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Ontology Technology

Overview of the engineering applications of ontology technology

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ABSTRACT

The following work is an overview of the use of ontology technology on engineering applications. A philosophical background for ontologies is defined, as well as the reasons to start researching on ontology technology, then based on the philosophical assumptions, the different approaches are explained with examples. Finally, there is a summary of advantages based on previous attempts to implement ontology technology in the industry as well as the main challenges in this implementations.

Contents

1 INTRODUCTION

The approach of this work is to illustrate the different kinds of ontologies that can be applied for chemical engineering problems. In order to do so, the first task is to define the concept "Ontology", based on the philosophical theories proposed along the centuries. Once there is a clear definition of ontology, its different branches will be explained.

1.1 WHAT IS ONTOLOGY?

The term ontology comes from the greek *ontos* which refers to "being, or that which is" and *–logia* which means "study, science, theory" (Harper, 2014). Thus, ontology could be defined as the study of being. This study has been traditionally included as a part of the philosophical branch of metaphysics.

When it comes to the study of being, the subjects studied can be many, considering existence, becoming, reality, entities and their relations. Ontology deals with the problem of defining entities, if they exist, how can they be grouped and if there is a hierarchy based on their similarities, differences and relations.

One of the first ontological theories in order to describe the nature of existence was from Parmenides. He proposed two ideas about existence. The first, and very important for western philosophy, was that nothing comes from nothing, thus existence is eternal. The second one, and the most relevant for this work, is that everything is part of a single entity. This is a first step towards the unifying theories in physics, which in a similar way can be applied for engineering concepts and integration among several disciplines.

Later Anaxagoras and Leuccipus, proposed that the reality of being was not static and unchangeable by introducing the idea of "Becoming". Each of them (Anaxagoras and Leuccipus) arrived to the same conclusion by different ways. We shall focus on the Leuccipus way, who stated that reality is based on vacuum and basic indivisibles entities (Atoms) and their intrinsic movement in this vacuum. This idea was further developed by Democritus and later by Epicurus.

Many different disciplines and theories have been defined along the years since the classical greek ideas until this day. Now each discipline counts with a distinctive terminology, which defines the processes and objects that are comprehended as a part of that discipline. Nonetheless, a discipline is not only defined *just* by the vocabulary used; as (Knowledge based systems, 1994) explains, one must provide rigorous definitions of the grammar governing that vocabulary to make statements and make clear the logical relations between those statements. When talking about "an ontology", we refer to a structured way to represent this information about a domain.

1.2 TYPES OF ONTOLOGIES

Nowadays the definition of ontology is still a matter of debate. However, different methods and approaches to describe reality have been developed throughout the years. According to (Petrov, 2011) these can be classified depending on their domain, applications and the degree of abstraction:

1. Upper ontology: concepts supporting development of an ontology, meta-ontology
2. Domain ontology: concepts relevant to a particular topic or area of interest, for example, information technology or computer languages, or particular branches of science
3. Interface ontology: concepts relevant to the juncture of two disciplines
4. Process ontology: inputs, outputs, constraints, sequencing information, involved in business or engineering processes

This is one of the most widely accepted classifications from a philosophical context. Nonetheless, the approaches found and further explained in this work include characteristics of all those categories.

For this work focused on engineering applications and modelling, the approach proposed by (Erden, et al., 2008) is much more suitable. This classification can be used for very abstract ontologies as well for very simple ones. Each type of ontology is defined based on different assumptions, as follows:

1. Device ontology: In this ontology, any system or device can be defined as a network of input-output relations between black box components with attributes that can change because of these relations.
2. Functional ontology: In this case, the ontology is proposed from a teleological poin of view. This means defining a system or entity by its purpose and the purpose of its parts.
3. Process ontology: Though the term is the same as in (Petrov, 2011), the definition is different. For this case, the focus is not to define a system by its components but rather by its processes. This means that there are no black box entities but rather participants in the process. In addition, the attributes of the entities are dynamic; these changes in the attributes are not as a result of an input-output relation but due to the effects of the processes.

In this document, each of the last three categories will be explained in more detail. It should be noted that a functional ontology is usually constructed on a device or process ontology basis.

1.3 WHY WORK ON ONTOLOGY TECHNOLOGY?

Large engineering projects are carried out by using knowledge from many different domains. Each of these different domains contributes with a small part of the whole picture. However, the success and efficiency of this engineering process depends largely on how integrated are these different knowledge clusters. A first challenge that appears when trying to integrate the different clusters is the lack of a common language, as each of them is part of a different domain (Knowledge based systems, 1994).

In this aim of integration among the different participants of an engineering project, ontologies are a very important and functional tool. Using an ontology, a process can be described in a much more general way, which includes relationships that are part of different domains. An example of this situation would be the case of the design of a new chemical plant. Counting with access to an ontology that contains the information about the synthesis of the desired component will give insight for the process designers about the production constrains and ways in which the plant should be operated. If, in addition to the component synthesis ontology, there is access to an economic ontology, the design process can be heavily improved in terms of profit, as there is also available the economic insight, which accounts for relationships and processes that are affected by the design but that are not directly considered by the design. In this sense, it is very important to have a rich compendium of the relevant ontologies within a company in order to have a more efficient way to share information.

As mentioned earlier, another important issue when it comes to integration is the existent language between disciplines. Sometimes different domains use similar terms when referring to different objects, an example of this would be term “state”, which for control engineers is a short way to refer to the state variables, which are the smallest amount of variables that can represent a system at a given point in time. However, the same term “state” in physiscs, refers to one of the distinct forms that matter takes on. This communication issue can become a very important matter when decisive information fails to be transmitted from one domain to other. In this sense counting with robust ontologies are a very useful tool to standardize the language as they condense the concepts and relations between those in a robust and accessible form.

Another issue that emerges refers to the reusability. Among engineering activities, there is a lot of effort put into the recreation of information that has been already recorded elsewhere. A solution for these issues comes from programmers. When it comes to programming, there are many similar routines that are used several times for different applications. Thus, libraries including these common routines have been developed. This solution can be extrapolated to more disciplines by creating ontology libraries, which can include general as well as domain specific ontologies relevant for the application of interest (Knowledge based systems, 1994).

2 DEVICE ONTOLOGY

2.1 DEFINITION

One of the early approaches on device ontology is (Brown & de Kleer, 1984) qualitative physics, this work stated that the behaviour of a physical structure can be described by the behaviours of its constituents. Another early work in device ontology is the “german systematic design” proposed by (Pahl & Beltz, 1977). These and more device ontology works can be found in the good summary of device ontology works that was made by (Erden, et al., 2008). For this work, the focus will be on the work carried out by (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004), because of its simplicity and their proposed integration with functional ontologies.

When it comes to design a new artefact there are two major approaches: Device-centered and Process-centered views. Each ontology Device and Process are based on their respective viewpoint. As mentioned earlier device ontology considers any entity as a composition of devices or agents, which through input-output relations achieve the goals needed by the users. On the other hand, process ontology does not have the concept of agent, but instead the concept of participants, which participate on a given phenomenon.

Device ontologies have been dominant to date regarding modelling artefacts by several reasons (Mizoguchi, Functional ontology of artifacts, 2008):

- Device ontology is straight forward.
- Every artefact can be considered as a conglomerate of sub artefacts.
- The concept of function is attributed to an agent which realizes the function.
- Saves a lot of reasoning as it hides the internal details of the devices.
- Configuring devices allows modelling almost any artefact in a device ontology world unless there is the need to include new devices, new combination of phenomena or new phenomena.

For device ontology is each agent or device is seen as a black box. Though parent devices can be seen as a configuration of several smaller devices, the internal behaviour for these small devices is still hidden. Then in cases where the reality cannot be modelled as devices, such as the case of a chemical reaction, process ontology is useful, as it does not focus on the devices but on the phenomena.

2.2 DEVICE ONTOLOGY COMPONENTS

Some of the main concepts for device ontology have been proposed by (Brown & de Kleer, 1984), however more modern approaches have expanded those concepts (Mizoguchi, 2008) (Kitamura & Mizoguchi, 2004). The following are the top categories of device ontology:

- Entity: The real and basic things existing in the world.
- Agent: Actor that does the required action.
        - Object (operand): what which is processed by the agent
        - Medium: where the object is carried
        - Conduit: Agent, which transmits an operand, without any change.
- Role: the part that an entity does during the process in which the device works.
    - Structural roles
        - Input: What is incoming to the structure (Can be not material)
        - Output: What is exiting the structure (Can be not a product)
        - Component: Part of the device that forms a structure
    - Functional roles
        - Material: main source of results from the device and output (all have input role)
        - Product: regular output of the device made of the material
- Structure: configuration of agents
    - Inlet: What comes to an agent
    - Outlet: What exits an agent
    - Connections: Relations between agents
- Device Behaviour: A situation-independent conceptualization of the change between input and output.
    - Transitive behaviour: Focused on the change of the object coming into and out of the device.
    - Intransitive behaviour: Focused on the change on the agent.

2.2.1 Device behaviour

The kinds of behaviour could be expanded into four different kinds of behaviours, by not only considering their relative change in location but also in time (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004).

- B0 behaviour: it is the change of the value of an attribute of and operand at the same location over time. An example would be a temperature increase of a fluid over time on a fixed measuring point.
- B1 behaviour: it is the variation of the value of an attribute of an operand from the input to the output. An example would be the temperature change of a fluid that goes through a heat exchanger.
- B2 behaviour: it is the change of something inside an agent. In this case "something" can be the motion of a part of the device, like changing the gear in a transmission, or a change in the state of the device.
- B3 behaviour: it is defined as the behaviour to another device.

It should be noted that based on the previous classification behaviours B0 and B1 are transitive while B2 and B3 are intransitive. The figure 1 illustrates these different behaviours.

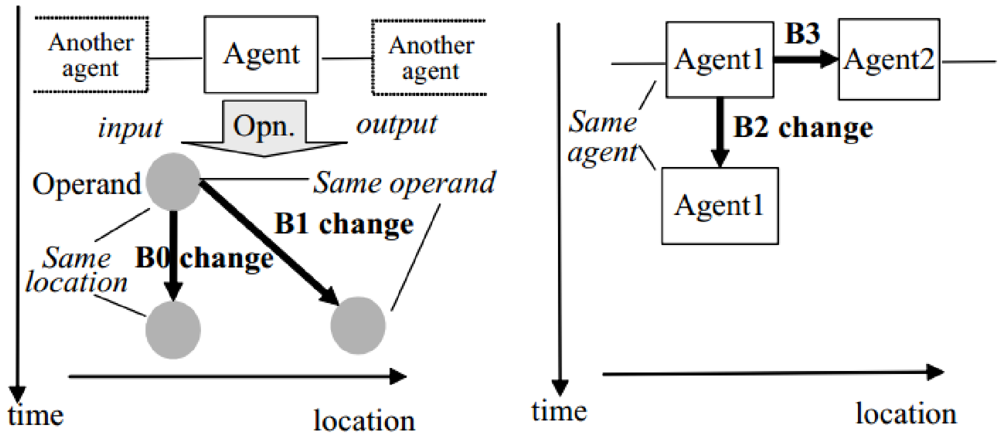


Figure 1. Different behaviours. (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004)

2.3 EXAMPLE

To illustrate the concepts earlier mentioned, let us consider the following system (Figure 2). It consists of an inlet stream made out of a light and a heavy component, which goes into a pump, then to a heat exchanger and finally to a flash tank in which both components are separated.

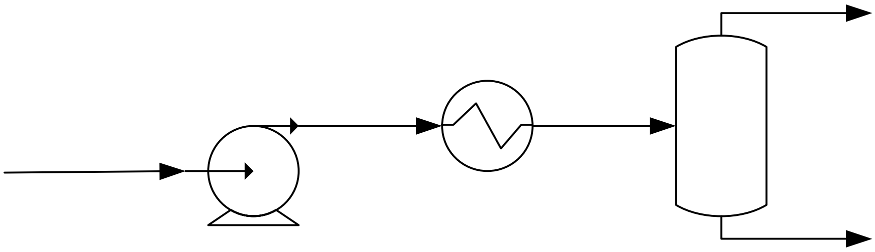


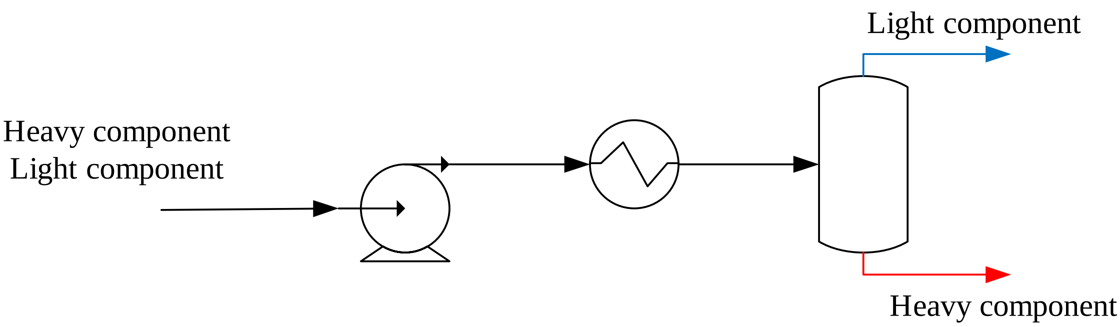
Figure 2. Example flow sheet.

Now a device ontology could be proposed for this process based on two domains being, mass and energy. The ontology concepts for each domain are resumed in table 1.

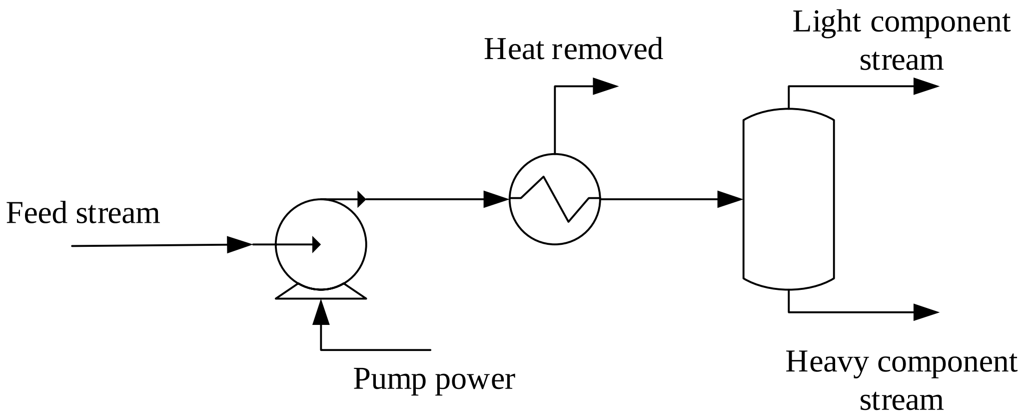
Table 1. Different domains for the device ontology example.

	Energy	Mass
Agents	Tank, pump, exchanger	Tank, pump, exchanger
Operand	Energy	Heavy & light component
Medium	Fluid, power, utility fluid	Fluid
Conduit	Pipes, cables (electricity)	Pipes

On figure 3, it is possible to see the two different structures for each domain.



(a)



(b)

Figure 3. Different structures for different domains (a) mass (b) energy.

Now in this system the different behaviours can be seen:

- B0: Can be the behaviour of the temperature after the heat exchanger.
- B1: The difference between the inlet and outlet flows for the flash tank.
- B2: A change in the efficiency of the pump or fouling in the heat exchanger.
- B3: For this system after pressure increase the expected behaviour is a cooling stage.

Further examples, including domains that are more advanced, are shown in (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004) as well as in (Mizoguchi, Kozaki, Sano, & Kitamura, 2000).

3 FUNCTION ONTOLOGY

3.1 TELEOLOGY

Before defining function ontology, it is necessary to introduce the concept of Teleology. The term “Teleology” comes from the Greek telos, which means purpose and –logia, which means study. Then teleology can be defined as the study of purpose.

For the purpose of things, there are two kinds of purposes. The first is the intrinsic, which is independent of human notions; for instance the purpose of a seed to become a tree. The second is the extrinsic purpose, which is based on human notions; an example of this would be a fork, which serves as a tool.

The teleology originated from Plato and Aristotle’s philosophy. Plato concluded that to give an explanation of something is determining its purpose. As for Aristotle, he proposed the concept of natural purpose. Kant has further discussed teleology during the 18th century in his Critique of Judgment.

Nowadays this concept is applied to define entities by their purpose (extrinsic purpose). In the context of this work, using the device ontology terminology, a teleological approach would define different agents based on their goal.

The main issue now is to define the purpose of those entities, and more generally to define the concept of function. The starting point to define this concept is based on the concept of behaviour, which was stated earlier as a context independent conceptualization of the change from input to output.

In contrast to the behaviour, a function needs a context and it is defined by the intentions of the designer or the user. Thus, a same behaviour can have different functions depending on the context. An example of this would be a heat exchanger, this unit can be used as a heater or a cooler. The behaviour is the same independently of which is the stream of interest. However, its function changes as the stream of interest is different. Hence, in the case that the cold stream is the important stream, the heat exchanger becomes a heater; in a similar manner, if now the interest is on the hot stream, the heat exchanger becomes a cooler. As it can be seen, the different functions are set by the context.

Several discussions have been carried out regarding the definition of function and behaviour. For this work, the definition for function will be “behaviour plus information for teleological interpretation” (Kitamura, Koji, & Mizoguchi, An ontological model of device function, 2006).

3.2 APPLICATION ON DEVICE ONTOLOGY

The reason to choose (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004) as the main work to illustrate how device and process ontology work is that based on the device ontology system they further elaborate it using teleological concepts in order to have a more robust ontology system. Hence, all the terminology defined on the previous chapter is still valid for this approach.

As explained in the previous section the concept of function is heavy context reliant. This limits the uses of functional ontologies. However, one way to make the function ontologies reusable is to generate abstractions of the functions.

The initially function (behaviour plus information for teleological interpretation) will be considered the “base” function, and its further abstraction is going to be the “meta” function.

The way a function is achieved is described by the method of function achievement, in which a series of sub-functions are performed and these ultimately lead to the achievement of the main function. Now, when it comes to conceptualize the principles or the phenomena that justifies why and how a function is known as way of function achievement, this is related to the essential properties of the structure and the behaviour that is achieving the function.

After studying a function with the previous methods it is possible to have a conceptualization of a base function and the relationships within. A base function focuses on the change of the operands in the domain, the meta functions is concerned about base functions. A meta functions, then, gives a teleological interpretation of the causal relationships between base functions.

3.3 PLANT EXAMPLE

The following example is taken from (Kitamura & Mizoguchi, Ontology-based systematization of functional knowledge, 2004) and (Mizoguchi, Kozaki, Sano, & Kitamura, 2000). This is the case of a power plant. Table 2. Shows the device ontology approach with function on it from two different domains.

Table 2. Key device ontology concepts for a plant from two different domains.

	Plant: Energy	Plant: Entity
Device	Boiler, turbine, etc.	Boiler, distiller, etc.
Conduit	Pipe	Pipe, Belt conveyer
Operand	Heat energy	Fluid, stuff, etc.
Medium	Fluid (Water, steam, etc.)	Fluid, tool or nothing
Function	Generate, give, rob, cool, etc.	Divide, distil, separate, process, etc.

Having defined these concepts for the power plant it is possible to introduce the whole approach from a structure layer to a meta-function layer (Figure 4). It can be appreciated on figure 4 the different stages of the ontology. The two bottom layers correspond just to a pure device ontology interpretation, as the upper two include teleological information and are considered part of the functional ontology. Additionally the top layer is the one most complex dependant as well as the most abstract, while as all the other layers are oriented towards objects this last one is systems oriented, due to its degree of conceptualization.

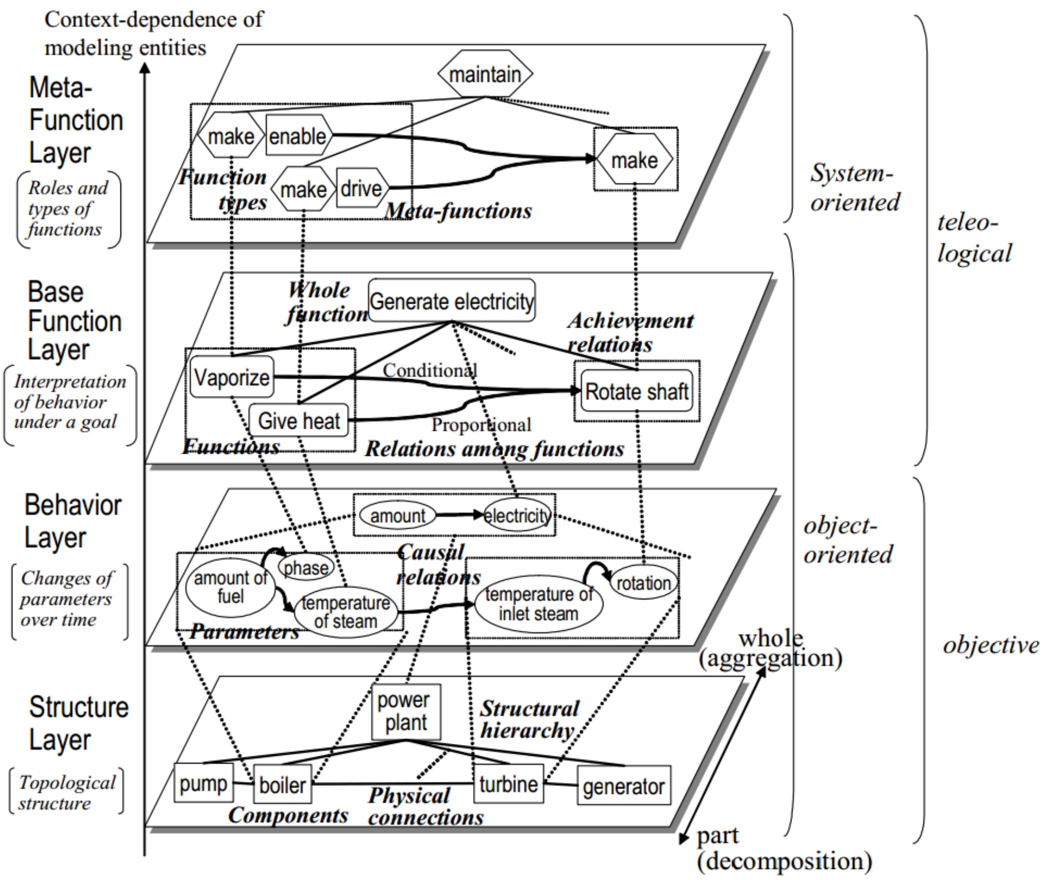


Figure 4. Hierarchy of a target object (power plant).

4 PROCESS ONTOLOGY

4.1 PROCESS DEFINITION

Device ontologies are based on a particularism approach; this can be seen by the way entities are modelled by agents. However, there are several entities that cannot be modelled by a black-box agent, and example would be a chemical reaction. For this cases, the approach varies and considers the idea of process.

What are processes then? An initial definition would be something that is not particular at all in the traditional sense. To explain this, let us consider a chair, if we divide the chair in the particularism, we have that it is composed by several parts, but none of these parts is a chair itself. Now let us consider the rain, it is an action, when one thinks about rain one does not think of a static object. If we take one part of the rain, it will be still rain, in contrast to the chair example. There are still plenty of discussions about the definition of process, as explained in Campbell's work (Campbell, 2005).

An interesting approach is the one carried out by (Yoshioka, et al., 2004). This is regarded as a process centred approach by (Erden, et al., 2008), nonetheless it does not rely in the abstract concept of process explain before but instead uses physical concepts and entities as the bricks to build their framework.

4.2 CONCEPTUAL APPROACH

In (Yoshioka, et al., 2004) the main issue is to integrate engineering design not only from a data level but, from a conceptual level across the different domains. This will work on an upper level, as it will allow by integrating the domains on a knowledge level to use multiple design modelling systems from different domains.

In order to achieve this it is necessary to understand how the engineering knowledge structure works (Figure 5). It is divided in three layers. The first corresponds to a conceptual level ontology, which is also known as "metamodel", in this an object is represented as a network of concepts. The second layer corresponds to the modelling knowledge; this is the information about how to use that model and its inputs and outputs. Finally, the last layer describes the model specific knowledge.

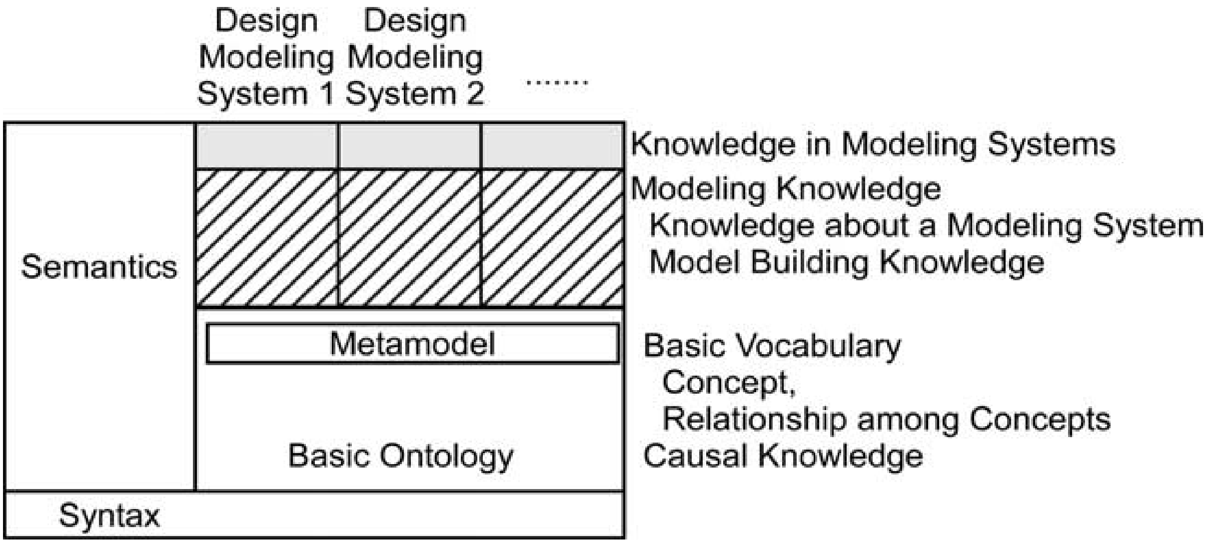


Figure 5. Model of engineering knowledge structure.

4.2.1 Basic concepts

In a similar manner as for the case of the device ontology, there are some important concepts to be defined before proposing an ontology based on this approach.

- Entity: atomic physical object
- Relation: relationship between entities that forms a static structure
- Attribute: concept attached to an entity, it takes a value to indicate the state of the entity.
- Physical phenomenon: designates the physical laws that govern the behaviours.
- Physical law: simple relationship between attributes.

4.3 EXAMPLES

4.3.1 Bycicle transmission example

In order to illustrate the main concepts, the transmission of a bicycle will be used. (Figure 6)

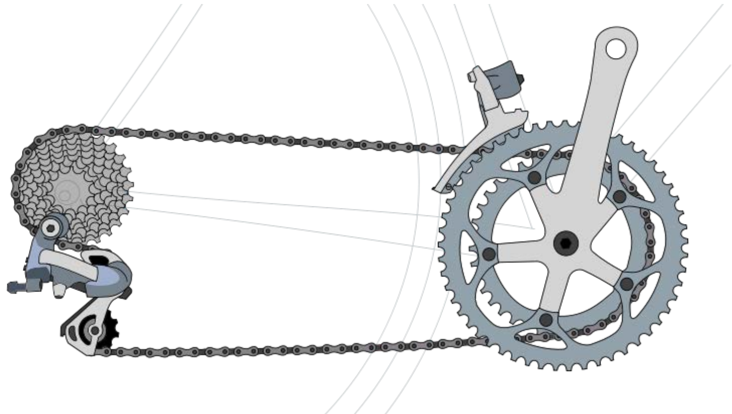


Figure 6. Bicycle transmission.

A bicycle transmission is formed by three main elements: The front gear, the chain and the rear gear. The mechanism allows to transmit the force from one gear to the other, based on their relative sizes. Applying the mentioned concepts, we have the following basis for an ontological approach:

Table 3. Ontology for a bicycle transmission.

Entities	Front gear	Rear Gear	Chain
Relation	Attached to the chain	Attached to the chain	Attached to both gears
Attributes	Ratio, angular velocity	Ratio, angular velocity	Linear speed
Physical phenomenon	Torque, rotating motion, conservation of force	Torque, rotating motion, conservation of force	Linear motion, conservation of force.
Physical law	Equations ex. $v_{fg} = r_{fg} * w_{fg}$	Equations ex. $v_{rg} = r_{rg} * w_{rg}$	Equations ex. $v_{rg} = v_{fg} = v_{chain}$

Figure 7 shows the representation of these relationships on a conceptual basis (metamodel).

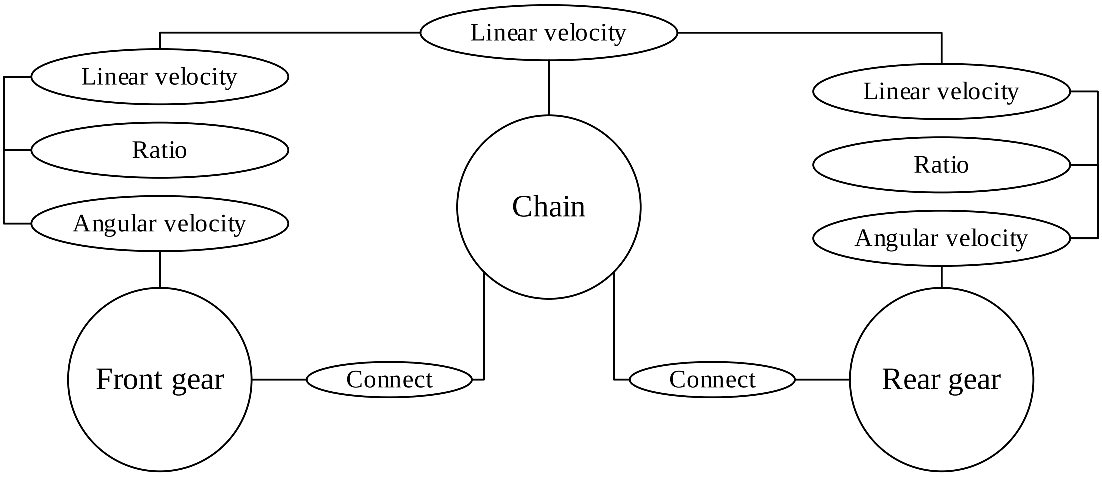


Figure 7. Bicycle transmission metamodel.

As it can be seen for each entity, there are a series of concepts associated to each identity and how they interact with each other. In this case the ontology was proposed for just one domain.

4.3.2 Flash tank

Now let us consider an adiabatic flash tank, in which two components are being separated (Figure 8). It is necessary to model the tank also considering economics.

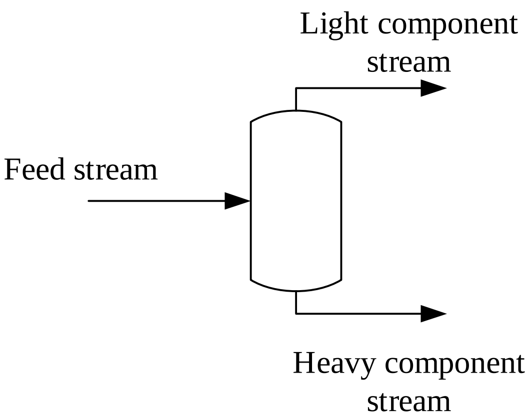


Figure 8. Flash tank.

The first step is to propose a meta model. Which includes all the necessary concepts (Figure 9).

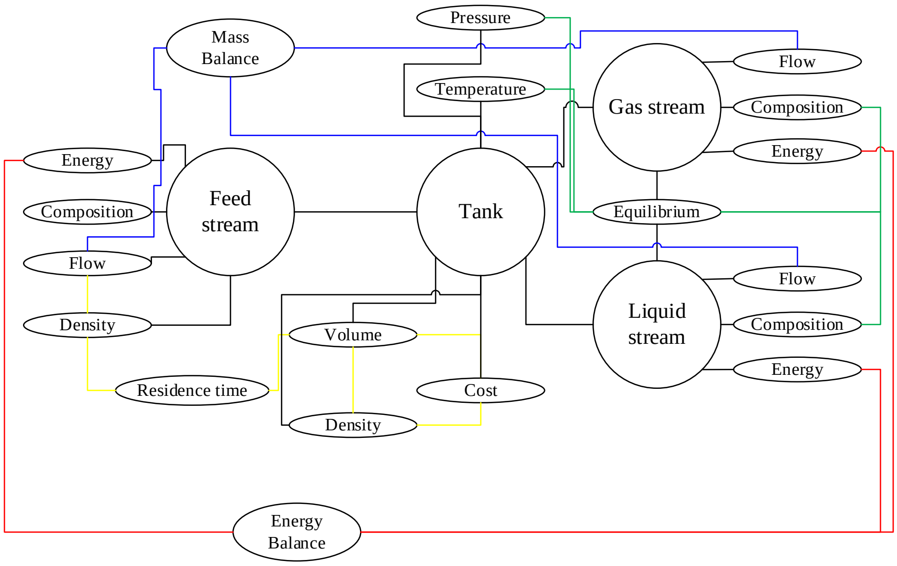


Figure 9. Metamodel for an adiabatic flash tank.

It can be seen in figure 9 the different relations between all the different concepts. The different colours correspond to different kinds of relationships as follows:

- Black: Physical interaction, belonging attribute.
- Red: Energy balance
- Blue: Mass balance
- Green: Phase equilibrium
- Yellow: Sizing and economic estimation.

In this case, each one of the relationships will feed the parameters for each model, as follows:

Table 4. Second and third layer of the engineering knowledge framework applied to the flash tank.

Domain	Inputs	Outputs	Specific knowledge
Mass balance	Streams flow and composition, equilibrium.	Remaining flows and composition of all streams	Mass conservation
Energy balance	Streams enthalpy	Remaining streams enthalpy	Energy conservation
Phase equilibrium	Temperature, pressure	Relation between compositions	VLE information, Raoult's law, Henry's law, etc.
Economic evaluation	Type of material, weight	Annualized cost	Economic estimation correlations.

5 APPLICATIONS & CHALLENGES

The previously exposed approaches are very general and their aim was to introduce some basic concepts of ontology technology as well as some basic assumptions common to many ontology systems. Nonetheless, these explanations are still abstract and it might be difficult to figure the real applications of ontology technology. There are still many steps in between this conceptual descriptions and the actual implementation, such as the development of interfaces, programming, definition of syntax, etc. The following section will show some of the advantages and challenges of implementing ontology technology in the industry based on (Erden, et al., 2008).

5.1 APPLICATIONS

The main applications of ontology technology can be separated in four main fields: (1) Evolvability, (2) Detection of unpredicted interferences, (3) Reliability, availability, maintenance and safety.

5.1.1 Evolvability

There are several differences between description of contemporary systems and those of their first releases. Usually as the time passes by and new technologies are developed, new functionalities are included in the systems making them more complex. A system is then evolvable if it complexity does not increase in unmanageable proportions after adding a new functionality.

Towards this aim ontology design should leave a place open for further developments, in a way that the initial behaviours are not changed. An example of this would be proposing general metamodels, in which potential future relations could be considered.

This also applies for ontology technology parts not studied in this work such as the interfaces, programing and implementation of the ontology frameworks.

5.1.2 Detection of unpredicted interferences

The use of ontology technology allows to see relationships between concepts and entities from different domains. As the engineering labours are carried out in a domain specific approach, the use of ontologies allows to notice unexpected couplings between variables from different domains. In this sense it, ontologies make easier to propose a design based on these “hidden” effects.

5.1.3 Reliability and safety

Ontologies allow the user to have a broader view from the system, independently of the domain. This means that possible sources of risk can be taken into account earlier. When it comes to maintenance and reliability, ontologies offer a systematic approach in which these two tasks could be optimized. This is closely tied to the previous application.

5.2 CHALLENGES IN INDUSTRIAL APPLICATIONS

Based on (Kitamura, Koji, & Mizoguchi, 2006) the first issue related to the implementation of ontology technology in the industry was the used of new technologies. Usually engineers are too occupied to learn how to use new technologies. Then, it is needed a strong motivation in order to learn these new technologies. However, when it comes to knowledge management projects, the knowledge authors have no effective motivation to write down their knowledge and share it.

The main benefits for engineers came as they used ontologies as a test and view by themselves the new and more efficient possibilities that ontologies offer in design or diagnosis situations.

The second issue was to teach engineers the ontology framework. A recurring problem was the formulation of ontologies in a way which could not compile and therefore not reusable for other products. Additionally, it was very difficult for engineers to formulate concepts in appropriate ontological way, as they are very attached to their domain specific terminology.

6 CONCLUSIONS & FURTHER WORK

The present work is just an introduction to some of the works and approaches that have been developed in ontology technology applied to different engineering tasks. It could be appreciated the advantages of including ontological approaches into the engineering processes. However there is still plenty of challenges in order to make the implementation and use of ontologies widespread in the industry. As there are many different approaches to ontologies from a conceptual to implementation level which makes more difficult to find a common ground among ontologies, it is similar to the case of programing languages.

For further projects, it would be really interesting to consider the implementation of ontologies, from a programming level. In other works, to see how challenging would it be to propose an ontology system pertinent to chemical engineering applications.

Another work would be to illustrate different approaches within the same ontology kind. An example would be to consider two or more different ontology approaches based on process ontology and evaluate their applications on a same case.

7 REFERENCES

Brown, J. S., & de Kleer, J. (1984). A framework for a qualitative physics. *Proceedings of the Sixth Annual Conference of the Cognitive Science Society*, 11-18.

Campbell, R. (2005). *A process based model for an interactive ontology*.

Erden, M. S., Komoto, H., Van Beek, T. J., D'Amelio, V., Echavarria, E., & Tomiyama, T. (2008). A review function of modeling: Approaches and applications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 147-169.

Harper, D. (2014, 09 23). *Ontology*. Retrieved from Online Etymology Dictionary: http://www.etymonline.com/index.php?term=ontology&allowed_in_frame=0

Kitamura, Y., & Mizoguchi, R. (2004). Ontology-based systematization of functional knowledge. *Journal of engineering design*, 32-351.

Kitamura, Y., Koji, Y., & Mizoguchi, R. (2006). An ontological model of device function. *Applied ontology*, 237-262.

Knowledge based systems. (1994). *IDEF5 Method report.* College Station, Texas: University Drive East.

Mizoguchi, R. (2008). *Functional ontology of artifacts.* Osaka University. Osaka, Japan: Keio University Press.

Mizoguchi, R., Kozaki, K., Sano, T., & Kitamura, Y. (2000). *Construction and deployment of a plant ontology.* Osaka: Osaka University.

Pahl, G., & Beltz, W. (1977). *Engineering desing: a systematic appoach.* Berlin: Springer-Verlag.

Petrov, V. (2011). Chapter VI: Process ontology in the context of applied philosophy. In V. Petrov, *Ontological Landscapes: Recent Thought on Conceptual Interfaces Between Science and Philosophy.* . Ontos Verlag. .

Yoshioka, M., Umeda, Y., Takeda, H., Shimomura, Y., Nomaguchi, Y., & Tomiyama, T. (2004). Physical concept ontology for the knowledge intensive engineering framework. *Advanced engineering informatics, 18*, 95-113.