise the issues that arise from semantic differences and subjectivity of definitions.

<H1>5. Conclusions

A method to model a chemical engineering curriculum using knowledge modelling and ontologies in specific was presented. The ontology was created using links from educational concepts extracted from the module descriptors for the chemical engineering degree program. The modelling employed semantic reasoning in order to provide new information relating to curriculum structure, horizontal integration, vertical alignment and curriculum development. Through reclassifications of the information in the ontology, core topics and learning relationships were identified in order to assess curriculum development options. The use of ontologies reduces the modelling effort while it increases the flexibility and reusability of the curriculum ontology. The validation of this method of curriculum modelling for chemical engineering education leads to future work such as completion of the ontology to reflect on the current status of the curriculum. Thereby allowing the development of a user interface that will facilitate the use of the ontology as a tool for curriculum design, from a wide range of academics, while removing the responsibility of ontology related tasks from the user. Future work will also involve probing for potential intra-institutional alignment, consideration of new modules and a potential general ontology for accreditation bodies.

Appendix A. Ontology formulation

As proposed, the curriculum development and review process is orchestrated by an ontology representing the domain of curriculum development for chemical engineering, e.g. classifications of modules, classification of learning outcomes and classification of topics, as well as the process of separation of materials from more complex materials, change management and supporting consultation and collaboration. More precisely, the n_M modules $x = \{x_1, x_2, \cdots, x_{n_M}\}$, n_L learning outcomes $y = \{y_1, y_2, \cdots, y_{n_L}\}$ and n_T topics $z = \{z_1, z_2, \cdots, z_{n_T}\}$ are all instances of the curriculum domain ontology, which takes format of a 6-tuple $O = \langle H^I, H_C, R_i^C, R^C, E^C, S_i^J \rangle$ consisting of:

i) n_I instances $s_i^J, J = \{M, L, T\}$ with each one representing curriculum entity, i.e. n_M instances representing modules ($J = M$), n_L instances representing learning outcomes ($J = L$) and n_T instances representing topics ($J = T$). Instances are characterised by a set of n_P properties, $P_i^{n_P} = \{p_{i,j} | i = 1, \cdots, n_I\}_{j=1}^{n_P}, p_{i,j} \overset{char}{\Longrightarrow} s_i^J$ and organised into classes S_i^J as

$$S_i^J = \{s_j^J\}_{j=1}^{n_C}, p_{i,j} := p_{i,k} \ \wedge \ \forall\, j, k \geq 0, j \neq k \qquad (1)$$

where n_C is the total number of instances sharing n_P common properties, that is instances with intensionally equal<xps:span class="xps_endnote">3</xps:span> properties $p_{i,j} := p_{i,k}$. For $j = 0$, in eq. (1) S_i^J is an empty class still having properties $p_{i,j}$ and generally used to enhance semantics of the ontology O. The properties $p_{i,j}$ are in ontology engineering referred to as data properties;

ii) A set of n classes $H^J = \{S_i^J\}_{i=1}^{n}$. Each class S_i^J is given a domain related and distinct name N_i^J and hence representing a concept with respective semantic. Note that the terms *class* and *concept* will be used interchangeably in this paper because concept is in essence a class with given name. As all instances s_i^J of a class S_i^J share the common properties (see eq. (1)), then the set of properties $P_i^{n_P}$ semantically describes the class S_i^I. Consequently, the intension I_i^J of the class S_i^J is defined as 3-tuple (Junli et al., 2006);

$$I_i^J := \langle N_i^I, P_i^{n_P}, S_i^I \rangle \qquad (2)$$

The significance of the intension I_i^J given by eq. (2) is in the fact that it defines the essence features of a concept including name, properties and instances associated with it.

iii) A graph $H_C = (S_i^J, isA)$ forming a subsumption hierarchy in ontology sense, called the *subsumption*, were isA indicates the edge between the nodes of the graph representing the classes (or concepts). As such, the edge isA represents class (S_k^J) - subclass (S_i^J) participation which assumes common instances (from a class to a subclass) and property inheritance (from a subclass to a class), such that

$$S_i^J \subseteq S_k^J, \forall\, P_k^{n_P} \subseteq P_i^{n_P} \ \wedge \ i \neq k \qquad (3)$$

In other words, instances of a subclass S_i^J are also instances of the class S_k^J. Also, all the properties $P_k^{n_P}$ of a class S_k^I are inherited by the subclass S_i^I. The two non-empty classes S_l^J and S_m^J are disjoint classes, if they do not share, or, more rigorously, are prevented from sharing instances such that $S_l^J \cap S_m^J = 0, \forall l \neq m$;

iv) <LIST ><iv)**1**>The class relationship R_i^C which is a set of bijective relationships $r_{i,j}$ between all elements of domain class S_i^J and range class S_j^J other than class-subclass participation (isA relationship) and which is defined as:</LIST>

$$R_i^C = \left\{ r_{i,j}\left(S_i^J, S_j^J\right) \middle| \forall \left(\left(S_i^J, S_j^J\right) \in H^J, i \neq j \right) \right\} \tag{4}$$

Here, the term $r_{i,j}\left(S_i^I, S_j^I\right)$ refers to a predicate calculus form. The relationships $r_{i,j}$ are also given unique names $N_{i,j}^R$ representing the associations between concepts which, in turn, further enhances the semantic of the ontology and forms the base for (tacit) knowledge representation. The relationships $r_{i,j}$ are in ontology engineering referred to as *object properties*;

v) n_R-dimensional subsumption R^C of properties R_i^C defined as

$$R^C = \left\{ r_{i.j}\left(S_i^J, S_j^J\right) \middle| \forall i \neq j \right\}_{i,j=1}^{n_R} \tag{5}$$

Note here that although the inclusion mapping $i = j$ in eq. (4) and (5) is generally possible, we exclude such a reflexive relationship for the purpose of simplifying the process without limiting practical aspect of the application in mind. For $r_{j,i}^{-1}$ being inverse instant relationship of $r_{i,j}$, then $R_i^{C^{-1}}$ $\left(= \left\{ r_{j,i}^{-1}\left(S_j^J, S_i^J\right) \middle| \forall \left(\left(S_j^J, S_i^J\right) \in S, i \neq j \right) \right\}\right)$ is the inverse class relationship of R_i^C The inverse relationships are also given unique names $N_{j,i}^R$ representing the 'opposite nature' of association between concepts S_i^J and S_j^J;

vi) Extension E^C of a class S_i^I which is defined by the relationship R_i^C which profiles the structural properties of the class by its relations with other classes (Junli et al., 2006). For S_i^D being a subset of relationship domain S_i^J and S_i^R being a subset of relationship range S_i^J, then the restriction of $S_i^J = \mathrm{dom}\left(R_i^C\right)$ to S_i^D is the partial function $f_D = \mathrm{dom} R_i^C|_{S_i^R}$ providing inclusion mapping $S \xrightarrow{f_D} S$ as

$$f_D : S_i^I \xrightarrow{f_D} S_i^D \tag{6}$$

and the restriction of $S_j^J = \mathrm{rang}(R_i^C)$ to S_j^R is the partial function $f_R = \mathrm{rang} R_i^C|_{S_i^D}$ providing inclusion map $S \xrightarrow{f_R} S$ as

$$f_R : S_j^I \xrightarrow{f_R} S_j^R \tag{7}$$

In consequence, f_D (and f_R) establishes the binary relationship between:

1. <LIST ><1.**1**>Domain class S_i^D and range class S_j^R based on universal and existential quantifiers over properties R_i^C of S_i^J,
2. <2.**1**>Doman class S_i^D and $n, n \in \mathbb{N}$, based on cardinality quantifiers over properties $P_i^{n_P}$ of S_i^J, and

3. <3.**1**>Domain class S_i^D and v, $v \in s_i \vee N$, based on equality quantifiers over properties $P_i^{n_P}$ of S_i^J.</LIST>

For R_i^C *and* R_j^C being the extensions of classes S_i^J and S_j^J, respectively, then S_i^J and S_j^J are equivalent classes, if $R_i^C = R_j^C$and if $S_i^J \cap S_j^J = S_i^J \cup S_j^J$.

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Junli, W., Zhijun, D. & Changjun, J., 2006. GAOM: Genetic Algorithm based Ontology Matching. In *IEEE Asia-Pacific Conference on Services Computing (APSCC'06)*.

Appendix B: Table of Interpreted Learning Outcomes

Code and title, Learning Outcomes	**Verb (Bloom)**	**Object**	**Context**	***notes***	**CODE**
LEVEL 1					
Scientific Fundamentals					SCFU
Distinguish between the function of different biological systems and cell organelles	Distinguish (Co)	Organelle Biological systems functions	Biology		1
Describe and classify enzymes and enzymatic reactions	Identify (K)	Enzymes	Biological systems		2
Design and appreciate simple bioengineering processes based on simple biological knowledge	Design (S)	Biological systems	BioSystems engineering		3
Derive and describe basic chemical equations	Derive (An)	Chemical equations	Chemical reactions		4
Appreciate the properties and behaviour of various chemical solutions	Explain (Co)	Properties Behaviour	Mixtures		6
Appreciate the relevance of chemical equilibrium to the requirements of chemical processes	Explain (Co)	Chemical equilibrium	Chemical processes		5
Appreciate the universal application o Newton's laws to everyday engineering	Apply (Ap)	Newton's laws	Engineering		7
Describe the link between the behaviour of molecules and bulk thermodynamic properties such as specific heat capacity	Interrelate (An)	Molecular behaviour Thermodynamic properties	Chemical mixtures		8
Mass and Energy Balances					MAEB
Recognise the foundations of different unitary systems and convert quantities between them.	Convert (Co)	Units of measurement	Measurement data		1
Explain the Ideal Gas laws and confidently analyse systems containing ideal gas mixtures	Apply (Ap)	Ideal gas laws	Ideal gas systems		2
Confidently use saturated vapour pressure data to analyse single component vapour-liquid equilibrium and using Raoult's Law and Gibb's phase rule extend this analysis to multi component liquid/gas/vapour systems	Analyse (An)	Pressure data (measurement) Raoults Law (law of an ideal solution) Gibbs phase rule (law of mixtures)	Multi-component liquid/gas/vapour systems (Mixtures)		3

Demonstrate an ability to formulate a solution and solve process material balances which may involve any combination of the following: reactions, multiple phases, multiple series or parallel process units, recycle/bypass/purge.	Solve (Ap)	Material balance *denoted as Mass Balance*	Chemical engineering systems		4
Recognise the need for and be able to accurately calculate process energy balances	Calculate (Ap)	Energy balance	Chemical engineering systems		
To confidently integrate process material and energy balances for both reactive and non-reactive systems with and without phase change	Integrate (Ap)	Material balance Energy balance	Chemical engineering systems		5
Transferrable Skills and Laboratory Skills					TSLS
Demonstrate an ability to prepare, perform and effectively report experimental investigations	Produce (Ap)	Written report	Practical laboratory		1
Demonstrate an awareness of the principles and importance of experimental measurement	Apply (Ap)	Experimental measurement	Practical laboratory		2
Analyse and interpret experimental data	Analyse (an)	Measurement data	Practical laboratory experiments		3
Conduct academic research with a knowledge of the resources available to you	Apply (Ap)	Academic research	Chemical engineering		4
Handle your academic resources with academic integrity				*Encompassed in 4*	
Present and structure your work in a formal academic style				*Encompassed in 1*	
Use MS Excel in support of your academic studies, especially in handling experimental data	Apply (Ap)	MS Excel	Measurement data		5
Structure and deliver a short oral presentation, chair presentations and provide verbal feedback after a presentation	Criticise (E)	Oral presentation	Chemical engineering		6
Demonstrate a movement towards independent development of transferable skills commensurate with level 1				*Encompassed in all*	
Industrial Chemistry					INDC

Discuss the manufacture of some important inorganic and organic chemicals	Discuss (Co)	Manufacture process Chemical Processes	Chemicals (Sub class inorganic and organic)		1
Understand the origin and winning of the starting materials for these important chemicals e.g. extraction of materials from ores – mining and manufacturing	Comprehend (Co)	Source material	Industrial chemical processes		2
Discuss and explain the factors affecting the location of specific chemical industries	Comprehend (Co)	Geo-effects	Industrial chemical processes		3
Appreciate the regulatory frameworks in which the modern chemical industries exist	Explain (co)	Regulations	Chemical industries		4
Engineering Materials and Sustainability					EMAS
Demonstrate a qualitative and quantitative understanding of the mechanical behaviour of metals, ceramics, polymers and composites and the parameters which govern the use of these materials in engineering applications	Comprehension (Co)	Mechanical Behaviour	Materials	*Materials encompasses the subgroups mentioned.*	1
	Comprehension (Co)	Material parameters	Mechanical behaviour		3
Demonstrate knowledge of the interactions and integration management between engineering (process) systems, environmental and bio-systems and socio-economic enterprise systems in sustainable development	Interrelate (An)	Engineering Environment SocioEconomics	Sustainable development		2
Have gained experience in group working to deliver a written report	Co	Written report	Group work		4
Fluid Mechanics and Thermodynamics					FMTD
Demonstrate a comprehensive understanding of scientific principles and methodology relating to fluid statics, dynamics and the 1st law of thermodynamics	Explain (Co) Explain (Co) Apply (Co)	Fluid statics Fluid dynamics 1st law of thermodynamics	Thermofluids		1
Apply mathematical and scientific models to problems in basic thermo-fluids and appreciate the assumptions and limitations inherent in their application	Apply (Ap)	Math models (*in maths)*	Thermofluids		2

Describe the performance and characteristics of thermo-fluid systems and processes	Describe (K)	Characteristics	Themofluids		3
Demonstrate understanding of sustainability principles in energy generation and conversion processes using carbon fuels and alternative resources	Explain (Co)	Sustainability principles	Energy conversion	*Generation is a form of conversion*	4
Undertake a brief research topic and evaluate of a simple thermodynamic system to estimate its energy efficiency	Evaluate (E)	Simple thermodynamic system	Energy efficiency		5
Mathematics 1					MA T11
Use of vector algebra and applications of this to mechanics	Apply (Ap)	Vector algebra	Mechanics		1
Manipulation of standard functions	Manipulate (Ap)	Standard functions	Mathematics		2
Use of complex numbers	Apply (Ap)	Complex numbers	Mathematics		3
Use of the techniques of differential and integral calculus for functions of one variable	Apply (Ap)	Integration Differentiation	Mathematics	*The application exceeds the use*	4
Application of differentiation and integration to determine physical engineering properties e.g. in mechanics	Apply (Ap)	Integration Differentiation	Mechanical properties		5
Manipulation of simple series and their use in e.g. approximations	Apply (Ap)	Series	Mathematics		6
Mathematics 2					MA T2
Select and apply appropriate techniques of differential and integral calculus to engineering problems	Select (Ev)	Differentiation Integration	Engineering problems	*To select application must already be achieved.*	1
Solve straightforward ordinary differential equations as encountered in engineering problems	Solve (Ap)	Ordinary differential equations	Engineering problems		2
Discuss the role of mathematical modelling and be able to produce and explain simple mathematical models of physical problems	Produce (Sy)	Mathematical models	Physical problems	*To produce you must be able to explain*	3
Solve typical engineering-related second order partial differential equations	Solve (aP)	Partial differential equations	Engineering problems		4
Manipulate matrices in appropriate contexts and use matrix methods to solve sets of linear algebraic equations	Solve (Ap)	Sets of linear equations	Matrices		5

Determine matrix eigenvalues and eigenvectors, use to solve engineering systems modelled by differential equations and relate the results to characteristics of the physical system	Evaluate (Ap)	Eigenvalues Eigenvectors	Differentiation Physical problems		6
Present and summarise simple statistical data graphically and numerically	Analyse (An)	Data	Statistics		7
Recognise appropriate probability distributions and use them to calculate probabilities and apply to e.g. simple ideas of quality control	Interpret (Ap)	Probabilities	Statistics		8
LEVEL 2					
Chemical Reaction Engineering and Numerical Methods					CR NM
Explain the operation of homogeneous batch, CSTR, plug flow reactors and confidently propose the appropriate reactor for a specified duty	Choose (Ev)	CSTR PFR Batch	Reaction engineering	*Have parent class 'reactors' with 'children' as PF, CSTR and Batch*	1
Propose a reactor design and methodology and then correctly solve the volumetric design of batch CSTR and plug flow reactors processing simple reversible and irreversible reactions operating under both isothermal and thermal conditions	Design (S)	CSTR PFR Batch	Chemical engineering		2
Explain the complexity of reactor design, the need for safe design and the responsibilities of the designer of chemical reactors	Explain (Co)	Safety	Reactor design		3
Use a range of standard numerical methods to solve complex engineering problems	Apply/solve (Ap)	Numerical methods	Engineering problems		4
Use Matlab and programming as a tool to solve engineering problems particularly those associated with homogeneous reactor design	Use (Ap)	Matlab	Reactor design		5
Chemical Thermodynamics and Laboratory Safety					CT LS
Calculate the energy changes involved in chemical composition and physical state changes	Calculate (Ap)	Energy conversion	Physical changes Chemical reactions		1

Calculate chemical and phase equilibria for ideal and non-ideal systems from readily available physical property data and state equations	Calculate (Ap)	Phase and chemical equilibria	Ideal and non-ideal systems		2
Recognise the principles whereby process flow-sheeting programmes use chemical thermodynamics to model equilibrium conditions in various unit operations	Recognise (K)	Chemical thermodynamics	Flowsheeting Process plant unit operation Chemical equilibrium		3
Record analyse and present experimental data from small – scale laboratory equipment that depict a range of chemical engineering plant / operations	Analyse (An)	Experimental data	Chemical engineering plant / operations		4
Operate small-scale lab equipment	Apply (Ap)	Experimental techniques Practical laboratory techniques	Small-scale lab equipment / chemical engineering		5
Plan experiments to solve chemical engineering problems and / or validate theoretical concepts underlying chemical engineering operations				*Encompassed in 5*	
Recognise the safety and legal processes involved in performing laboratory experiments	Recognise (K)	Lab safety	Practical laboratory		6
LEVEL 3					
Chemical and Biological Reaction Engineering					CBRE
Explain the mechanisms which occur in bioreactors, heterogeneous catalytic and non-catalytic reactors	Explain (Co)	Reaction mechanisms	Bio-reactors Heterogeneous catalytic reactors Heterogeneous non-catalytic reactor		1
Recognise the rate limiting factor for bioreactors, heterogeneous catalytic and non-catalytic reactors	Analyse (An)	Rate limiting factor	Bio-reactors Heterogeneous catalytic reactors Heterogeneous non-catalytic reactor	*Even though it is a comprehension verb, it requires analysis*	2
Derive from first principles kinetic expressions and concentration profile expressions for catalytic and non-catalytic reactors as well as bioreactors	Derive (S)	Kinetic expressions Concentration profile expressions	Bio-reactors Heterogeneous catalytic reactors Heterogeneous non-catalytic reactor		3
Discuss the analytical and experimental techniques for the characterisation of various reactors and reactor elements in chemical and biochemical engineering.	Discuss (Co)	Chemical analysis Physical analysis	Reactor characterisation		4

Evaluate the reactor characteristics in bioreactors and heterogeneous catalytic and non-catalytic reactors	Evaluate (Ev)	Reactor characteristics	Bio-reactors Heterogeneous catalytic reactors Heterogeneous non-catalytic reactor	5

<H1>6
<H1>7
<H1>3. **<REF>References**
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<Figure>Figure 1. The high level structure of ChEEdO

<Figure>Figure 2. An excerpt of ontology and the implementation of the object property Uses

<Figure>Figure 3. A representation of the two parent topics, ReactionEngineering and ProcessAnalysis

<Figure>Figure 4. The Protege 3.5 interface demonstrating the range of parent topics and modules covered.

<Figure>Figure 5. Example of a restriction to define a reclassification subclass ObjectDifferentiationLO

<Figure>Figure 6. An example of mapping two learning outcomes, SCFU1 and SCFU2, each with context and learning objects

<Figure>Figure 7. Demonstration of the reclassification of learning outcomes related to Measurement.

<Figure>Figure 8. Results of the LearningOf Differentiation reclassification.

<Figure>Figure 9. Example of selected learning outcome.

<Figure>Figure 10. Results from the two reclassifications about topics which UsesDifferentiation and UsesSustainability.

<Figure>Figure 11. Results from two queries about which topic Uses Chemistry and MassBalance.

<Figure>Figure 12. A reclassification to investigate where chemistry and physics were covered in the curriculum.

<Figure>Figure 13. Topics that contribute to the topic ReactionEngineering.

Tables

<Table>Table 1. Object properties and their characteristics

Object Property	**Domain**	**Range**	**Inverse Property**	**Transitive?**
hasLearningOf	*Module* *LearningOutcome*	*Topic*	*isLearntIn*	Y
hasContextOf	*LearningOutcome*	*Topic*	*isContextIn*	N

isPartOf	*Topic*	*Topic*	NA	Y
Uses	*Topic*	*Topic*	NA	Y

<Table>Table 2 Indicative high level restrictions

Domain Class (S_i^J)	Property dom(R_i^C)	Type	Value Range ($S_j^R/n/v$)
Module	*hasLearningOf*	some	*LearningOutcome*
LearningOutcome	*hasContext*	some	*Topics*
LearningOutcome	*hasLearningOf*	some	*Topics*
LearningOutcome	*isLearntIn*	some	*Module*

<Table>Table 3. Properties used to describe learning outcomes and the level of learning

Learning Level	**Learning Verb**	**Inverse Learning Verb**
	hasLearningOf (Parent verb)	*isLearntIn (Parent inverse verb)*
Knowledge (K)	*hasKnowledgeOf*	*isKnownIn*
Comprehension (Co)	*hasComprehensionOf*	*isComprehendedIn*
Application (Ap)	*hasApplicationOf*	*isAppliedIn*
Analysis (An)	*hasAnalysisOf*	*isAnalysedIn*
Evaluation (Ev)	*hasEvaluationOf*	*isEvaluatedIn*
Synthesis (S)	*hasSynthesisOf*	*isSynthesisedIn*

<Table>Table 4. Construction of the semantic model based on learning outcomes

1080 Scientific Fundamentals: Learning outcomes	Learning Verb	Learning Object	Context	Code
Distinguish between the function of different biological systems and cell organelles.	Distinguish (Co)	-Cell organelle -Biological systems	Biology	SCFU1
Describe and classify enzymes and enzymatic reactions.	Describe (K)	Enzymes	Biological systems	SCFU2

<Table>Table 5. Demonstration of verbs and objects related to the context and learning Measurement.

Learning Outcome Code	**Learning Property**	**Learning Object**	**Context**
MAEB1	*hasComprehensionOf*	Units of measurement	Measurement data
MAEB3	*hasAnalysisOf*	Pressure data Raoult's Law Gibbs phase rule	Mixtures
TSLS5	*hasApplicationOf*	MS Excel	Measurement data

TSLS2	*hasApplicationOf*	Experimental measurement	Practical laboratory
TSLS3	*hasAnalysisOf*	Measurement data	Practical laboratory experiments
MAT27	*hasAnalysisOf*	Measurement data	Statistics

TDENDOFDOCTD

<en><xps:span class="xps_label">1</xps:span>For a functional property there can be at most one instance that is related to another instance via that property. Mathematically, if a property P is tagged as functional, then for all individuals s_1^J, s_2^J and s_3^J we have $P\left(s_1^J, s_2^J\right) \& P\left(s_1^J, s_3^J\right) \Rightarrow s_2^J = s_3^J$.

<en><xps:span class="xps_label">2</xps:span>If a property P is transitive, and the property relates individual s_1^J to individual s_2^J, and also individual s_2^J to individual s_3^J, then we can infer that individual s_1^J is related to individual s_3^J via property P as $P\left(s_1^J, s_2^J\right) \& P\left(s_2^J, s_3^J\right) \Rightarrow P\left(s_1^J, s_3^J\right)$.

<en><xps:span class="xps_label">3</xps:span>Two instances are intentionally equal, if they have the same structure of the properties, not necessarily the same property values.