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A MANUFACTURING ONTOLOGY FOLLOWING PERFORMANCE INDICATORS APPROACH

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ABSTRACT

Ontology can be considered as the core of a knowledge management system, since it provides a formal and explicit description of concepts in a discourse domain. This paper aims at defining a manufacturing ontology, capable of modelling manufacturing systems, with special emphasis being given to four performance indicators, namely cost, time, flexibility and quality. The proposed ontology determines an overall scheme for the description of manufacturing knowledge, including four sub-schemes for the performance indicators, the product, the orders and the plant. The classes of each sub-scheme, their relationships and their attributes are presented in detail. Cost and time assessment rules are defined, enhancing the ontology with reasoning mechanisms, and facilitating the decision making process.

KEYWORDS

Ontology, Manufacturing Systems, Manufacturing Performance Indicators

1. INTRODUCTION

The demand for a manufacturing system's knowledge management, throughout the whole factory lifecycle, from requirements to the dismantling phase, has been increasing steadily in the past years. During the design phase, more than 75% of the activities comprise reuse of previous design knowledge to address a new design problem (Wildemann, 2003). Currently, engineers have to rely upon their experience and search for past relevant solutions in their companies' databases. Therefore, a framework supporting the knowledge management systems, within a whole manufacturing system, would create a great advantage (Chryssolouris et al, 2009). The basic core of such a framework is a manufacturing ontology that models and represents the knowledge domain.

The Process Specification Language (PSL) is a language capable of describing discrete manufacturing and construction process data (Gruninger et al., 2003) based on the CYC, a commercial ontology including 200,000 terms, (Cycorp, Inc., 2008), (Schelnoff et al., 1999).

In the context of the network-based assembly design support, the morphological characteristics of assembly joints are modelled utilizing an ontology study (Kim et al., 2009). A variety of geometrically and topologically similar joints, using open standard technologies, are modelled and the assembly joint knowledge technology is described in a standard way using the ontology. In particular, the assembly hierarchical relationships are modelled so as to define a set of assembly structures, a set of parts and a set of form features, while the mere topological representation of assembly joints is utilized for the definition of various different assembly joints. In (Alsafi and Vyatkin, 2010) an ontology is proposed as the basis for an agent based reconfiguration mechanism. The agent uses, without human intervention, a manufacturing environment knowledge represented by ontology. In this way, the overhead costs of the reconfiguration process are minimized since the procedure has been automated. The main classes cover tools, machines, material resources, the manufacturing operations related to the manufacturing environment, the logistic operation and the controller. Ontology, also describes the relationships among the classes and their connection, providing hierarchies in general. Similarly, in the context of reconfiguration needs, a comprehensive equipment ontology is proposed to facilitate the effective design of reconfigurable assembly systems that is based on the function-behaviour-structure paradigm (Lohse et al., 2006). The specific ontology emphasizes on the functional capabilities of the equipment that can be selected and integrated effectively. This ontology covers five main knowledge domains, concerning product, process, equipment, function and behaviour concepts that are included in three representation levels. The first one the knowledge representation level describes the way that the different concepts, attributes, constraints and rules are implemented. At the level of ontology, all the specific domain concepts, attributes, constraints and rules are defined, while the last is the instantiation level. The equipment structure is modelled with a hierarchy, and so is the assembly activity function structure. The described ontology is applied to a simple assembly scenario that concerns the replacement of a SCARA-type robot with a new one. Another research, aiming to provide an equipment ontology, in particular, a machine tool model that aims to facilitate manufacturing information and knowledge management, is provided in (Kjellberg et al., 2009). The identified ontology concepts, constituting the core of the ontology, are mapped with the information models, utilizing different standards. The mapping prescribes what application objects to be used and how. Taking into consideration the type of information to be modelled, a variety of standards can be used. The paper presents a mapping example of machine tool kinematics, connecting this way the ontology with the information standard. In particular, concepts of the tool model ontology, such as “travel range” and “kinematic range” are instantiated with the AP214 model. The proposed ontology is expendable, allowing the addition of new concepts that can be later connected with the existing standards of the users’ interest.

In (Lin and Harding, 2007), a manufacturing ontology is proposed aiming to decrease the complexity in exchanging manufacturing information and sharing knowledge among companies in various different projects. A general manufacturing system engineering (MSE) knowledge representation scheme is proposed, aiming to facilitate the communication and information exchange in inter-enterprise, multi disciplinary engineering design teams by utilizing the standard semantic web language (RDF, RDF schema and ontology) (Lin and Harding., 2007). The present ontology addresses inter-company issues, related to the requirements of information semantic interoperability for knowledge sharing. The top level classes are the enterprise, the project the flow, the resource, the process and the strategy, all of which are linked with relationships. In the context of the knowledge management system for process planning an ontology is developed for the description of the process planner environment (Denkena et al., 2007). In particular, the instances and classes of the process-planning ontology, concerning facility data, such as machines, tools, raw data and order data such as product geometry, product dimensions, order quantity and due data, are organized in facility and order data hierarchies. Finally, the classes and their relationships have been implemented in the Protégé platform. In (Chen et al., 2009), an integration mechanism for the product lifecycle knowledge, concerning activities such as coordination, communication and control is proposed. The developed ontology is structured in three different layers. The collaborative enterprise defines a sharable local ontology, following the local ontology schema as it is described by the dominant enterprise. This layer concerns the distributed local ontology. The second layer is related to the product lifecycle. The dominant enterprise defines a product lifecycle ontology, based on the lifecycle phases and activities of the required product lifecycle. Furthermore, the local ontologies distributed, are integrated with the product lifecycle ontology, constituting the integrated global ontology layer. In this way, the cooperating enterprises can share their knowledge and can exchange information by utilizing the developed product lifecycle ontology. The problem of product knowledge exchange for collaborative manufacturing is also identified in (Jiang et al., 2010). In this approach, an ontology based framework consisting of smaller integrated ontologies is being proposed. The framework includes five elements. Domain enterprises define the required knowledge and transform it not as a product knowledge ontology but as a local ontology. The local ontologies of each enterprise are integrated into the global ontology. Through this global ontology, the enterprises can share and exchange product knowledge leading to an increased knowledge value. The process of ontology integration consists of the following two steps, the ontology mapping and the ontology merging. The first one concerns the similarity measurement, sorting, filtering and linking of the ontology schema, while the concept names of merging, compose the second step. The last element has to do with the ontology querying. The user, based on his own needs, is able to search for the ontology. The knowledge output derives from similarity computations for all the knowledge searched.

In conclusion, the existing enterprise ontologies are too generic to address the knowledge representation needs of manufacturing. In particular, this kind of ontologies is restricted to terminological problems. On the other hand, a variety of manufacturing ontologies that have been proposed in the last years, emphasize on a specific domain of manufacturing systems, and do not allow an abstract description of the problems. For instance, a lot of specific ontologies focus on the representation of knowledge issues in assembly processes, in product design or in collaboration management and do not provide a holistic overview of the manufacturing systems. Moreover, ontologies that seem to be providing an adequate modelling knowledge of the manufacturing domain, they still do not cover the performance indicators and their connection with the manufacturing classes such as processes and resources.

The current ontology attempts to fill in this gap by providing a generic framework that will enable the successful knowledge representation for a factory's lifecycle. The proposed ontology includes a description of the manufacturing attributes domain and associates them with the plant, product and process classes. Apart from the knowledge representation, the association of the manufacturing attributes with the rest of the ontology classes, emphasizes on the development of reasoning mechanisms. The reasoning mechanisms are responsible for deducing the manufacturing attributes' values, depending on the manufacturing system's characteristics and the different production system's hierarchies.

The introduced ontology is implemented in the Protégé tool editor by utilizing the OWL-DL language. The rules that are incorporated into the ontology are developed with the use of the SWRL rules tab from Protégé, while the execution of the rules can be performed with the enabling of the Jess engine plug in.

The rest of the paper is organized as follows. Chapter 2, is dedicated to describing the structure of the ontology and to presenting the proposed knowledge representation of the manufacturing domain. Chapter 3, describes the reasoning mechanism used for deducing the manufacturing attributes' values, as well as for providing a description of the rules and the associations related to the manufacturing attributes. In chapter 4, an instantiation of the proposed ontology is presented. Chapter 5, concludes the basic outcomes of the work and suggests future research directions.

2. MANUFACTURING ONTOLOGY SCHEME

There are three main questions that must be answered before the development of an ontology (Noy McGuinness, 2002),

- What is the domain that the proposed ontology will cover?
- What is the purpose of the ontology?
- What are the questions that the ontology will answer?

The current ontology aims to cover the manufacturing domain, to model the structure and the relationships among the primary physical and virtual entities of a manufacturing system. The purpose of the ontology is to represent plant, product, orders, manufacturing attributes and define their interconnections, in order to support the modelling and the analysis of alternative plant configurations useful for the different phases of the factory lifecycle, such as design and planning. The ontology will answer questions concerning the assessment of manufacturing performance indicators for alternative plant configurations or alternative task planning activities, providing this way a decision support mechanism.

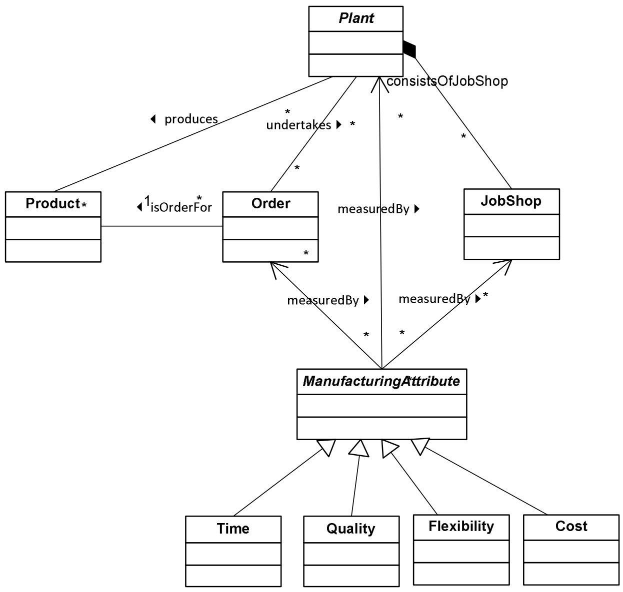

Figure 1 –Basic classes of the proposed manufacturing ontology and their relationships

The overall ontology scheme is illustrated with the help of figure 1. On the left side, the product class and the orders class are presented while in the center of the figure, the plant class is illustrated and beyond it the manufacturing attributes structure is depicted. The basic scheme of the ontology is further analysed in the following paragraphs.

2.1. PLANT HIERARCHY

The structure of the factory is represented with the use of the plant hierarchy. A five layer hierarchical model of production control including: (i) facility, (ii) shop, (iii), cell, (iv) workstation and (v) equipment is proposed in (*Jones and McLean 1986,McLean et al 1982*). A more extended hierarchy taking into account the production network scale, apart from the plant scales, consists of seven levels,namely: (i) production network, (ii) production location/site, (iii) production segment, (iv) production systems, (v) production cells, (vi) workplaces/machines and (v) processes (*Westkämper and Hummel 2006*). In the current ontology, there has been adopted a more coherent approach for plant hierarchy, following a four-level hierarchy (Chryssolouris, 2006), including:

- Factory level
- Job shop level
- Work center level
- Resource level

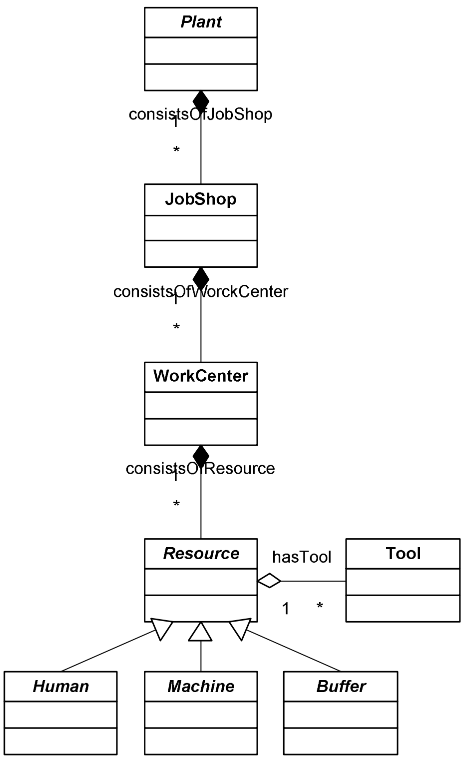

Figure 2 – Plant hierarchy scheme

The factory is the highest level in the hierarchy and corresponds to the system as a whole, while it also consists of job shops that represent a group of workcenters. The workcenters are considered as a set of resources that perform similar manufacturing processes. A resource is regarded as a generic entity that can be a machine, a human worker or a storage area. In the present ontology, each level is modeled as a class, as it is illustrated in figure 2. The Plant is connected with the Jobshop using the relationship *consistsOfJobShop*. Similarly, the jobshop class is connected with the workcenter, with the relation *consistsOfWorkCenter*, and the workcenter class with the resource class, with the relation *consistsOfResource*. The class Resource is includes (i.e. is-a UML notation) the classes of Machine, Human and Buffer. The Machine specializes in the resource and can model a robot or lathe or any other type of machine in general. Similarly, the *Buffer* also specializes in the resource and represents the storage area between machines. Finally, the *Human* models the laborer, as a specialization of the *Resource* as well. The *Tool* represents the tools used by a machine or a human in order for a task to be performed. Consequently, the *Resource* is associated with tools via the object property *hasTool*.

2.2. PRODUCT HIERARCHY

A generic and abstract structure of a product is proposed for the needs of the ontology. The main class of course is the *Product.* This concept represents the actual finished goods, produced by the plant. The ontology object property that connects the product to the model is *consistsOfModel* indicating that a product may have more than one model. This object property can be used for associating an instance of the class *Product* with instances of the class *Model*. The class *Model* is connected tothe class *Variant* with the relationship *consistsOfVariant*. Part, is the lower level in the product hierarchy specialized by the *SinglePart* and the *Subassembly.* The relationships of the subassembly, simple part and part are modelled following the composite design pattern (Gamma, 1995).

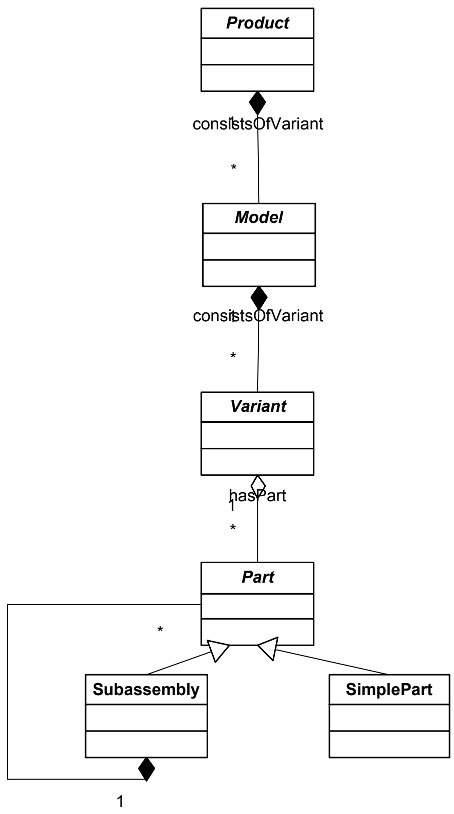

Figure 3 – Product hierarchy

2.3. ORDERS HIERARCHY

Corresponding to the plant hierarchy there is also the workload hierarchical breakdown. Orders are broken down into jobs, which in turn, consist of a number of tasks. An order corresponds to the overall production facility and is divided into jobs that based on their specifications can be processed only by a suitable job shop. A job consists of tasks that can be released to one workcenter only. The tasks can be dispatched to more than one of the work center's parallel resources (Chryssolouris and Lee, 1994). Based on this concept, the orders hierarchy is modelled with the following classes.

The class Order models the actual order that is dispatched to a plant. Each instance of the class order is associated with a plant, via the object property *dipachedTo*. Additionally, each instance is associated with an instance of the class Product, via the object property *isOrderFor*. Finally, each product is associated with instances of the class Job, via the object property *consistsOfJob*. The class Job, represents the jobs that constitute an order. Each instance of the class Job is associated with an instance of the class Jobshop and the instances of the class Task, via the object properties *releasedToJobshop* and *consistsOfTask* respectively. Finally, the Task class models those tasks performed by the resources. Each instance of the class Task is associated with an instance of the class *WorkCenter* and an instance of the class *Resource* via the object properties *releasedToWorkCenter* and *dispatchedToResource* respectively.

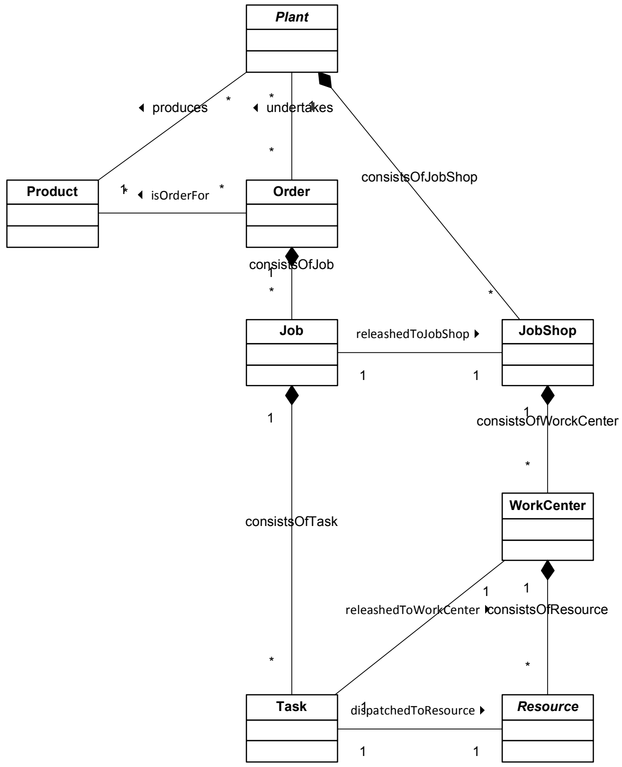

Figure 4 – Order hierarchy and its relationship with plant hierarchy

2.4. MANUFACTURING ATTRIBUTES HIERARCHY

The four most important attributes used for making a decision in manufacturing during the design, planning, operations and in general, during the whole factory lifecycle are cost, time, flexibility and quality (Chryssolouris, 2006). Therefore, the main classes of the performance indicators are classified into time, cost, quality and flexibility. Next, the classes are further analyzed with more specific subclasses and instances that are associated with the plant hierarchy and order hierarchy classes with the use of rules and ontology relationships. In the current study, flexibility has three subclasses, namely capacity, operational and product flexibility and cost subclasses that are modeled based on the Active Based Costing method, while Time includes, production rate and flowtime. The aim of the performance indicators hierarchy is to provide a general scheme for classifying manufacturing attributes and associating them with the plant and order classes, thus, facilitating the assessment of the performance indicators for a different level of the plant hierarchy.

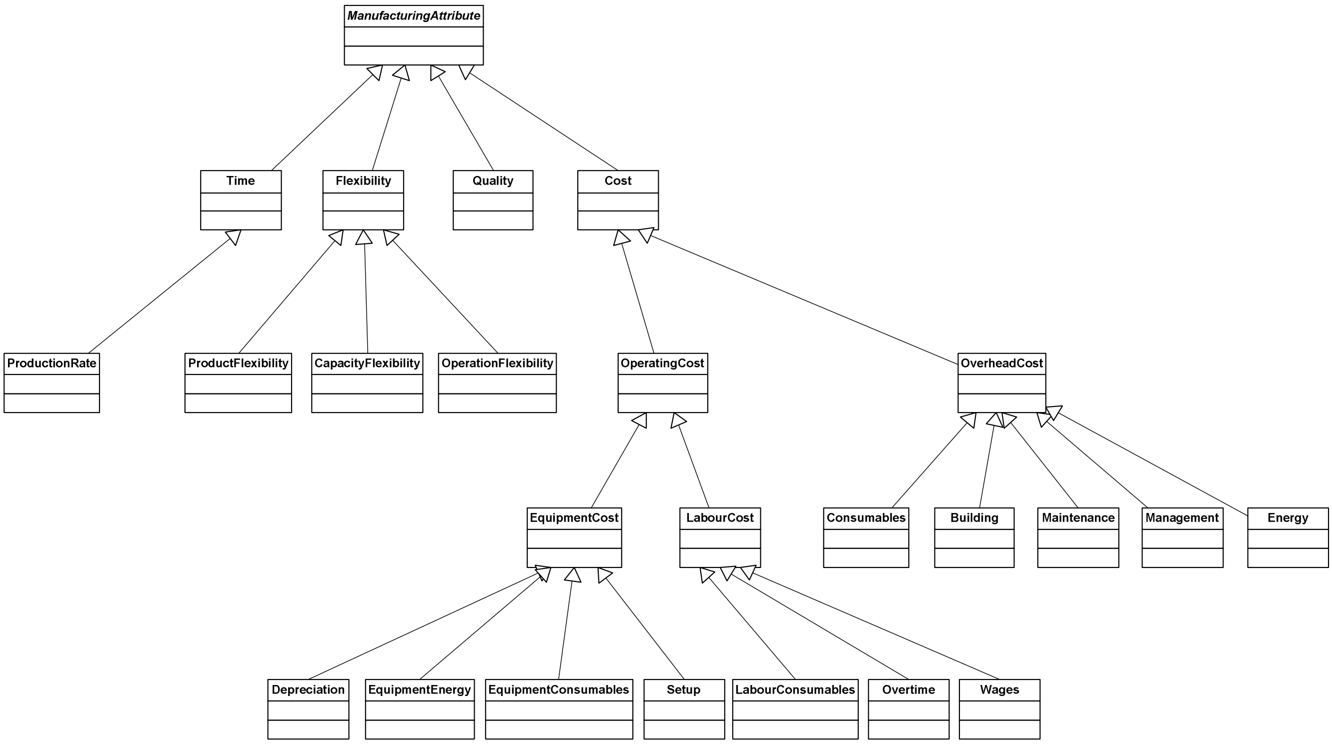

Figure 5 –Performance indicators classification scheme

2.4.1. Cost

The cost modelling is based on the Activity Based Costing (ABC) method. So, the main classes and their structure follow the ABC modelling.

The Cost class is specialized in overhead and operational cost classes. The Overhead class is further specialized from the classes Building, Consumables, Energy, Management, Maintenance. The Operational cost class is further specialized from the classes labour cost and equipment cost. The labour cost class is specialized from the classes overtime, wages and labour consumables. The equipment cost class is specialized from the classes depreciation, setup, equipment consumables, equipment energy.

2.4.2. Time

The class of Time is specialized in the subclass of Production Rate. The scheme can be easily enhanced with other specializations of the time related performance indicators, such as lead time, process time etc.

2.4.3. Flexibility

A high flexibility or a low sensitivity to a change provides a manufacturing system with three principal advantages. It is convenient to think of these advantages as arising from the various types of flexibility that can be summarized in three main categories as in (Chryssolouris, 2006), namely those of the product, capacity and operation flexibility.

Product flexibility enables a manufacturing system to make a variety of part types with the use of the same equipment. In the short term, this means that the system has the capability of economically using small lot sizes to adapt to the changing demands for various products (this is often referred to as production-mix flexibility). In the long term, this means that the system's equipment can be used across multiple product life cycles, increasing investment efficiency.

Capacity flexibility allows a manufacturing system to vary the production volumes of different products in order to accommodate any changes in the volume demand, while remaining profitable. It reflects the ability of the manufacturing system to contract or expand easily. It has been traditionally seen as being critical for make-to-order systems, but is also very important for mass production, especially for high-value products such as automobiles.

Operation flexibility refers to the ability to produce a set of products using different machines, materials, operations and sequences of operations. It results from the flexibility of individual processes and machines, that of product designs, as well as the flexibility of the manufacturing system structure itself. It provides a breakdown tolerance namely, the ability to maintain a sufficient production level even when machines break down or humans are absent.

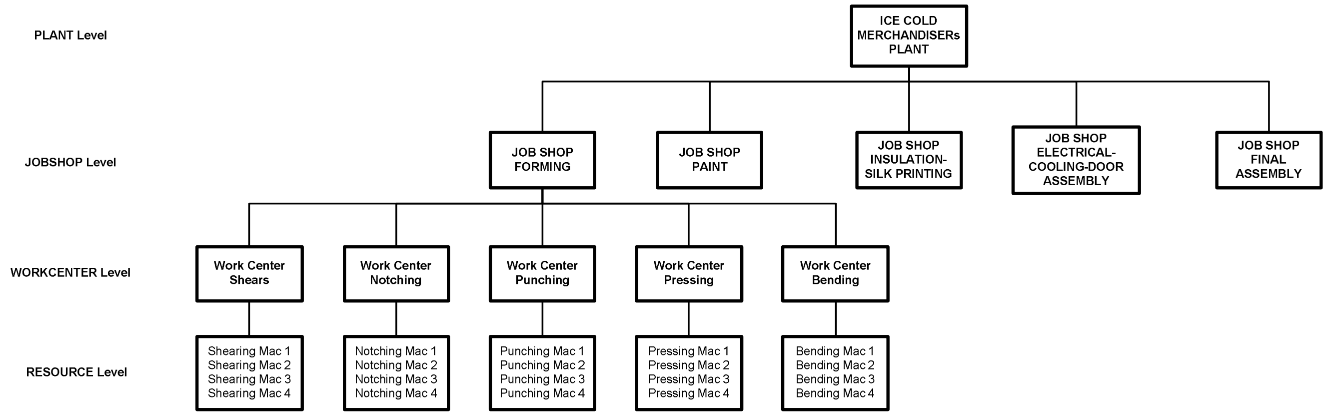

Figure 6 – ICM Plant Structure, detailed breakdown of the forming jobshop

3. REASONING MECHANISMS

The objective of the reasoning mechanisms is the definition of the rules that will allow for an estimation of the manufacturing attributes associated with ontology classes. Rules are divided into two categories. The first type, is responsible for aggregating performance indicators that belong to different plant hierarchy levels. For example, the investment cost of a workcenter is the aggregation of the investment cost of the resources belonging to it. The rules that are responsible for aggregating performance indicators are not restricted only to summation. Assessment of the minimum or maximum values of a performance indicator, characterizing a class in the plant hierarchy or the order hierarchy, can be also addressed by a rule of this type. The second type of rules, are responsible for defining the relationships among the different performance indicators. For instance, an operation cost is considered as the aggregation of the equipment and labour costs.

In the following sections, two rules for the assessment of the production rate and the cost are presented. The production rate assessment rule belongs to the first type of rules, while the cost assessment can be considered as a rule of the second type. Rules in the present approach, concern a serial production. Initially, the concept of each rule is described, with the classes and the subclasses that are involved, while afterwards, it is the SWRL human readable syntax of the rules that is provided.

3.1. PRODUCTION RATE ASSESSMENT RULE

The production rate of a production line, whose machines are in line, is dictated by the machine with the lowest production rate. Hence, a rule, identifying the minimum production rate of the production line and assessing this production rate to the production line, has been defined. The determination of such a rule allows the automatic assessment of the production rate of a production line.

The production rate of a jobshop is the minimum production rate of the workcenters, belonging to the jobshop. The SWRL syntax of the rule is provided hereafter.

ProductionRate(?pr) ∧ WorkCenter(?wc) ∧ consistsOfResource(?wc, ?res) ∧ measuredBy(?res, ?pr) ∧ hasValueAsIs(?pr, ?val) → sqwrl:min(?val)

For every resource (res) that belongs to a workcenter (wc) and is measured by the production rate (pr) whose value is (val), the minimum production rate value is estimated.

Where,

- pr: the variable, whose value is the production rate
- res: the variable of the resource
- wc: the workcenter variable
- val: the value of the production rate

3.2. COST ASSESSMENT RULE

The cost assessment rule has been developed in order for the cost of a workstation, performing a series of tasks to be calculated. Based on the cost hierarchy, as it is defined in section 2.4.1, the cost classes and subclasses are associated with the task, resource, workcenter and jobshop classes.

The total cost of a jobshop is considered the sum of the overhead costs and the operational costs for the tasks, performed by the resources of the workcenters belonging to the jobshop. This rule can be represented in the SWRL syntax with the following way.

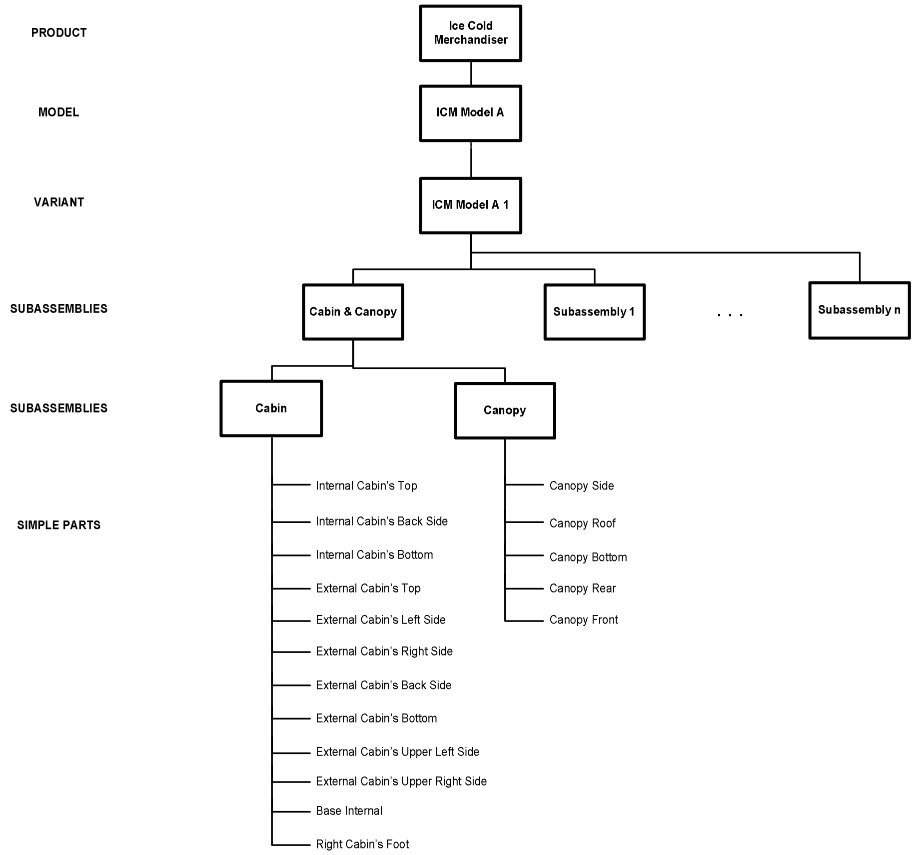

Figure 7 – Part of the ICM bill of materials, detailed breakdown of cabin and bucket

EquipmentCost(?eqc) ∧ hasValueAsIs(?eqc, ?eqcval) ∧ Task(?t) ∧ measuredBy(?t, ?eqc) → sqwrl:sum(?eqcval)

For every task (t) that is measured by the equipment cost (eqc) whose value is eqcval, the sum of the eqcval is calculated.

Where,

- t: is the variable of task
- eqc: the equipment cost variable
- eqcval: the value of the equipment cost

4. CASE STUDY

The manufacturing ontology is discussed in a real life scenario in an ice cold merchandiser's industry. An instantiation of the ontology is provided in order for the applicability of the approach to real industrial problems of knowledge representation to be presented.

A simple subassembly of an ice cold merchandiser, in particular Activator 700 and a job shop of the production system, are presented. Two main subassemblies of the Activator 700 are presented, i.e. the cabin and the bucket, in Figure 7. The cabin and canopy consist of 12 and 5 single parts respectively. The plant includes 5 jobshops, and the first jobshop, namely the Cabin forming includes 5 workcenters. The diagram of figure 6 presents the hierarchy of the plant as it is instantiated with the ontology.

The ontology is implemented in the Protégé 4 platform, while for the rules and the reasoning mechanisms the Jess engine has been utilized. Figures 8 and 9 present the instantiation of the product and plant respectively in the Protégé environment. In the same figures, in particular, on the left,, the main classes of the ontology can be viewed.

6. CONCLUSIONS

In this work an ontological approach for structuring a manufacturing reference knowledge model has been presented. The emphasis is given to the modelling of performance indicators. The basic plant and manufacturing attributes hierarchies and taxonomies developed are described. The reasoning mechanisms, utilizing the SWRL rules that are included in the ontology, are also described. Finally, an industrial use case is presented in order to show, in the context of knowledge representation, the ontology's efficacy in real industrial problems..

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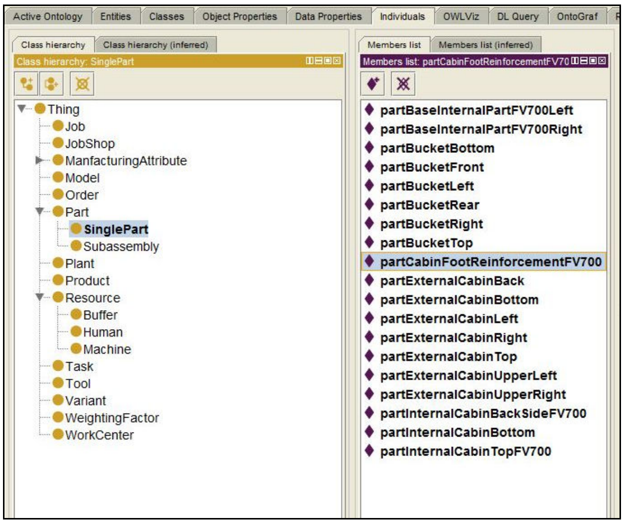

Figure 8 – Instantiation of product hierarchy classes

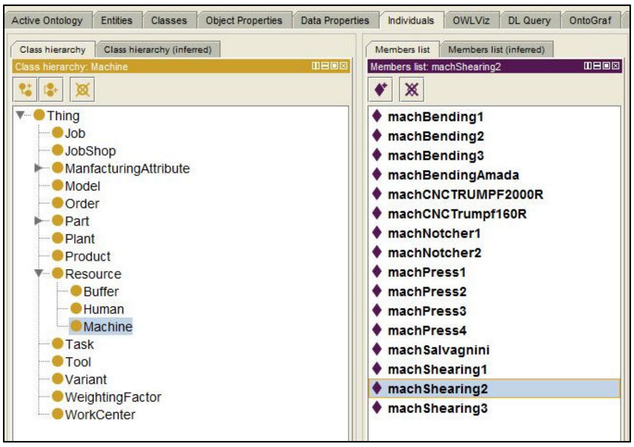

Figure 9 – Instantiation of plant hierarchy classes

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