Domain Ontology for Processes in Infrastructure and Construction

Article *in* Journal of Construction Engineering and Management · July 2010

DOI: 10.1061/(ASCE)CO.1943-7862.0000178

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Domain Ontology for Processes in Infrastructure and Construction

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Abstract: With the increasing demands for domain-wide integrated construction and infrastructure development, there is a need for developing a domain ontology to build a knowledge model that describes the multistakeholder project development process. This paper presents a domain ontology for supporting knowledge-enabled process management and coordination across various stakeholders, disciplines, and projects. The ontological model is composed of concepts, relations, and axioms. Concepts represent the "things" in the domain of interest; relations establish the interconcept links; and axioms specify the definitions of concepts and relations and constraints on their behavior and interpretation. The ontology models the most fundamental concepts in the domain in a structured, extendable, and flexible format to facilitate future evolution and extension of the ontology for representing application-specific and/or enterprise-specific knowledge. The ontology was evaluated through technical evaluation and user evaluation. User evaluation was conducted through one-to-one expert evaluation interviews.

DOI: 10.1061/(ASCE)CO.1943-7862.0000178

CE Database subject headings: Project management; Infrastructure; Construction industry; Information management; Knowledge-based systems.

Author keywords: Project development; Infrastructure; Construction industry; Process modeling; Information and knowledge management; Knowledge-based computer models; Ontology.

Introduction

Academic and industrial experts from multiple disciplines within the infrastructure and construction domain and from different countries around the world are recently calling for the development of a domain ontology to help the industry build a knowledge model of its processes (Vanegas et al. 2004). The term "Ontology" originates from philosophy. In that context, Ontology is the study of being or existence. It is the branch of metaphysics that seeks to identify and describe the type of things that actually exist. However, in more recent years, research on ontology has migrated from the domain of philosophy to the domains of computer science and information systems. As such, given a more technical perspective in developing and using ontologies, "an ontology is an explicit specification of a conceptualization," while "a conceptualization is an abstract simplified view of the world that we wish to represent for some purpose," and "explicit" refers to the fact that it is explicitly represented (Gruber 1995). An ontology models information and knowledge in the form of concept hierarchies (taxonomies), interrelationships between concepts, and axioms (Noy and Hafner 1997; Noy and McGuinness 2002). The axioms, along with the hierarchal structure and relationships, define the semantics (the meaning) of the concepts. Ontologies are thus the foundation of content-based information access and semantic interoperability over the web.

Few research projects have been undertaken, and several others are underway, to formalize a set of construction ontologies. However, most of these ontological modeling efforts focused on the building industry. Other efforts in the infrastructure domain focused on sector-specific knowledge, such as the highway sector (El-Diraby and Kashif 2005) and the telecommunications sector (El-Diraby and Briceno 2005). A domain ontology, on the other hand, would offer a rich conceptualization and a shared reusable representation of domain-wide knowledge. Currently, domain knowledge is distributed among various disciplines and sectors and, thus, is inconsistently represented across the domain. A domain ontology would provide an unambiguous formalized representation of domain-wide knowledge in an attempt to provide a shared understanding of domain processes among the various stakeholders for supporting integrated construction and infrastructure development. It would serve as a core domain process model that can be used as a basis for developing further model extensions, domain or application ontologies, software systems, and/or semantic web tools.

This paper proposes an Infrastructure and Construction PROcess Ontology (IC-PRO-Onto). The purpose of the ontology is to offer a conceptualization and formal representation of domain process knowledge. It is important to note, however, that the IC-PRO-Onto is not intended to be "the one and only one" process model for the domain. There is no "perfect" ontology and no "optimum" classifications or concept hierarchies (Taivalsaari 1996). No one single ontology could be able to fully cover a

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Note. This manuscript was submitted on October 24, 2008; approved on December 10, 2009; published online on June 15, 2010. Discussion period open until December 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 136, No. 7, July 1, 2010. ©ASCE, ISSN 0733-9364/2010/7-730–744/$25.00.

domain of interest. As such, the scope of the IC-PRO-Onto is not intended to exhaustively cover every concept in the infrastructure and construction domain. Rather, it is intended to capture the most fundamental concepts in the domain in a structured, extendable, and flexible format.

Methodology

The methodology for developing the IC-PRO-Onto ontology included 10 core elements:

- Purpose, intended use, domain, and scope definition (Uschold and Gruninger 1996): this initial task explicitly addresses the following fundamental questions. Why is the ontology being developed? Who are the intended users of the ontology? What are the intended uses of the ontology? What is the domain of the ontology? What is the scope of the ontology?
- Development of competency questions (CQs): CQs are a set of requirements that are formulated as questions, which the ontology should be able to answer (Gruninger and Fox 1995). These questions were used in formulating the ontological model (i.e., defining the main concepts, their modalities, their attributes, relations, and axioms). CQs were also used in evaluating the ontology (as further discussed in the "IC-PRO-Onto Evaluation" section). Four main types of CQs were developed: (1) partonymy and inheritance CQs, which define part-whole and is-a relationships between concepts—for example, what are the subprocesses (subparts) of process X? (2) modality CQs, which define process modalities and belonging to process modality families—for example, is process X planned? (3) attributive CQs, which define process attributes and their classification—for example, what is the productivity level of process X? and (4) relational CQs, which define relationships between concepts—for example, who is involved in process X? For the complete set of CQs, the reader is referred to El-Gohary (2008).
- Definition of the philosophical and conceptual foundation of the ontological model: a review of philosophical ontological literature was conducted. Special attention was given to the following philosophical notions: intrinsic versus extrinsic properties, object-oriented versus prototype-oriented modeling, and identification versus reidentification (Tamma and Bench Capon 2002).
- Taxonomy building: the taxonomy was developed through two main iterative steps: (1) extraction and identification of the main concepts in the domain and (2) organization of these concepts into a hierarchical taxonomy. The concepts of the domain were extracted based on a literature review of the major enterprise and process modeling initiatives [for example, Industry Foundation Classes (IFC) and Process Specification Language (PSL)], as well as a review of domain-specific literature about construction and management processes [for example, publications by the Project Management Institute (PMI) and the Construction Industry Institute (CII)]. Concepts were structured into a taxonomy using a combination of top-down and bottom-up approaches. A top-down approach starts by defining the most general concepts and follows down to the most specific concepts. On the other hand, a bottom-up approach starts by defining the most specific concepts and subsequently groups these specific concepts into general ones (Noy and McGuinness 2002). A combination of the two approaches was used, as it allows for more modeling flexibility and avoids two main problems. The first is the inclusion of unnecessary specific concepts in the ontology that may arise if the bottom-up approach is solely used. The second is the inclusion of "less meaningful" higher-level concept abstractions (general concepts) that may occur if the top-down approach is solely used.
- Process model development: the IC-PRO-Onto taxonomy has been extended into an ontology by (1) modeling the various classifications and clusterings/modalities of concepts; (2) modeling the relations between the concepts to identify the interlinks between concepts; and (3) using an iterative approach to enhance the ontological model.
- Ontology capturing: the capturing of the ontology included two core elements: (1) identifying the terms to be used to refer to the concepts and relations of the ontology and (2) producing a set of formal axioms (Uschold and Gruninger 1996).
- Ontology coding: the coding of the ontology involves (1) committing to the meta-terms that are going to be used to specify the ontological representation (for example, to decide whether the term "concept" or "class" is going to be used to refer to ontology concepts); (2) choosing the representation language; and (3) writing the code (Uschold and Gruninger 1996).
- Integrating existing ontologies: this refers to whether (partially or fully) and how to use an existing ontology during the development of a new ontology. At this stage, no existing ontology was integrated within the IC-PRO-Onto.
- Ontology evaluation: the ontology was evaluated through checking conformance to the CQs, automated consistency checking, and expert evaluation interviews.
- Ontology documentation: finally, ontology documentation includes a recording of the ontology concepts, definitions, relations, and axioms.

Main IC-PRO-Onto Model

The IC-PRO-Onto includes concepts, interconcept relations, and axioms. Concepts represent the "things" in the domain of interest, either concrete or abstract. At the highest level of abstraction, a thing is an entity, constraint, attribute, modality, or family. An entity is a project, action, actor, product, resource, or mechanism. An entity is controlled by a constraint, has an attribute, has a modality, and belongs to a family. Modalities define the belonging criteria of entities to families. From a process-oriented perspective, an action is modeled in the IC-PRO-Onto as a process or event that produces or updates a product, uses a resource, has an actor role involved, is part of a project, uses or defines a mechanism, is controlled by or defines a constraint, has an attribute, has a modality, and belongs to a family (see Fig. 1).

In the IC-PRO-Onto, actions are grouped into two main categories based on the temporal extent. Events are occurrences that have no or limited temporal stretch (i.e., have zero or short duration). Processes, on the other hand, are occurrences that have extended temporal stretch (i.e., have a duration). Another distinction criterion between processes and events is the actor involvement relationship. In contrast to processes, some types of events, such as natural events, could have an unknown actor (in other words, the environment or the act of God). As such, events are defined as noteworthy instantaneous or temporally short occurrences that might have an unknown actor. An event is an instantaneous achievement (e.g., a "start" of a process or project), an administrative outcome (e.g., an "approval"), an announcement (e.g., a "notice to bidders"), a possible occurrence (e.g., a "risk occurrence"), an accident (e.g., a "fall"), a natural event (e.g., a

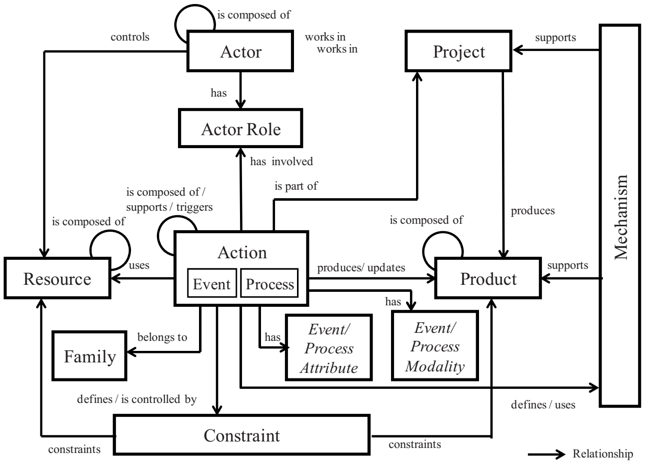

Fig. 1. Main IC-PRO-Onto model

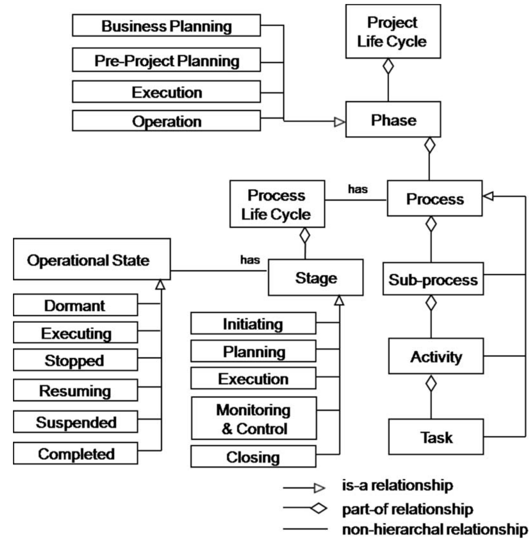

Fig. 2. Process composition

"flood"), a planned event (e.g., a "bid opening"), or a transaction (e.g., a "sale transaction").

Concepts in the ontology are related according to the following major relationship types:

- Subsumption (is-a): the is-a relationship reflects the sub-superordinate relationship. Some subconcepts are specializations of other superconcepts. For example, the concept "civil engineering process" is subsumed by the more general concept "engineering process." Subsumption relationships are used for the progressive specialization of the general concepts into specialized concepts, forming subsumption hierarchies. A hyponymy relationship reflects a subconcept relation (subordinate) to its superconcept (superordinate), while a hypernymy relationship reflects a superconcept relation (superordinate) to its subconcept (subordinate). Multiple inheritance is also permitted.
- Partonymy (part-of): aggregation or part-of relationship is used to decompose concepts into its parts. Partonymic relationships structure processes into partonymic hierarchies. Two main types of partonymic relationships are used: *functional-part-of* and *temporal-part-of* (as further discussed below). A holonymy relationship reflects a relation between a whole and its parts, while a meronymy relationship reflects one between a part and its whole.
- Cross-concept relationships: these establish nonhierarchal semantic links between concepts. Cross-concept relationships add further semantics through highlighting the "meanings" of these links through the "naming" and classification of the links.

In the IC-PRO-Onto, the whole-part relationship is modeled as follows. A process is composed of a set of subprocesses, a subprocess is composed of a set of activities, and an activity is composed of a set of tasks. Processes and their subclasses (subprocesses, activities, and tasks) are composed of a set of stages, which represent the process life cycle: initiating stage, planning stage, execution stage, monitoring and control stage, and closing stage (see Fig. 2). It is not a necessity, however, that each process goes through all five stages. For example, in some emergency situations, a planning stage could be so short that it is considered nonoccurring. On the other hand, each stage passes through one or more of the following operational states: dormant, executing, stopped, resuming, suspended, and completed.

Process-Related IC-PRO-Onto Concepts

Products

A process or event produces or updates a product. Products encompass four major subproducts:

- Knowledge: almost every process or event that involves humans produces or updates our knowledge. "Knowledge" is a "work plan" (e.g., a "cost management plan"), a "work assessment" (e.g., an "audit"), a "work change" (e.g., a "change request"), a "design," an "objective," etc.
- Knowledge item: while knowledge refers to a mental construct (something in the minds of humans), a "knowledge item" is the physical or symbolic manifestation of such knowledge. For example, a "cost management plan document" is the manifestation of the "cost management plan." As such, knowledge items include documents, reports, records, etc. Typically, a piece of knowledge could be manifested into more than one knowledge item, and similarly a knowledge item could include a manifestation of more than one piece of knowledge.
- Physical product: this refers to tangible physical products. It includes basic products (such as a beam, a column, and a footing) and complex products (such as a house, a bridge, and a water distribution system).
- Decision: not all actions lead to a physical product. Some actions produce or update a "decision," such as a "make-buy decision."

Actors

A process "has involved" at least one "actor role." An actor role could be viewed from several perspectives. The IC-PRO-Onto focuses on the actor role from a project-oriented perspective and thus defines one main type of actor role: a "project role" which comprises several roles such as "contractor," "consultant and expert," "designer," "developer," etc.

Constraints

A process is controlled by or defines a constraint. A "constraint" comprises two main types: "external constraint" and "internal

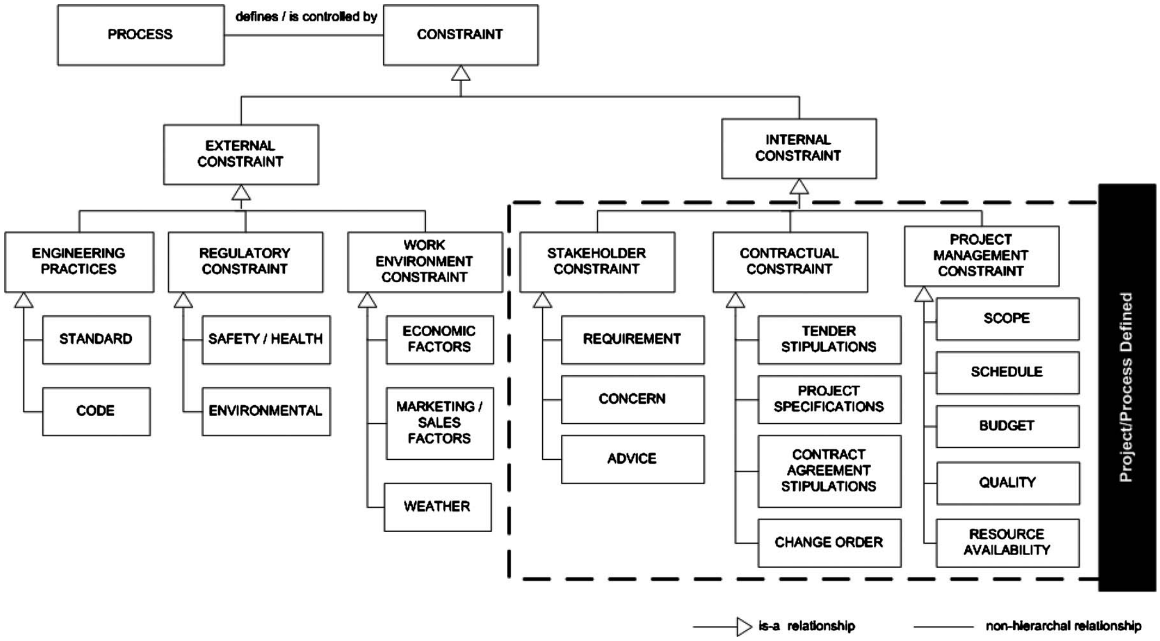

Fig. 3. Constraints

constraint." External constraints are those imposed from the outside—by regulatory bodies, engineering practice, or work environment—on the project. On the other hand, internal constraints are generated within the project as a result of project-specific decisions and conditions, such as stakeholder requirements, project specifications, and project budget. An upper classification of constraints is depicted in Fig. 3. Each type of constrain is further decomposed. For example, a "requirement" could be a "performance requirement," a "budget requirement," or a "schedule requirement."

Mechanisms

A process uses or defines a "mechanism." Mechanisms include three main types:

- Guide: guides are the mechanisms that direct the performance of processes, including algorithms (such as "resource allocation algorithm"), strategies (such as "risk response strategy" which could be "risk avoidance," "risk transference," etc.), and best practices (such as "scope management best practice").
- Method and technique: methods and techniques are the means or manners of procedure that are used to perform processes. For example, "risk management technique" includes "risk planning technique," "risk identification technique," "risk analysis technique," and "risk control technique." Further, risk identification technique includes "assumptions analysis," "SWOT analysis" (SWOT=strengths, weaknesses, opportunities, and threats), "Delphi technique," etc.
- Measure: measures are the mechanisms that are used to measure the conformance or performance of processes. This covers tests and metrics. "Test" is a measure for the physical entities, such as "compressive strength test." "Metric" is a measure for the nonphysical entities.

Resources

A process or event uses a "resource." Resources encompass the following:

- Knowledge: almost every process or event that involves humans uses knowledge.
- Knowledge item: similar to products, a knowledge item is the physical or symbolic manifestation of knowledge.
- Physical resource: a physical resource refers to tangible and traditional resources. A physical resource is a "material," "equipment," or "software."
- Human resource: human resources include "labor," "engineer," "consultant and expert," etc.
- Financial resource: financial resources cover "budget," "loan," etc.

Taxonomical Structure of the IC-PRO-Onto

The ontology presents processes in an object-oriented fashion that supports polymorphic views of the same process. As such, organizations (using different process models) can use the ontology to map their work processes despite the heterogeneity of their underlying process models. The ontology provides a consistent way for presenting this polymorphic nature of the concepts through "process modality families." For example, "scope initiation process" may be viewed as "initiating process," "scope management process," "preproject planning process," and "engineering process" depending on the perspective: *management purpose* (initiating, planning, execution, monitoring and control, and closing), *process function* (scope management, risk management, time management, etc.), *project phase* (business planning phase, preproject planning phase, execution phase, and operation phase), and *domain* (engineering, architectural, environmental, economic, social, political, legal, accounting, etc.). The following clustering framework presents a set of features that could be used to generate concept classifications in a consistent way.

In developing the taxonomy, the same concepts were classified/clustered into various modality families (forming parallel taxonomical hierarchies) to allow for a multiperspective viewing of concepts in its different possible contexts. This was performed through identification and reidentification of ontological concepts. From a philosophical point of view, conceptual modeling is based on the notion of identity. Identity is the logical relation that holds a thing to itself. As such, identity is context independent and is based on the intrinsic properties of an object (the properties that are always present). According to Tamma and Bench Capon (2002), "in order to find suitable identity criteria (which permit to identify a concept), a knowledge engineer should look at *essential properties*, that is, those properties which hold for an individual in every possible circumstance in which the individual exists." On the other hand, reidentification is the recognition of an object by a cognitive agent in all its possible forms. As such, reidentification is context-dependent and is based on the extrinsic properties of an object (on the role played by the object in a specific context). "It is not the mere problem of identifying an entity in the world that is central to the ontological representation of the world, but the ability to reidentify an entity in all its possible forms or more formally reidentification in all possible worlds (Tamma and Bench Capon 2002)." Reidentification of IC-PRO-Onto concepts was conducted in two different ways: (1) a priori for classification of concepts based on "prototypical" properties and (2) a posteriori for classifications of concepts based on "possible" or "exceptional" properties according to attribute values through axioms. For example, a "bidding process" is recognized as an "electronic process" if its modality "electronic style" has a value of "electronic."

Functional Process Modality View

The essential property ("function") that holds for a process in "almost all" contexts was defined in order to develop the main taxonomical hierarchy. Thus, in the IC-PRO-Onto model, the main modality view is function-based. Other modality views were introduced in order to reidentify processes in other possible contexts. For example, the "process domain view" categorizes processes based on their belonging to a domain of knowledge being social, political, economic, etc.

For the function modality, the aggregational part-of relationship between processes, subprocesses, activities, and tasks is functional. In other words, the "functional part of" represents the contribution of the part to the function of the whole; e.g., a "risk analysis process" is functional-part-of "risk management process." In the IC-PRO-Onto model, processes serve a variety of functions, resulting in four main functional-based views of processes:

- Core processes: these are product-specific processes that create a primary project product or deliverable such as a design or constructed facility (or parts of it). Core processes are mostly technical and highly dependent on the characteristics and sector of the project and as such are highly variable from project to project and require technical expertise. A core process could be a "*technical design process*" which covers pure technical design processes, such as "geometric design process," "structural design process," etc., or a "*technical construction process*" which includes pure technical field processes, such as "concerting process," etc.
- Management processes: these enable core processes and ensure that the design and constructed facility are delivered according to project objectives. Management processes are related to each other by their performance for a common purpose. The purpose is to initiate, plan, execute, monitor and control, and close a project. They also occur throughout the project life cycle. Management processes include "scope management," "time management," "risk management," etc.
- Knowledge integration processes: these use an integrated approach to extensively and formally embed key concepts, knowledge, and experience into a project throughout its life cycle. "Constructability process," "value engineering process," and "maintainability process" are examples.
- Support processes: these are necessary to support the other types of processes and include administration processes, communication processes, information management processes, etc. Support processes cannot be ignored and are vital for project success, but they do not serve a direct primary project objective or purpose. These processes are key enablers and indirect influencers for achieving project objectives. They are also highly repetitive (being either periodical or continuous) throughout the project life cycle.

Every project requires a blend of these four types of processes. For example, the scope of the project cannot be managed in the absence of some understanding and interrelation with the technical design process. To further develop the function-based taxonomical process hierarchy, each of these four main processes was decomposed through functional-part-of relations. The rationale for decomposing the "management process" is presented in the following paragraphs for illustration of de-aggregation methodology.

Generally, project management in construction aims at achieving a set of objectives through managing core project operations while using project resources, handling relationships with project partners, and controlling project variables. Some of the functions of project management include the following:

1. Defining and achieving project objectives in terms of scope, time, cost, quality, and safety;
2. Managing the core operations (the design, procurement, and construction processes);
3. Managing resources (human, financial, knowledge, and physical resources);
4. Handling relationships and resolving conflicts with stakeholders and contractual parties; and
5. Taking control over project variables such as risk, changes, and emergency events.

Accordingly, management processes have been classified into five main categories: objective-centered management processes, core operation management processes, resource management processes, relation management processes, and variable management processes, as shown in Fig. 4. For modeling the following management processes, the work carried out by the Project Management Institute (2004) in describing the project management processes and the project management knowledge was benchmarked: scope, time, cost, quality, risk, procurement, and human resource management processes.

1. Objective-centered management process has the following subprocesses:
   a. Scope management process: it is composed of processes that are required to ensure that the scope of the project is properly defined and maintained to reduce possible scope risks such as poor scope definition and scope creep, for example, "scope definition process" and "scope monitoring and control process."
   b. Time management process: it is composed of processes that are needed to provide and maintain an effective project schedule, such as "planning and scheduling process" and "schedule control process."

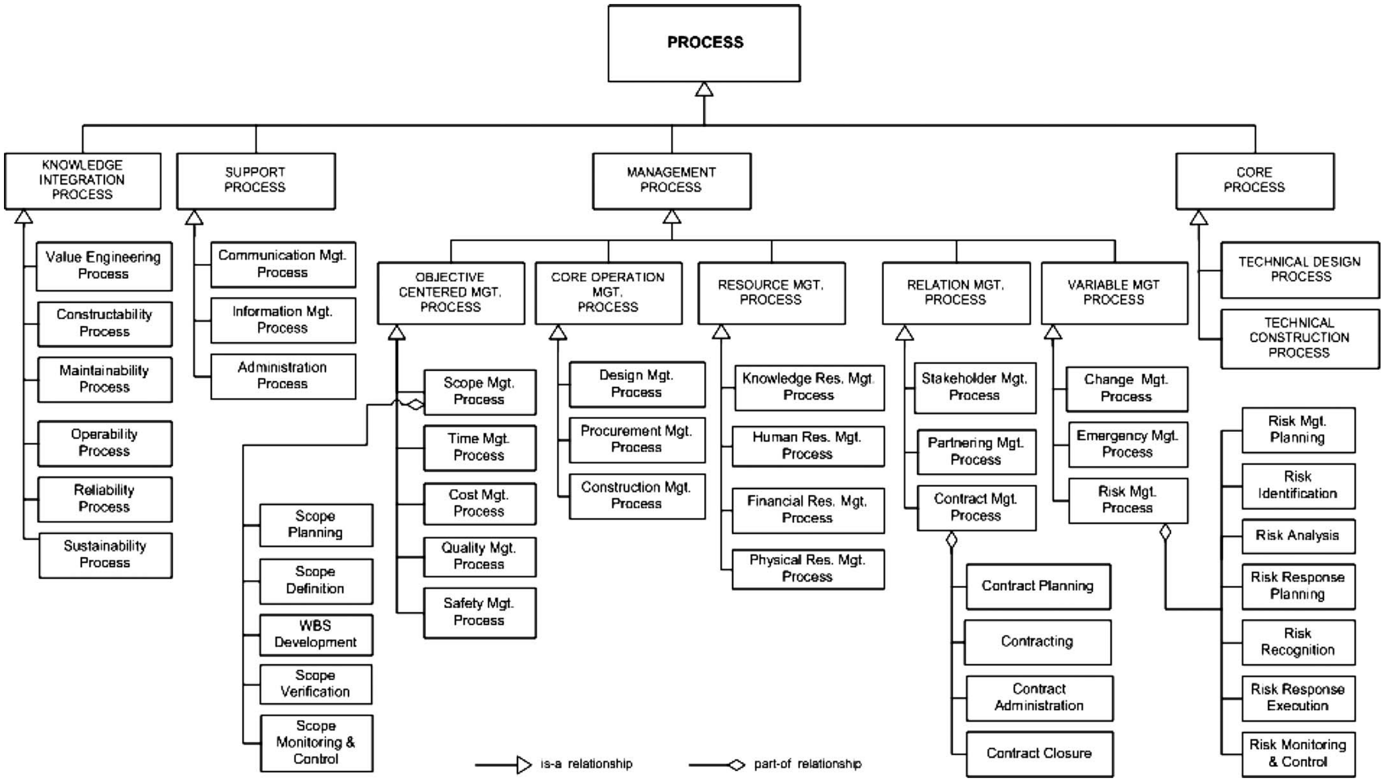

Fig. 4. Process functional modality

c. Cost management process: it is composed of processes that are necessary to maintain effective cost control of a project, for example, "cost estimating process" and "financial management process."

d. Quality management process: it is composed of processes that are required to design, apply, and maintain a quality management system, such as "quality planning process," "quality control process," and "quality assurance process."

e. Occupational health and safety (OHS) management process: it is composed of processes that are necessary to ensure consistent and continuous application for health and safety in the workplace, such as "OHS planning process," "OHS emergency management process," and "OHS control process."

2. Core operation management process has the following subprocesses:

a. Design management process: it is composed of processes that are needed to properly manage the design operations, such as "design planning process," "design coordination process," and "design control process."

b. Procurement management process: it is composed of processes that are required to obtain necessary resources from external sources, such as "procurement planning process," "seller selection process," and "contract administration process."

c. Construction management process: it is composed of processes that are needed to properly manage technical construction and site operations, such as "site planning process," "site security management process," and "site work control process."

3. Resource management process has the following subprocesses:

a. Knowledge resource management process: it is composed of processes that are necessary to properly manage information and knowledge, such as "information planning process" and "knowledge acquisition process."

b. Human resource management process: it is composed of processes that are needed to properly manage human resources (labor, engineers, and consultants), such as "human resource development process" and "human resource control process."

c. Financial resource management process: it is composed of processes that are required to properly manage financial resources (budget, loans, etc.), such as "financial planning process," "financial sourcing process," and "financial control process."

d. Physical resource management process: it is composed of processes that are performed to effectively allocate and manage physical resources (material, equipment, and software), such as "equipment management process" and "information technology and software management process."

4. Relation management process has the following subprocesses:

a. Stakeholder management process: it is composed of processes that are carried out to capture and incorporate stakeholder input in the project development, such as "stakeholder participation process," "stakeholder differences resolution process," and "stakeholder management program control process" (El-Gohary et al. 2006).

b. Contract management process: it is composed of processes that are essential to maintain and effectively manage contractual agreements, such as "contracting process," "contract administration process," and "contract closure process."

   c. Partnering management process: it is composed of processes that are necessary to benefit from and effectively manage partnering relationships, such as "partnering education and planning process" and "partnering control process."

5. Variable management process has the following subprocesses:
   a. Risk management process: it is composed of processes that are performed to properly allocate and manage project potential risks, such as "risk identification process," "risk analysis process," and "risk control process."
   b. Change management process: it is composed of processes that are needed to effectively manage and control change, such as "change management planning process," "change notification process," and "change impact analysis process."
   c. Emergency management process: it is composed of processes that are required to plan for, prevent, respond, and mitigate emergencies, such as "emergency management planning process," "emergency prevention process," and "emergency mitigation process."

Top-level concepts in the functional-based process modality view are presented in Fig. 4.

Process Phase Modality View

The phase modality view represents the "temporal-part-of" relation. In other words, a process should exist in a certain temporal context, here being a phase, to become part of the whole. Projects have life cycles that span several phases. Four main phases are used to express the timeline of a project, as proposed by the Construction Industry Institute (CII) (1995): business planning phase, preproject planning phase, execution phase, and operation phase. For example, "conceptual design process" is a temporal-part-of "preproject planning process."

Process Management Purpose Modality View

Five process groups are used to classify processes according to the project management purpose they serve, as proposed by the Project Management Institute (2004):

- Initiating process: an "initiating process" defines and authorizes the project, a project phase, or a major project process, such as "scope initiation process."
- Planning process: a "planning process" defines and refines project/process objectives and plans the course of action required to attain these objectives, such as "risk management planning process."
- Execution process: an "execution process" integrates project elements to carry out the project/process, such as "concreting process."
- Monitoring and control process: a "monitoring and control process" measures and monitors the project/process performance for evaluation and possible correction, such as "cost control process."
- Closing process: a "closing process" formalizes the acceptance of a project or element of a project, such as "commissioning process."

Process Domain Modality View

This classification is used to develop domain-oriented process types: a grouping of processes according to different fields of knowledge (engineering, law, sociology, etc.), for example,

- Engineering process: an "engineering process" belongs to the engineering domain of knowledge, such as "mechanical engineering process."
- Environmental process: an "environmental process" belongs to a wide range of scientific disciplines and domains of knowledge that are related to the natural environment (including environmental science and environmental engineering), such as "site waste management process," "air testing process," and "environmental impact identification process."
- Economic process: an "economic process" belongs to the economics domain of knowledge, such as "economic sustainability evaluation process."
- Social process: a "social process" belongs to the sociology domain of knowledge, such as "existing social elements analysis process."
- Political process: a "political process" belongs to the political science, public policy, and governance domain of knowledge, such as "public policy planning process."

Other relevant domain-oriented processes are modeled in the ontology, such as "architectural process," "legal process," "accounting process," etc.

Process Sector Modality View

This group classifies processes according to infrastructure and construction industry sectors. This results in several sector-based process classifications, such as "transportation process," "telecommunications process," "energy and utility process," and "building process."

Process Scope/Level Modality View

From a professional point of view, some processes occur on the industry level and other processes deal with a smaller scale, namely, the company scale or project scale. On the other hand, from a governmental perspective, some processes occur on the federal, provincial, or municipal level. For example, a "corporate finance process" or a "strategic planning process" is performed on the company level, while an "estimating process" or a "preproject planning process" is performed on a lower level, namely, the project level. Another example is an "urban planning process" that deals with the physical, social, and economic developments of a whole Metropolitan region, municipality, or neighborhood, while a "preproject planning process" deals with a smaller scale of development, namely, the project scale. As such, six main groupings were modeled in this regard, "federal-level process," "provincial-level process," "municipal-level process," "industry-level process," "company-level process," and "project-level process."

Process Temporal Extent Modality View

Four process groups are used to classify processes according to the temporal extent of the process:

- Continuous process: a "continuous process" is almost temporally continuous. It usually occurs on a daily basis throughout the project life cycle, from the start until the end of the project. "Communication process" and "information and knowledge

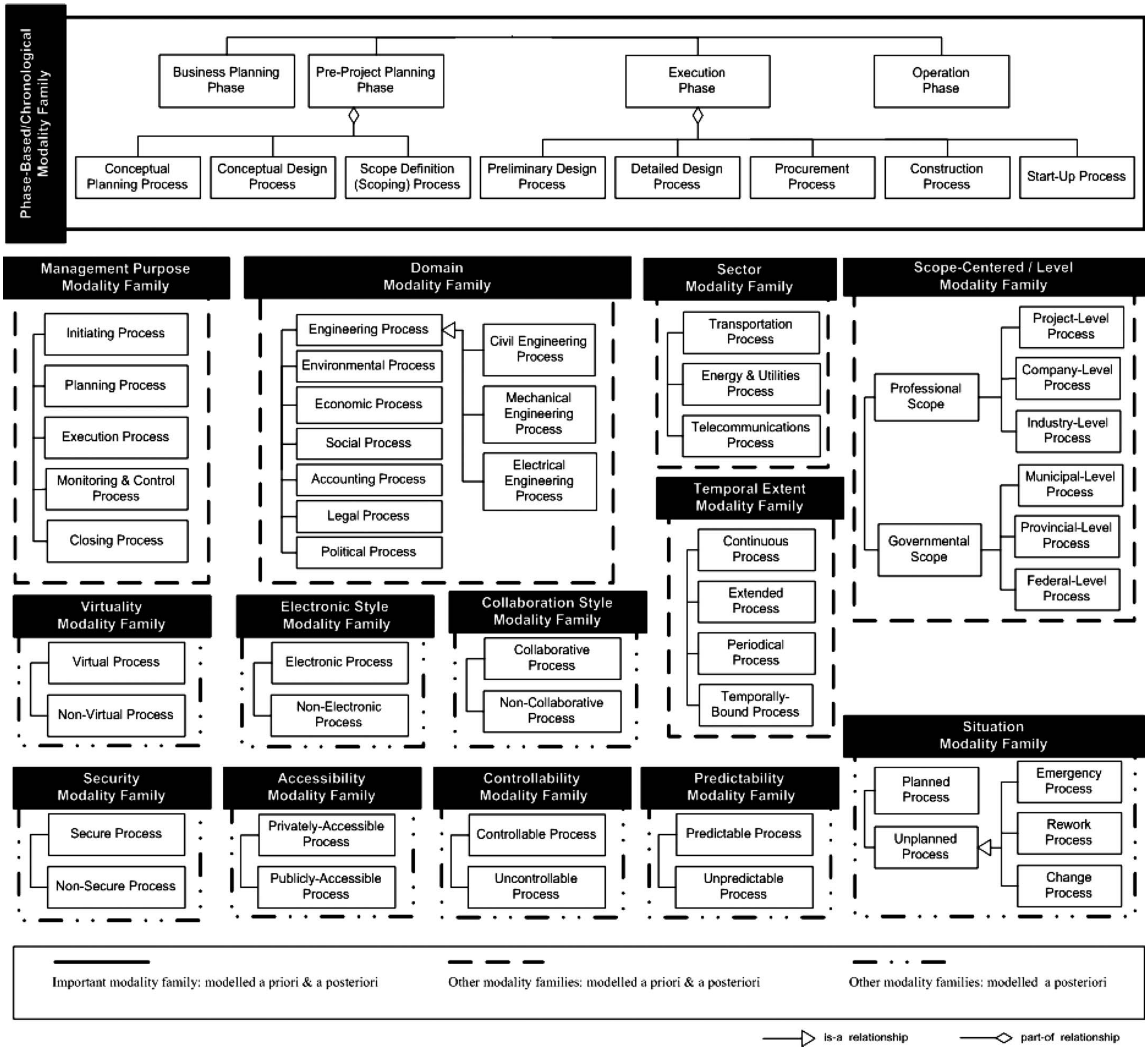

Fig. 5. Process modality families

management process" are examples of continuous processes. In general, a "support process" is usually continuous in nature.

- Extended process: an "extended process" is temporally stretched out or prolonged. It occurs within a relatively long time span, in comparison to the project life cycle. In some cases, an extended process spans the entire (or almost the entire) project duration. For example, a "scope management process" usually spans the entire duration of the project, since the "scope planning process" usually starts with the start of the project (usually starts during the "business planning phase") and the "scope monitoring and control" process usually extends until the completion of the project (usually extends until the end of the "execution phase"). Similarly, a "constructability process" may stretch out through the project, since the "constructability planning process" usually starts during the "preproject planning phase" and the "constructability lessons learned process" may extend until the end of the "execution phase."
- Periodical process: a "periodical process" occurs at regularly recurring intervals throughout the project life cycle. "Payroll process," "progress payment requesting process," and "progress evaluation process" are examples of processes that usually occur on a periodical basis.
- Temporally bound process: a "temporally bound process" is temporally limited or bound by clear start and finish times. As such, it occurs within a limited time span, with respect to the project life cycle, and/or has a clearly defined time span. For example, "concreting process" and "design brief development process" are temporally bound processes. In general, "technical design" and "technical construction" processes are usually temporally bound in nature.

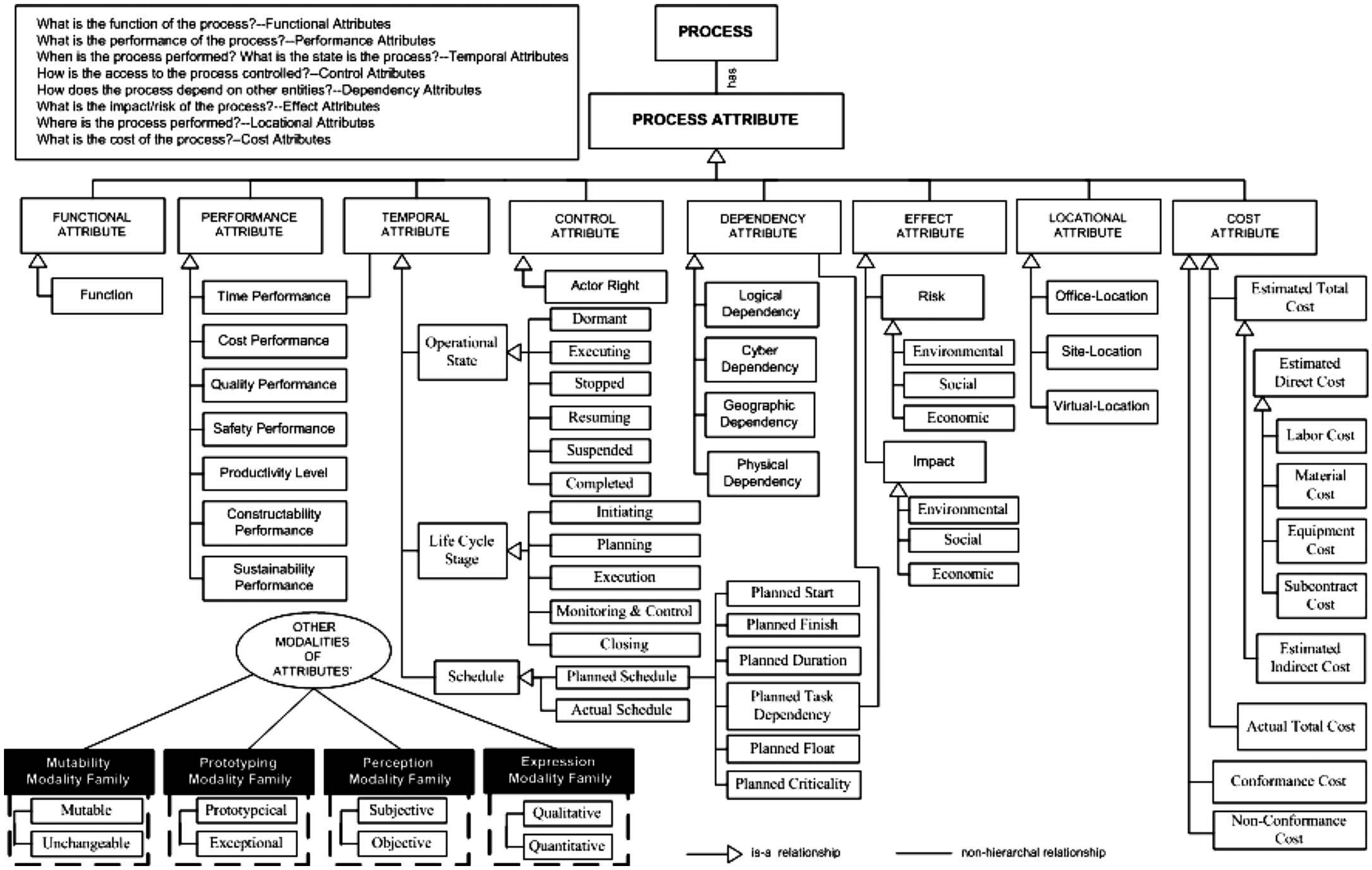

Fig. 6. Process attributes

More Process Modality Views

More modality views are included in the IC-PRO-Onto. For example, a process could be virtual or nonvirtual (based on a virtuality view), electronic or nonelectronic (based on an electronic style view), collaborative or noncollaborative (based on a collaborative style view), secure or nonsecure (based on a security view), publicly accessible or privately accessible (based on an accessibility view), predictable or unpredictable (based on a predictability view), controllable or uncontrollable (based on a controllability view), and planned or unplanned (based on an operational situation view). An unplanned situation is either an emergency, rework, or change situation (El-Diraby et al. 2005). An overview of all modality views (except for the functional modality view) is presented in Fig. 5.

IC-PRO-Onto Attributes and Modalities

An "attribute" is defined as *a characteristic that describes a thing*. On the other hand, a "modality" is defined *as a characteristic that describes a thing and denotes its belonging to a particular group or category* (here being a modality family). For all concepts, not only processes, the definition and classification of attributes and their modalities are very useful in a variety of contexts. It is important for the specification of construction works as you define your specifications in terms of performance properties. It is also crucial for the semantic search of construction entities in terms of their attributes and modalities. Moreover, it is vital for the development of sound information systems (Ekholm 2002). As such, the IC-PRO-Onto includes a classification and typing of attributes (see Fig. 6) and modalities.

In the IC-PRO-Onto, attributes are modeled as concepts and are described in terms of attribute values. Modeling attributes of concepts as classes allows not only for the characterization of concepts, but for the characterization of attributes as well. For example, through the definition of "productivity level" as a subclass of "performance attribute," the attribute productivity level is characterized as being a performance-related attribute. Similarly, through the definition of "collaboration style" as a subclass of "behavioral modality," the modality collaboration style is characterized as being behavioral.

Orthogonal to the above classifications, attributes (and similarly modalities) are further grouped according to the following four modalities of attributes:

- Mutability—mutable versus unchangeable attributes: mutability characterizes attributes according to their behavior over time (Tamma and Bench Capon 2002). Attributes that may change their value over the lifetime of a concept are mutable. On the other hand, attributes that have a fixed value over the concept lifetime are considered to be unchangeable.
- Prototyping—prototypical versus exceptional attributes: attributes which are usually used to describe a concept are called prototypical. On the other hand, attributes that are unusually used to characterize a concept are considered to be exceptional.
- Perception—objective versus subjective attributes: attributes which exist independently of human perception or attributes that are described based on a well-established conventional

system, such as mass, are considered to be objective. On the other hand, attributes that highly depend on human perception and/or conception are regarded as subjective.
- Expression—qualitative versus quantitative attributes: quantitative attributes are represented in numeric values. On the other hand, qualitative attributes are represented in linguistic terms.

IC-PRO-Onto Cross-Concept Relationships

In discussing cross-concept relationships, two important aspects are highlighted. First, cross-concept relationships are usually context-dependent and application-specific. For example, the relationship "general contractor is involved in preliminary design process" would not hold in the context of design-bid-build. Second, the semantic representation of cross-concept relationships could be further enriched through the provision of semantic "flavors" to the "naming" of relationships and the introduction of more details (i.e., more levels) to the relationship taxonomy. For example, the relation "is involved in" in "general contractor is-involved-in preliminary design process" could take several "semantic naming flavors" such as "participates in," "is responsible for," "facilitates," "manages," "observes," etc. With respect to the relationship taxonomy, these flavors would become a specialization of the relation "is involved in." Such semantic detailing, however, would also depend highly on the context and application. It would also introduce fuzziness to the representation of interconcept link types.

As such, a limited number of cross-concept relationships, which represent the most common relationships in the domain, were modeled a priori in the IC-PRO-Onto (1) in order not to limit the generalization of the ontology; (2) in order to avoid the introduction of fuzziness in the representation of relationships; and (3) in order to limit the scope of the ontology.

These relationships were categorized into six types based on a meta-classification of relationships: attributive, causal, functional, provenience, constraint, and human action. Other meta-classification of relationships (that are not applicable to these relationships) may include temporal and spatial relationships. For example, the "uses" relation could be clearly modeled as a "functional relation." This allows for the characterization of relations, which further enriches the semantics of the ontological model.

Further, the relationships of the IC-PRO-Onto could be extended, "as needed," in the following ways:
- Using the existing set of generic relations ("supports," "triggers," "produces," "updates," "has involved," "uses," "defines," "is controlled by," "has," and "belongs to") in order to establish other combinations of interconcept links. For example, the relation "defines" may link a "process" to an "event."
- Adding new relations to incorporate additional types of semantic links.

IC-PRO-Onto Axioms

As mentioned above, axioms are necessary to define the semantics of both concepts and relations. They specify the definitions of concepts and relations in the ontology and constraints on their interpretation. Generally, two main types of axiomatization are distinguished:
- Domain axiomatization: domain axiomatization defines the intended meaning of domain concepts and constraints on their interpretations, rather than how these concepts will be used. These axioms define the semantics for the major concepts in the domain. These are the higher-level axioms that present the most fundamental rules. Axioms of the IC-PRO-Onto are presented in natural language and first order logic (FOL).
- Application axiomatization: application axiomatization includes more specialized axioms that constrain the use of domain concepts according to the application perspective. They may define rules of behavior and conduct, specific application constraints, etc. Thus application axioms may change depending on the application scenario. Application axioms are outside the scope of the IC-PRO-Onto since the IC-PRO-Onto is a domain rather than an application ontology.

It is important to emphasize that application axioms were deliberately excluded from the scope of the IC-PRO-Onto as they define application-specific procedures and constraints. As such, since application axioms may vary depending on application scenarios and/or organizational procedures, they cannot be "enforced" on domain-wide users. IC-PRO-Onto follows the notion of minimal ontological commitment introduced by Uschold and Gruninger (1996) which states that an ontology should make as few claims as possible about the world being modeled, giving the parties committed to the ontology the freedom to specialize and instantiate the ontology as needed. A similar notion has been discussed by Tamma and Bench Capon (2002) stating that "often it is not true that more is better."

However, including a minimal set of axioms does not entail a limitation to the expressivity of the ontology. On the contrary, the IC-PRO-Onto is extendable. Application-oriented axioms could be added, in the future, according to application requirements. In general, ontologies are evolutionary in nature. The writers further believe that axioms are the most evolutionary part of the ontology as they highly depend on the implementation context and scenario. Thus, it is important to note that, given the profound impact they have on restricting the use of the ontology, axioms need to be tested against several contexts and scenarios prior to use. Further illustration is provided through the following example of application axioms.

Example: a constructability analysis process has to conform to an approved constructability implementation program: $(\forall x)(\text{constructability\_analysis\_process}(x) \supset (\exists y)(\text{constructability\_implementation\_program}(y) \wedge \text{approved}(y) \wedge \text{has\_to\_conform\_to}(x,y)))$.

While this axiom might be valid for an organization that has a formally developed constructability implementation program, it would not be valid for an organization that performs constructability analysis, yet without following a formal constructability program. Further, even if an organization uses a formal constructability program, there is not necessarily a mandate that every constructability analysis process has to conform to the guidelines established within that program. In fact, this axiom would only be valid in case an organization has a formal and detailed constructability implementation program that formally establishes guidelines for each and every constructability analysis process and that mandates conformance to those guidelines. This example illustrates that axioms that are applicable in a certain scenario might not be valid in a different scenario. Including such axioms in a domain ontology would "harmfully" restrict the use of the ontology domain wide.

In the IC-PRO-Onto, domain axioms are further classified in three different ways: a classification based on restrictive depth and representational form, a classification based on axiom pur-

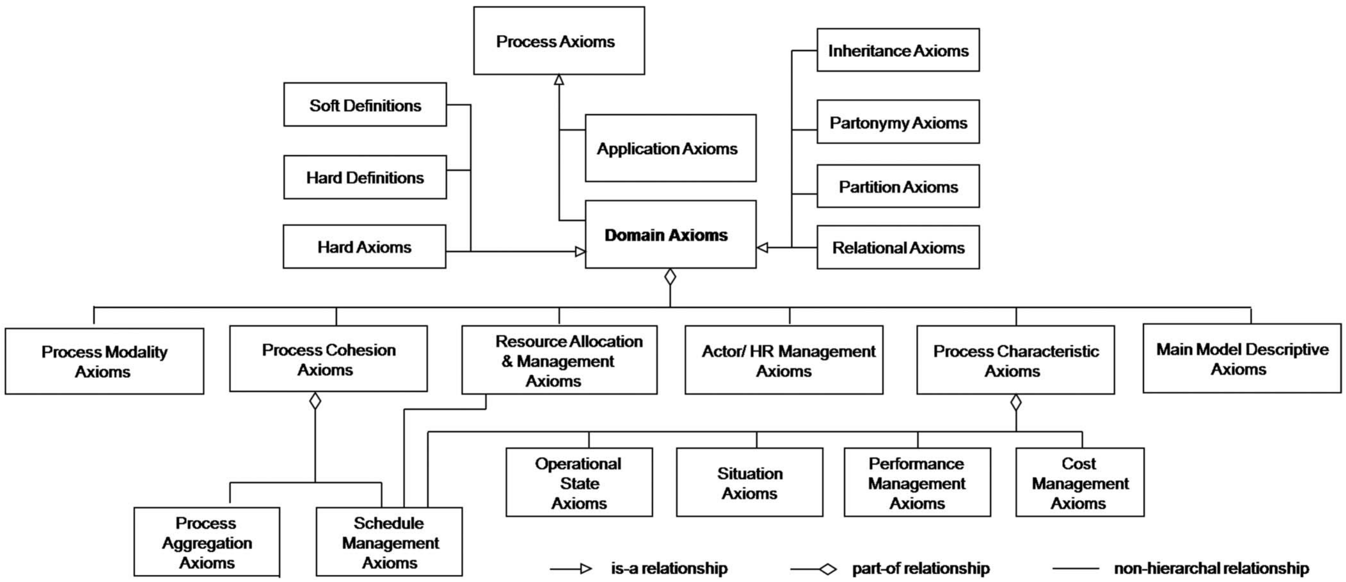

Fig. 7. Process axioms

pose, and a classification based on the type of constrained relation. As such, process axioms are initially classified into three main types (soft definitions, hard definitions, and hard axioms) according to its restrictive depth and representational form (see Fig. 7) (El-Gohary 2008).

Soft Definitions

Soft definitions are the axioms that specify the meaning (definitions) of the concepts and relations of the ontology in natural language. A soft definition could be imprecise and as such could be difficult to express in a formal language, such as FOL. For example, a *planned* process is a process that is explicitly or implicitly part of an original scope, plan, schedule, or industry norm.

Hard Definitions

Hard definitions are the axioms that specify the scope and constraints of the concepts and relations of the ontology in an unambiguous formal language/way. Hard definitions are represented in FOL in terms of ontological concepts. In other words, hard definitions define the identity criteria of the ontological concepts. Note that an ontological concept could be defined using both a soft definition and a hard definition (see the following two examples):

- A continuous process is a process that has a temporal extent modality of type "continuous temporal extent," $(\forall x,y)((\text{process}(x)\wedge\text{continuous\_temporal\_extent}(y)\wedge\text{has}(x,y))\supset\text{continuous\_process}(x))$.
- A planned process is a process that has an operational situation modality of type "planned situation," $(\forall x,y)((\text{process}(x)\wedge\text{planned\_situation}(y)\wedge\text{has}(x,y))\supset\text{planned\_process}(x))$.

Hard Axioms

Hard axioms are the axioms that specify the limitations and constraints on the interpretation and use of the ontology concepts and relations. These are the most restrictive type of axioms in the IC-PRO-Onto. Similar to hard definitions, hard axioms are represented formally in FOL. The following two axioms are a sample of the IC-PRO-Onto hard axioms:

- If all process stages have a completed operational state, then the operational state of the process is completed, $(\forall p1,s1,v1)((\text{process}(p1)\wedge\text{has}(p1,s1,v1)\wedge\text{operational\_state}(s1)\wedge\neg((\exists p2,s2,v2)((\text{process\_stage}(p2)\wedge\text{has}(p1,p2)\wedge\text{has}(p2,s2,v2)\wedge\text{operational\_state}(s2))\wedge(v2=\text{executing}\vee v2=\text{resuming}\vee v2=\text{dormant}\vee v2=\text{stopped}\vee v2=\text{suspended})))\supset v1=\text{completed})$.
- A process must have at least one actor role involved, $(\forall x)(\text{process}(x)\supset(\exists y)(\text{has\_involved}(x,y)\wedge\text{actor\_role}(y)))$.

From another perspective, axioms are reclassified according to the axiomatic purpose they fulfill. For example, "process cohesion axioms" define how the cohesion of processes is modeled in the ontology. As such, axioms are classified as process modality, process cohesion, resource allocation and management, actor management, process characteristic, and main model descriptive axioms. Process cohesion axioms are composed of process aggregation and schedule management axioms. On the other hand, process characteristic axioms are composed of operational state, situation, schedule management, performance management, cost management axioms, etc. Further, process composition axioms, schedule management axioms, operational state axioms, and situation axioms could all be viewed as "temporal axioms" since they all deal with the temporal dimension of the ontology. Finally, axioms are further reclassified according to the type of relation that is modeled/constrained by the axiom. As such, axioms are classified as inheritance, partonymy, partition, and relational axioms, as per Fig. 7.

IC-PRO-Onto Coding

The IC-PRO-Onto taxonomy and relations were coded using Protégé. Protégé is a free open source ontology editor. The Protégé platform supports modeling ontologies via the Protégé-

OWL editor. As such, the Protégé IC-PRO-Onto ontology can be exported into a Web Ontology Language (OWL) format. The IC-PRO-Onto concepts are represented as Protégé-OWL classes. The IC-PRO-Onto taxonomy was modeled through the structuring of the Protégé-OWL classes into a superclass-subclass hierarchy. The IC-PRO-Onto relations are represented through Protégé-OWL "existential property restrictions" and "necessary conditions." Hard definitions and hard axioms of the IC-PRO-Onto are stated in natural language and coded in FOL. Some of these axioms are also expressed in Protégé-OWL, namely, partition axioms and modality axioms. Partition axioms are represented in Protégé-OWL through the use of "disjoint classes." Making two classes disjoint ensures that a member of one class cannot be a member of the other class as well. Modality axioms are represented into Protégé-OWL through the use of "existential property restrictions" and "necessary and sufficient conditions." Finally, soft definitions of the IC-PRO-Onto are stated in natural language and are represented into Protégé-OWL through the use of "rdfs:comment." The remainder of axioms was not coded in Protégé-OWL because of the tool's inability to represent such axioms. This is a limitation of the current version of the software. However, the extendibility of OWL by initiatives such as the Semantic Web Rule Language (SWRL) is envisioned to fill this gap in the near future. For more information about Protégé notations, the reader is referred to Horridge et al. (2004).

IC-PRO-Onto Evaluation

Ontology evaluation is a judgment of the ontology content with respect to a particular frame of reference. There are two types of ontology evaluation: technical developer evaluation and user evaluation. Technical ontology evaluation includes ontology verification and ontology validation. Ontology verification focuses on checking that the ontology correctly implements the ontology requirements or CQs or functions correctly in the real world. On the other hand, ontology validation aims at proving that the real world model is compliant with the formal ontological model. Finally, ontology user evaluation is referred to as ontology assessment and aims at judging the ontology content from the user's perspective (Gomez-Perez et al. 2004). In this regard, the IC-PRO-Onto was evaluated through (1) technical evaluation by a. checking conformance to the predefined CQs and b. automated consistency checking and (2) ontology assessment (also referred to as user evaluation) through expert evaluation interviews.

Based on benchmarking the work of El-Diraby et al. (2005) and El-Diraby and Briceno (2005), these three evaluation tools were used to evaluate the ontology with respect to the following four criteria as per Table 1:

- Representation: how representative are the concepts of the ontology?
- Coverage: does the ontology cover the main concepts and relations within the domain?
- Consistency: are the representations of the ontology consistent?
- Ease of use: how easy is it to understand and navigate through the ontology?

Other criteria for ontology evaluation have been suggested by other researchers but are difficult to evaluate (Yu et al. 2007). Expandability and sensitiveness are examples of such criteria. Expandability refers to the required effort to extend an ontology without altering the existent content/semantics, while sensitiveness relates to how small changes in an axiom alter the existent content/semantics of the ontology (Gomez-Perez et al. 2004). These two criteria deal with the extendibility of an ontology. Ontologies by their nature are extendable. Once the knowledge of a certain domain is captured, in the form of an ontology, it can be reused and extended without the need to "reinvent the wheel." As such, extendibility is an intrinsic feature of ontologies. Despite that, measuring the level of effort that is needed to extend an ontology is a more challenging task. It requires domain expert involvement over a longer period of time to assess the ability of the ontology to be extended further to describe several specific subdomains or application areas.

Table 1. Ontology Evaluation Criteria and Tools

Evaluation tools	Evaluation criteria: Representation	Coverage	Consistency	Ease of use
CQs	✓	✓		
Automated consistency checking			✓[a]	
Expert evaluation interviews	✓	✓		✓[b]

[a]Consistency checking did not cover hard axioms (except partition axioms).

[b]The ease of use of hard axioms (except partition axioms) was not assessed since they were not represented in OWL.

Answering CQs

CQs serve as a frame of reference or requirement specification against which the ontology could be evaluated. The IC-PRO-Onto was checked for its conformance to the set of predefined CQs (please refer to the "Methodology" section). Specifically, the upper-level concepts, the relations, and the axioms of the ontology were checked for whether or not they are able to answer the CQs. This check was conducted manually by the writers rather than formally and automatically by a reasoner due to the Protégé-OWL's inability to represent all forms of axioms (as discussed above).

Automated Consistency Checking

The IC-PRO-Onto was automatically checked for consistency using a Description Logic reasoner: Renamed ABox and Concept Expression Reasoner (RACER). A Description Logic reasoner is able to perform various automated inferencing services, such as determining whether or not the ontology includes an inconsistent class. A class is inconsistent if it cannot possibly have any instances. Automated consistency checking is crucial as manual checking would be highly time-intensive. RACER, Pellet, and FaCT++ are some of the popular Description Logic reasoners that can perform intelligent automated reasoning over OWL ontologies. RACER has been selected for the following reasons (Racer Systems GmbH and Co. KG 2005): (1) it is one of the fastest available OWL reasoners and (2) it has demonstrated considerable stability in many applications.

Expert Evaluation Interviews

Eight one-to-one expert evaluation interviews were conducted in order to assess the ontology content from the user's point of view. El-Diraby et al. (2005) emphasized the importance of domain expert involvement in ontology evaluation since the evaluation requires judgment with respect to abstraction, classification, and coverage.

Each interview consisted of three parts:

- The first part of the interview covered a presentation about the motivation and scope of the research.
- The second part of the interview included a more detailed and closer overview of the IC-PRO-Onto taxonomy, relations, and axioms. The IC-PRO-Onto (coded in Protégé) was presented to the respondent, through a navigation of the ontology tree and a presentation of some of the concepts and their associated soft definitions, relations, and OWL-coded hard definitions and axioms. The respondent was also given the chance to navigate, by himself/herself, through the ontology tree in Protégé.
- Finally, in the third part of the interview, the respondent was requested to evaluate the ontology through a questionnaire. The questionnaire consisted of five main sections: respondent information, background, and familiarity with survey scope, abstraction and categorization effectiveness, navigational ease, and overall evaluation. For Sections 2 to 5, a Likert six-point scale was used to record the responses of experts, with 1 being the most favorable.

Through two direct questions, Section 2 aimed at confirming that the interviewee conforms to the main selection criteria, having technical expertise in the infrastructure and construction domain, as well as awareness about information/knowledge modeling. It is important to note, here, that respondents were selected using purposive sampling, which is a type of nonrandom sampling. Overall, respondents' familiarity with the challenges and needs of planning, design, and construction coordination within the domain ranged between "very familiar" to "familiar," with a mean score of 1.25 and a median of 1.0 (1 being very familiar and 6 being "very unfamiliar"). Similarly, respondents' awareness of information/knowledge modeling ranged between "highly aware" and "aware," with a mean score of 1.38 and a median of 1.0 (1 being "highly aware" and 6 being "not aware").

Sections 3–5 of the questionnaire aimed at gathering respondent opinion about the ontology. Following a methodology similar to that proposed by El-Diraby et al. (2005) for the evaluation of ontologies, these three sections of the questionnaire were designed in order to evaluate the ontology with respect to three main criteria: abstraction and categorization effectiveness, ease of navigation, and representation and overall user evaluation.

Section 3 aimed at capturing expert evaluation of the abstraction and categorization effectiveness of the ontology. Effective abstraction and categorization are important in supporting (1) consistent and "semantically correct" categorization of concepts; (2) semantically rich categorization of concepts through multiperspective viewing of concepts in their different possible contexts; and (3) extendibility of the ontology. A set of concepts and their corresponding taxonomical hierarchy paths were listed. For each concept, respondents were asked to track the taxonomical hierarchy path and rate their level of agreement with respect to the abstraction and categorization effectiveness on a scale of 1–6 (1="strongly agree," 2="agree," 3="somewhat agree," 4="somewhat disagree," 5="disagree," and 6="strongly disagree"). Respondents' agreement with the categorization of concepts ranged from strongly agree to somewhat agree, with a mean score of 1.40 and a median of 1.0. The results indicate that, overall, respondents strongly agree with the abstraction and categorization of concepts.

Section 4 asked respondents to evaluate the navigational ease of the ontology. Generally, an ontology should be easy to navigate. In other words, locating a concept in the taxonomy should not be difficult. Ease of navigation is crucial as it facilitates knowledge access, retrieval, reuse, and maintenance. Experts were asked to locate a set of concepts. For each concept, the expert was requested to navigate through the taxonomy to find the concept and subsequently rate how easy it was to locate it on a scale of 1–6 (1="very easy," 2="easy," 3="moderately easy," 4="moderately difficult," 5="difficult," and 6="very difficult"). Respondents' rating of navigational ease ranged from very easy to moderately difficult, with a mean score of 1.81 and a median of 2.0. The results reveal that, generally, respondents find the navigation of the taxonomy to be easy.

Finally, Section 5 asked respondents to provide an overall evaluation of the ontology and its representation through answering five direct questions. The results indicate that

- Respondents find the navigation through the ontology to be "easy."
- Respondents find the concepts used to be "familiar."
- Respondents find the concepts used to be in the range of "very representative" to "representative."
- Respondents believe that the ontology "strongly covers" the main concepts within the infrastructure and construction domain.
- Respondents believe that the ontology "strongly covers" the main interconcept relations within the infrastructure and construction domain.

IC-PRO-Onto Applications

Fundamentally, ontologies are used to improve communication between people and/or computers (Uschold and Jasper 1999). By describing the intended meaning of "things" in a formal and unambiguous way, ontologies enhance the ability of both humans and computers to interoperate seamlessly and consequently facilitate the development of semantic (and more intelligent) software applications.

Potential ontology application areas are numerous. Ontologies can be applied in a wide variety of contexts and for various purposes (Uschold and Jasper 1999). One promising application area is ontology-based process integration. Integrating semantically rich processes (based on the explicit and formal semantics) may support integrated project development through

- Overcoming heterogeneities in the representation of processes across multidisciplinary stakeholders;
- Connecting (based on the semantics) processes across various stakeholders and making process interfaces explicit;
- Supporting information/knowledge flow across connected processes;
- Facilitating knowledge-based process coordination among various disciplines and stakeholders; and
- Supporting automated flow of changes across impacted processes.

Ongoing efforts by the writers' research teams are taking place to implement the IC-PRO-Onto ontology through the development of knowledge-based (ontology-based) software applications. As an example, a prototype ontology-based portal for collaborative process integration was developed. The portal aims at sup-

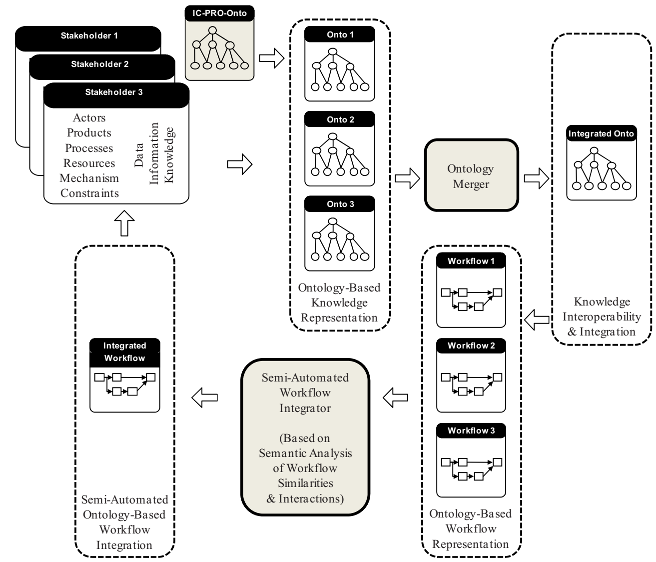

Fig. 8. Ontology-based integrated workflow

porting domain stakeholders in creating a knowledge-enabled collaborative-driven integrated workflow. The portal is founded on two main pillars: the IC-PRO-Onto and an ontology merger. Fig. 8 illustrates the following application scenario. Three stakeholders want to collaboratively integrate their workflows. Each stakeholder, independently, develops an ontology to represent his/her process knowledge in a semantic way. A stakeholder may reuse the IC-PRO-Onto in whole or in part (modify it, extend it, or just reuse elements from it). The ontology merger is then used to weave the three ontologies into one integrated ontology—forming a semantic and integrated representation of process knowledge. Each stakeholder, independently, drags and drops elements from the integrated ontology to describe his/her individual workflow. Based on the semantics, the workflow integrator (a portal module) analyzes the similarities and interactions between individual workflows. A portal coordinator uses the subject analysis to create an integrated workflow. For further description and discussion of the portal (including a case study), the reader is referred to El-Gohary and El-Diraby (2010).

The development and use of such software offer academics and industry professionals the opportunity to assess the benefits and limitations of the IC-PRO-Onto. Evaluating these benefits and limitations is the core task in developing the "business case" of IC-PRO-Onto-based tools (in particular) and of ontology-based systems (in general). Presenting a strong business case to the infrastructure and construction industrial community would foster further development and dissemination of ontology-based tools.

Maintenance of the IC-PRO-Onto

One of the important aspects of ontology development is ontology maintenance. Maintaining an ontology is an iterative process that focuses on keeping the ontology representation current within the ontology's domain of interest. Ontologies need to evolve in response to the constantly growing and evolving knowledge within the infrastructure and construction domain. Ontologies should also change as our understanding and interpretation of that knowledge changes. Ontologies might also be refined, if needed, as we strive to further improve the quality of the ontological model. Three strategies will be adopted by the writers to maintain the IC-PRO-Onto (refine it, modify it, and extend it),

- Stand-alone maintenance: frequent reviews of the IC-PRO-Onto to maintain the ontology by adding, resorting, and/or modifying concepts, relations, and/or axioms.
- Software-influenced maintenance: going through the process of ontology-based software development and observing the actual use of the software may result in discovering more about the knowledge that we need to describe in order to carry out useful computer-supported tasks. Such discoveries may change the way we need to represent, implement, and expand the ontological knowledge.
- Extension-influenced maintenance: several extension (subdomain) ontologies are being developed by the writers' research teams. The requirements of these ontologies and the way they link to the IC-PRO-Onto might provide more insight about the infrastructure and construction domain knowledge and how we need to represent that knowledge. In response, the IC-PRO-Onto will be updated as part of a continuous effort to maintain the ontology and keep it current and representative of the domain.

Conclusions

This paper presented an ontology for the infrastructure and construction domain. Five main concepts were used to represent the "things" in the domain: entity, constraint, attribute, modality, and family. An entity is a project, action, actor, product, resource, or mechanism. Concepts were structured into hierarchal taxonomies using subsumption and aggregation relationships. The taxonomical classification of concepts supports multiperspective viewing of the same process through "process modality views." The main modality view provides a functional clustering and deaggregation of processes. Within this view, four main categories of processes were modeled: core processes, management processes, knowledge integration processes, and support processes. Other modality views were introduced in order to reidentify and recategorize processes based on the multiple contexts in which they may exist. The semantics of the ontology was further enriched through the use of cross-concept relationships and axioms.

This ontology offers a leading initiative for developing a domain-wide ontology for infrastructure and construction. It offers a formal representation of domain knowledge with a breadth and depth of coverage. The ontology attempts to balance the programming (computer-interpretable) and the linguistic (human-interpretable) aspects as means to help realize the Semantic Web. One of the main contributions of the ontology is the ontological model which is not just a listing of processes, but rather, a philosophical view of process modalities and attributes. The ontology also offers richness in knowledge representation, including over 3,000 concepts, in addition to associated relationships and axioms.

The ontology is not intended to serve as "the one and only one" process model for the domain for two main reasons. First, no one single ontology could fully cover a domain of interest (Gruber 1995). Second, there is no "perfect" ontology and no "optimum" way for modeling a certain domain (Taivalsaari 1996). Therefore, the main goal for developing an ontology is not to build a model that would meet all requirements in a certain domain of interest, rather the goal is to reach a sufficient, "good enough," and extendable model that gets accepted by a group of people. For this reason, the ontology was evaluated through expert opinion. The ontology was also developed in a structured, extendable, and flexible format to facilitate future refinement, modification, and extension of the ontology.

Recognizing that the way we operate within the domain is not perfect either, the use of a domain ontology would also open opportunities for improving existing processes. As stakeholders semantically describe their processes through the development/extension and use of ontologies, it is important that they take the opportunity to rethink existing processes instead of taking them for granted. Rethinking and redesigning business processes are needed to achieve improvements in measures of performance, such as time, cost, quality, safety, and sustainability. In the context of process improvement, ontologies help stakeholders understand their processes as a prelude to analyzing and improving the way they do it.

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