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# An Ontology Model for Systems Engineering Derived from ISO/IEC/IEEE 15288: 2015: Systems and Software Engineering - System Life Cycle Processes

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***Abstract*—**ISO/IEC/IEEE 15288: 2015, Systems and Software Engineering - System Life Cycle Processes is an international standard that provides generic top-level process descriptions to support systems engineering (SE). However, the processes defined in the standard needs improvement to lift integrity and consistency. The goal of this research is to explore the way by building an ontology model for the SE standard to manage the knowledge of SE. The ontology model gives a whole picture of the SE knowledge domain by building connections between SE concepts. Moreover, it creates a hierarchical classification of the concepts to fulfil different requirements of displaying and analysing SE knowledge.

***Keywords*—**Knowledge management, model-based systems engineering, ontology modelling, systems engineering ontology.

## I. Introduction

IN the past decade, more data has been collected, more information has been published and more knowledge has been shared than in all of previous human history. With all this new information (also known as 'Big Data') and all these new systems (also known as 'Big Systems'), there has also been an associated growth in the research of interoperability among federated systems and interdisciplinary collaborations [1]. This exploration results in the development of the discipline of SE - an approach and standard that enables the realization of successful systems or even system of systems. A well-known standard is entitled as ISO/IEC/IEEE 15288: 2015, Systems and Software Engineering - System Life Cycle Processes (hereafter referred to as ISO/IEC/IEEE 15288: 2015), which is an international standard that provides generic top-level process descriptions to support SE. In 2015, the International Council on Systems Engineering (INCOSE) published its fourth edition of the Systems Engineering Handbook (hereafter referred to as the INCOSE guide), which is not only the newest practical guide that is consistent with ISO/IEC/IEEE 15288: 2015 in the four groups of processes that ISO/IEC/IEEE 15288: 2015 identifies - technical processes, technical management processes, agreement processes, and organizational project-enabling processes - but also provides additional guidance on how to conduct tailoring processes in the implementation of SE [2]. However, the processes defined in the standard lack integrity and consistency due to an isolated illustration called an input–process–output (IPO) diagram, which shows key inputs and resulting outputs of a single SE process, but does not offer any connections between processes. For instance, an input of a process can be an output of another process, while an output of a process may act as an input of another process. The IPO diagram presents one process at one time but the SE process is a life cycle process and consequently, should have a whole picture of an entire life cycle. Since the implementation of SE process not only requires a whole and systemic blueprint, but also needs a specified and detailed tracing of each input or output, there is a need for a model that can be used to define each process, to classify the SE elements, to clarify the relationships, and also to unify the terminology among interdisciplinary engineers.

A solution can be found by using information and knowledge modelling techniques. By identifying relevant elements within a specific SE process, placing them in a knowledge-based information model and referring to these elements from other process descriptions, it would significantly improve the integrity and consistency of the processes, and therefore, the interoperability. To enable the implementation of SE in a proper way, there is an urgent need to transform the SE knowledge into consistent, explicit and unambiguous process descriptions [3]. By means of a hierarchical representation of SE knowledge to contain all the relevant elements and their relations, it is known as *ontologies* nowadays [4]. Also, a common SE ontology is an enabler for standardization [5], and will fundamentally change the way in which systems are constructed [6].

In order to address this problem, this research explores the way to build an ontology for SE knowledge domain, based on ISO/IEC/IEEE 15288: 2015 SE standard, by adopting a six-phase methodology.

The finished ontology model contains 590 classes and 1669 logical axioms, which are the key concepts described in the ISO/IEC/IEEE 15288: 2015 and the INCOSE guide. The ontology model infers the hierarchy of the objects based on the constraints made by the properties, which are also known as the logic level of the ontology model. Moreover, the ontology model also links processes into a big network, and it is the object flows that build up the entire network, where an object is the input, output, control, or enabler of a process. Each class defined in the ontology model, no matter if it is a process or an

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object, is able to be an entry to view the SE knowledge domain, and can be extended with any other classes it may connect.

## II. Indicative Literature Review

SE is an interdisciplinary approach and means to enable the realization of successful complex systems. In recent years, SE has witnessed a steady flow of guidelines and standards [7]. For instance, ISO/IEC/IEEE 15288: 2015 is established to create a common framework of processes and associated terminologies from an engineering viewpoint; the Guide to the Systems Engineering Body of Knowledge (SEBoK) presents the knowledge that is the most relevant and important to the advancement of SE; the INCOSE guide gives a guideline for system life cycle processes and activities. Reference [5] demonstrates that the reason for the emerging of these guides is that the standardization is essential when applying SE approaches across teams, organizations, and industries in order to ensure consistency. However, the standards or guides are not directly helpful to the following two situations. As interdisciplinary applicants, system engineers must ensure the terminology shared among engineers from different disciplines and backgrounds, but involved in a common project, is well communicated and successful [8]. Meanwhile, with systems becoming more complex, system engineers also have the need for a method to capture and manage implicit knowledge for corporations, while the systems architecting discipline also grow fast [9]. These two requirements are not fulfilled by the standardization which is remaining to be urgently solved.

To address the problems, building ontologies for SE knowledge needs to be considered. Ontologies are engineering artefacts [10]. The name of ontology includes lots of different types of artefacts created and used in different communities [11]. Ontologies represent a shared understanding of concepts and relationships of a domain. They help to manage and exploit information. Ontologies clarify meanings among people in the form of explicit knowledge that can be executed by software, model processes and decision-making, and improve agility and flexibility while reducing costs.

As a result, an ontology for SE knowledge is essential and beneficial to promote the application of SE processes, SE thinking, and SE standards. Meanwhile, it helps to unify the semantics, and to capture and manage implicit knowledge of SE.

## III. Research Questions and Aims

SE is not only interdisciplinary in that it seeks to improve the way engineers from different disciplines work together, but at the same time, it also faces the challenge to communicate an evolving system concept and design with stakeholders who are non-engineers. Reference [12] shows that a common taxonomy will be a good start in the direction of enabling interdisciplinary collaboration. This research is exactly to explore the way to build an ontology for an SE knowledge domain, based on an authoritative SE standard: ISO/IEC/IEEE 15288: 2015 and its supportive handbook published by INCOSE. To ensure that the different applications shared a common terminology is the essence of the SE knowledge sharing and reuse. An ontology model for SE can make comprehensive definitions of SE processes, classify the SE knowledge, clarify the relationships contained in the knowledge, and unify the terminology among interdisciplinary engineers. Based on the above background, the research problems of this study are determined as follows:

1) How to classify and manage SE knowledge with a unified terminology?
2) How to analyse the SE processes as a whole?
3) What are the objects participated in or produced by each process?
4) What processes does an object go through in the life cycle of a system?

The aims and objectives of this research are:

1) To create a hierarchical classification of the concepts involved in SE knowledge to fulfil different requirements of displaying and analysing.
2) To give a whole picture of the SE knowledge domain by building connections between SE concepts.
3) To automatically generate the view of the IPO diagrams of each SE process.
4) To track the flow of the objects going through the SE processes in the life cycle.

## IV. Research Methodology

In order to support the development of ontologies, several methodologies have been proposed to date, facilitating the process of ontology development and ontology engineering. Ontology engineering is a discipline that investigates the principles, methods, and tools for creating and maintaining ontologies. An ontology engineering methodology caters the methodological aspect of ontology development. It gives a set of guidelines and activities to develop ontologies. A literature review shows that despite the fact that quite a number of ontology development methodologies have been proposed over the last two decades, the field still lacks widely accepted methodologies [13]. The main reason is that most methodologies applied for developing ontologies are a target to a project, which does not unveil much insight to encourage others to adopt it. Therefore, a series of related methods are considered and reviewed in the following statement. Reference [14] published the general steps about the Cyc development, which is an artificial intelligence project that attempts to assemble a comprehensive ontology and knowledge base of everyday common sense knowledge. Some years later, in 1995, on the basis of the experience gathered in developing the Enterprise Ontology [15] and the TOVE (TOronto Virtual Enterprise) project ontology [16] (both in the domain of enterprise modelling), guidelines for building ontologies were suggested. The methodology METHONTOLOGY [17] appeared one year later. Reference [18] brought up the On-To-Knowledge methodology as a result of the project with the same name in 2001. Reference [19] proposed a guide for developing domain ontologies in the same year, which has more universality than others published by Noy and McGuinness. Among the approaches, this research takes the Noy and McGuinness method as a reference, but modifies and tailors a lot according to the goals and aims. The research methodology used in this study is illustrated in Fig. 1.

Six distinct phases are used in order to conduct this research, which are:

1) Phase 1: Identify the scope: This phase incorporates defining the problem, identifying the gaps, targeting the study, and determining the scope of the research.
2) Phase 2: Choose the method: This phase involves comparing existing methods for developing an ontology, choosing the suitable one as references, and tailoring it to fulfil the study undertaken.
3) Phase 3: Collect data: This phase is collecting raw data so as to build data foundation for the study.
4) Phase 4: Build ontology: This phase comprises developing the hierarchy of the ontology model, designing use cases for further investigations, populating the ontology model with SE data, and validating the ontology model.
5) Phase 5: Analyse ontology: This phase is conducting analysis on the ontology model and implementing reasoning of designed use cases to fulfil the required goals.
6) Phase 6: Draw conclusions: The final phase is drawing conclusions from the previous analysis and suggesting future research directions.

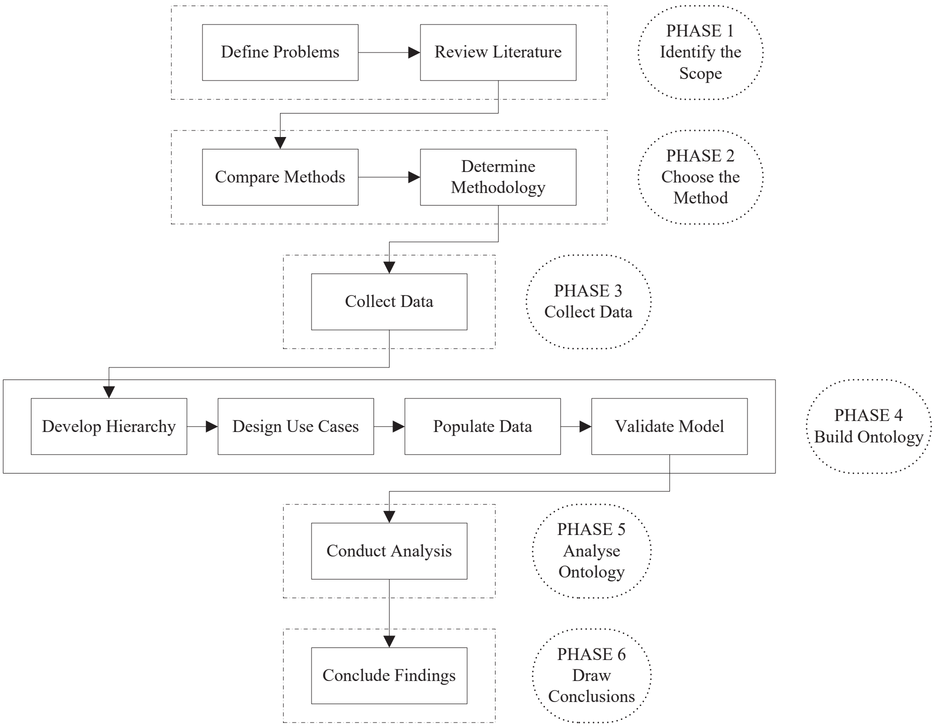


Fig. 1 Research methodology

## V. Findings

Firstly, concepts as being inputs, outputs, controls, and/or enablers are categorized with a multiple-choice condition, but also keep a consistency. Furthermore, as for the concepts being as outputs, the ontology model clarified their whereabouts, which are a) to be as an input to other processes, b) to be as a control to other processes, c) to be as an enabler to other processes, and finally d) to be as a final output. An output should belong to at least one of these four categories but it can be some or all of them at the same time. For example, there is a special class of input named as *OutputAsInput*, which means the classes under the *OutputAsInput* are as outputs in a process but are as inputs in another process. In other words, these objects are intermediate products. The Reasoner found 85 of these kinds of inputs in total, such as *AcquisitionNeed*, *ConfigurationBaselines*, etc.

Secondly, in the ontology model, each process is fully defined by properties and linked with appropriate objects. An example is illustrated in Fig. 2 which any IPO diagram can be represented in the same structured way. In Fig. 2, the yellow dash line represents the input relation (with an *isInputOf* property logically supporting behind) and the grey dash line represents the output relation (with a *hasOutput* property logically supporting behind). What the original IPO diagram cannot realize but is achieved by the ontology model is to trace every object's origin and whereabouts. For example, in Fig. 3, besides the inputs and the outputs of the *MaintenanceProcess*, the ontology can trace back and forth. This is also a network that connects and integrates the processes and objects together.

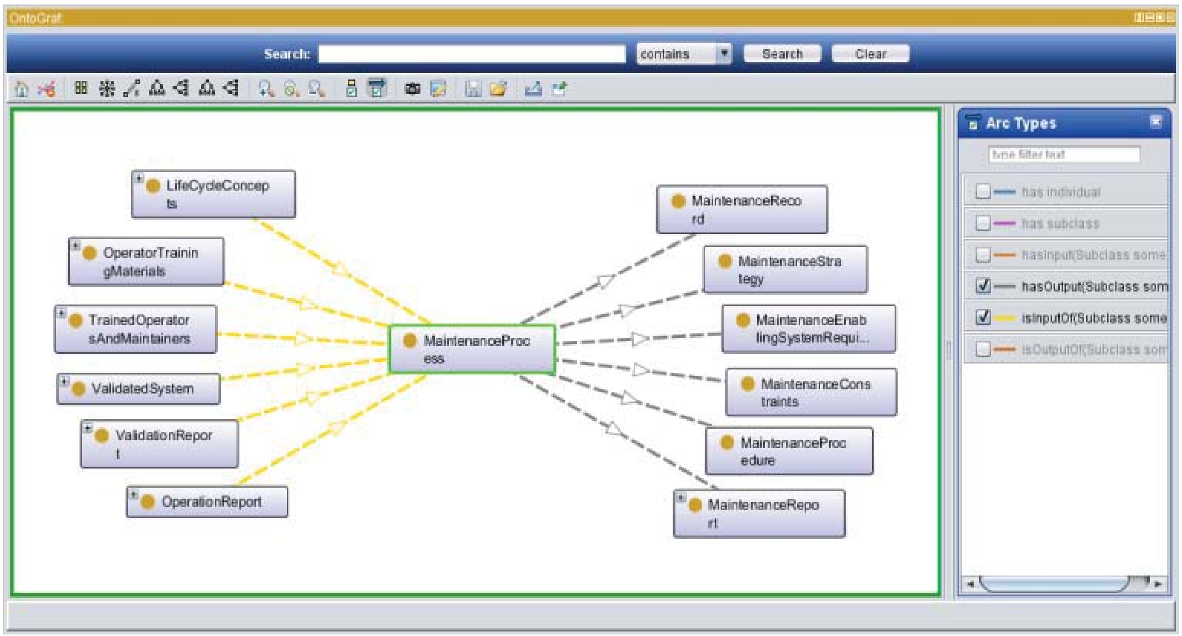


Fig. 2 Restore the IPO diagram by the ontology model

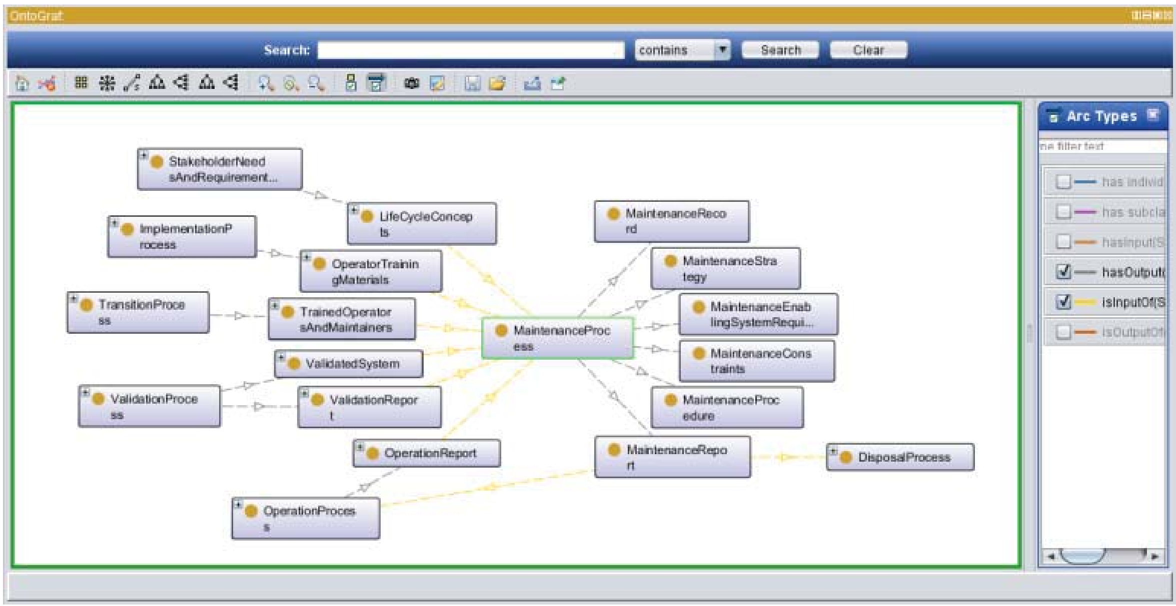


Fig. 3 Present SE knowledge from the process perspective

Thirdly, the SE process is a set of interrelated or interacting activities, which transform inputs into outputs. This is from the process perspective to define a process. However, the processes are not isolated, but are linked by the objects. Thus from the object perspective, it is the workflow of processing an object. Fig. 4 shows another achievement of the ontology model by taking ProjectDirection as an example. ProjectDirection is the organizational direction to the project that includes sustainment of projects meeting assessment criteria and redirection or termination of projects not meeting assessment criteria. As can be seen in Fig. 4, the ProjectDirection is an object (the purple straight line) and is also an intermediate product that is produced by PortfolioManagementProcess as an output (grey and purple dash lines). And then, it goes through ProjectPlanningProcess as an input (orange and yellow dash lines). It also acts as a control to NamedProcess (purple straight lines), which can be inherited by every superclass-subclass under the NamedProcess, which is categorized into five classes – the TailoringProcess, the TechnicalProcess, the AgreementProcess, the *TechnocalManagementProcess*, and the *OrganizationProjectEnablingProcess*.

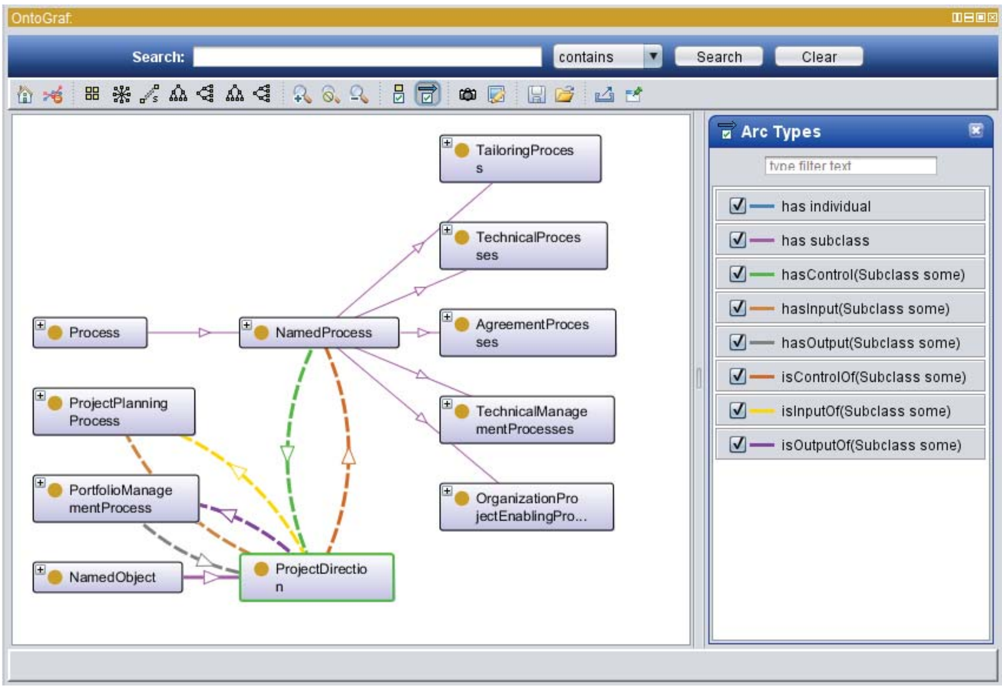


Fig. 4 Present SE knowledge from the object perspective

Finally, the ontology model contains 590 classes and 1,669 logical axioms in total. The quantity of properties is 10, and five of them are inverse properties to the other five. The annotation in the ontology model has a count of 2,046. The classes involved in the ontology are from the four processes defined in the ISO/IEC/IEEE 15288: 2015 and one tailoring process defined in the INCOSE guide. The hierarchy of the process classes strictly follows the definition in the ISO/IEC/IEEE 15288: 2015.

## VI. Discussion

The ontology presented in this paper, based on ISO/IEC/IEEE 15288: 2015 intents to be a practical approach of SE. Based on several experiences implementing an ontology, as described in this paper, requires executive management support, as well as project leaders and engineers with adequate skill, and competences to handle abstract and subjective matters that come with working with a taxonomy and ontology.

One of the important outcomes is that the finished ontology model gives multi-views of SE knowledge domain.

From the process's view, the ontology model can exhibit any process with its inputs, outputs, controls, and enablers that are defined as objects in the model, which is similar to the function of an IPO diagram. An object could act as a link between two processes, which create a chance to identify the relationship between two processes. The object between two processes becomes a messenger driving the whole SE process forward to a direction. Since the whole SE process contains so many objects, the ontology model serves as a terminology database with the information within the internal relationship between processes. On the other hand, from the object's view, the ontology model defines each of the objects by endowing values of properties. As a result, besides a textual definition, the ontology model makes it easier to understand the function of an object. The object could be regarded as a focus to restructure the SE process.

Another significant point is that the ontology model infers the hierarchy of the objects based on the constraints made by the properties, which are also known as the logic level of the ontology model. Moreover, the ontology model also links processes into a big network, and it is the object flows that build up the entire network.

SE processes may or may not fully apply to a given organization and/or project. Most are accompanied by a recommendation to adapt them to the situation at hand. The principle behind tailoring is to ensure that the process meets the needs of the project, while being scaled to the level of rigor that allows the system life cycle activities to be performed with an acceptable level of risk. Tailoring scales the rigorous application to an appropriate level based on need. In the implementation of SE processes, tailoring process is a necessary process to satisfy particular circumstances or factors. At the organization level, the tailoring process adapts external standards in the context of the organizational processes to meet the needs of the organization. At the project level, the tailoring process adapts organizational processes for the unique needs of the project. But when tailoring the processes, it is hard to know which objects are tailored or omitted because of tailoring the processes it participates in. Also, many of the processes described in the ISO/IEC/IEEE 15288: 2015 are being employed to handle the complexity but using a different terminology. The ontology model could guarantee the conceptualization of semantic clarity and consistency, and make better tailoring process when carrying on SE processes.

## VII. Conclusions and Contributions

By identifying relevant elements within a specific SE process, placing them in a knowledge-based information model and referring to these elements from other process descriptions, the model significantly improves the integrity and consistency of the processes, and therefore the interoperability. It serves as a knowledge base, which can express the knowledge of SE more flexible and can eliminate the conflicts between the definitions. The hierarchical classification of SE processes is created to accommodate new SE knowledge that can integrate broad and new knowledge-based terminologies for information gathering, integration, and sharing. It also serves as an international and multilingual reference standard for scientific comparability and communication purpose.

The finished ontology model contains the key concepts described in ISO/IEC/IEEE 15288: 2015 and the INCOSE guide. The ontology model can also infer the hierarchy of the objects based on the constraints made by the properties. Moreover, the ontology model can also link the whole life cycle process into a big network by considering the object flows. Each class, no matter it is a process or an object, can be as an entry to view the SE processes and can be extended with any other classes it may connecting.

The ontology model created for the ISO/IEC/IEEE 15288: 2015 is a structured knowledge base, which can express the knowledge of SE more flexible and can eliminate the conflicts between the definitions. To be more specific, the research problems, goals and solutions of the study are summarised in Table I.

The contribution of the study reflects in three aspects.

To begin with, the theoretical contribution is that the SE process knowledge is restructured. Not only defined from the process perspective, the knowledge of SE can be shared and reused in a consistent, explicit and unambiguous process description, especially from an object perspective.

Second of all, as for the methodology aspect, the study extends the Noy and McGuinness method by adding a use case definition part to fulfil the requirements of better usage of SE. Moreover, in the methodology, the method used is detailed specified into applicable activities while it is kept into three major phases, which is an innovation of Noy and McGuinness method for ontology engineering methodology.

Last but not least, the ontology itself becomes an application of implementation SE processes. The ontology model can be an enabler of good modelling in that it focuses on establishing well-defined domain concepts in terms of the terminology, definitions, and relationships as needed to model real world applications. In addition, the use of formal semantics is essential for modelling languages to properly represent the concepts, and to enable additional analysis to be performed by the systems. Furthermore, the ontology model can ensure the terminology shared among engineers from different disciplines and backgrounds but involved in a common project is well communicated and successful.

TABLE I
A Deployment of Problems, Goals and Solutions

| Problem | Goal | Solution |
|---|---|---|
| How to classify and manage SE knowledge with a unified terminology? | To create a hierarchical classification of the concepts involved in SE to fulfil different requirements of displaying and analysing SE knowledge. | (a) Terminologies are unified and abbreviations are managed as labels.<br>(b) The hierarchy of the classifications are built by adding properties between concepts.<br>(c) The hierarchy is able to be used as a way of displaying and more views are generated to analysing SE concepts. |
| How to analyse the SE processes as a whole? | To provide a whole picture of the SE knowledge domain by building connections between SE concepts. | (a) Eight kinds of properties are defined to build connections between SE concepts.<br>(b) Concepts from SE knowledge domain are organised and defined.<br>(c) The whole picture of SE is generated based on the relations between concepts. |
| What are the elements participated in or produced by each process? | To automatically generate the view of the IPO diagrams of each SE process. | (a) The IPO diagrams are restored in the ontology model.<br>(b) The view is dynamic and can be interacted with users. |
| What processes does a participant/element go through in the life cycle of a system? | To track the flow of the objects going through the SE processes in the life cycle. | (a) Two advanced functions are developed for tracking the SE knowledge.<br>(b) The view is dynamic and can be interacted with users from different perspectives. |

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