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Decision Making Support Based on a Process Engineering Ontology for Waste Treatment Plant Optimization

Edrisi Muñoz[a], Elisabet Capón-García[b], Konrad Hungerbühler[b], Antonio Espuña[c], Luis Puigjaner*[,c]

[a] Centro de Investigación en Matemáticas A.C., Jalisco S/N, Mineral y Valenciana 36240, Guanajuato, México
[b] Department of Chemistry and Applied Biosciences, ETH Zürich, 8093 Zürich, Switzerland
[c] Department of Chemical Engineering, Universitat Politècnica de Catalunya, Av. Diagonal, 647, E08028 Barcelona, Spain
luis.puigjaner@upc.edu

Industry has experienced an important growth during last decades, improving life quality standards in general. However, such development has brought forth important challenges related to safety issues and environmental impact of the industrial activities. In this sense, industries have received pressure to apply strategies to reduce their environmental impact and produce in an environmentally friendly manner. However, waste generation cannot be completely avoided, and an apropriate managing of waste treatment is crucial in order to reduce the overall impact. Precisely, the industrial waste treatment management stands for an end-of-pipe problem involving effluents, which contain contaminants originated from industrial activities. Indeed, waste streams must meet discharge constraints imposed by environmental regulations before being disposed of in the environment. Thus, waste treatment plants comprise several technologies, and treatment allocation decisions are usually taken based on company-specific selection criteria. Therefore, there is a large amount of data and information to be collected and organized, and the choice of the adequate option for an entire manufacturing site with hundreds of continuously changing effluents becomes an overwhelming task. This work presents a decision support system based on ontological modelling for representing waste treatment plants and improving the assessment of the plant performance by using information quality. Thus, the proposed system provides the operational and logistic functions of the plant with accurate information for optimization based techniques, which may lead to better solutions.

1. Introduction

Businesses are vital for the development and wealth creation in modern society. However, they also cause environmental degradation and depletion of natural resources in order to fulfil their operations and goals. Under the current market pressure, which demands environmentally friendly products and the tighter environmental legislations, companies strive to create value in a sustainable way. Therefore, decision-making turns out a highly challenging task in the alignment of decisions to support the success of plant performance and business goals. In this sense, enterprises comprise several functions, which interact with each other, such as production, marketing, sales, human resources, logistics, safety and environment. Therefore, it is important to provide systems capable of representing and considering the different elements involved in the enterprise. In this area, knowledge management technologies have proved to be highly promising for improving information sharing and communication, enhancing the enterprise operation.
In general, process industries can be regarded as highly complex system consisting of multiple business and process units, which interact with each other and share a large amount of information. The basis for solving a

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systems problem is the system representation in an adequate model, which captures the features relevant for the observer whose ultimate aim lies on decision-making.
The organization of the different scales and levels within such complex systems is crucial to analyze and understand their behaviour and function, as well as to implement any given requirement over them. Recent trends in process industries are shifting the focus from controlling process plants as stand-alone entities toward managing them as an integral larger system (Klatt and Marquardt, 2009). Such approach aims at exploiting the process and environment dynamics in order to maximize the plant economic indicators. Obviously, such understanding of process management entails the integration of the different decision level functions. Therefore, a current important challenge lies on the coordination of the decision-making and the optimization of different decision levels, both vertically across a single process plant, and horizontally along the different geographically distributed subsystems in a given time horizon. In this sense, only some modest attempts at integrating a small subset of enterprise-wide decision models exist, since the complex organizational structures underlying integrated process models challenge our understanding of cross-functional coordination and its business impact (Varma et al., 2007). Much effort must be still devoted to obtain improved models, integration and information tools as well as optimization algorithms, providing decision support tools within a coherent framework taking into account the available information on actual plant operations and market economics (Klatt and Marquardt, 2009).
For many years companies have been developing management information systems to help the end users in order to exploit data and models, with the final objective of discussing and decision-making. Nowadays, global competition has made some of these decisions (related to certain manufacturing characteristics such as economic efficiency, product quality, flexibility, reliability, etc.) essential for the viability of the enterprise (Venkatasubramanian et al., 2006). In this sense, semantic technologies offer an attractive platform for knowledge capturing, information management and work process guidance in the design and manufacturing processes including. They also support smooth integration of information modeling and mathematical modeling in a single modeling framework. Such technologies have to be integrated with existing tools and with the IT environment of an enterprise to be adopted by industrial practice (Klatt & Marquardt, 2009).
Therefore, infrastructures are required that continuously and coherently support fast and reliable decision-making activities in production processes (Venkatasubramanian, 2006). Collaborative support systems and optimization-based decision support systems produce an enormous amount of data that is stored in large databases. However, the usefulness of these data depends on the capacity to process and transform them into valuable information that can be stored, accessed and shared efficiently. One key aspect in the decision-making process is information extraction, which should result in information quality. Information quality refers to the precision of information in terms of the time, content and clarity required for a specific task. However, the interoperability of information contained in different systems is one of the most critical aspects in the daily operation of many organizations. Enterprise performance can be drastically improved by using process knowledge and expertise. In this sense, Decision Support Systems (DSSs) are information technology solutions that can be used to support complex decision-making and problem solving. DSSs are defined as "aid computer systems at the management company level that combine data and sophisticated analytic models for support decision-making" (Simon and Murray, 2007). The use of DSSs, which are directly or indirectly related to manufacturing indicators, has emerged as an essential tool for ensuring the enterprise viability in a global competition environment.
Overall, knowledge structure and organization are of key importance to decision-making. Knowledge is the application of data and information through the development of a system that models experience in a domain in a structured way. Recently, multiple models have been used in the chemical process domain to represent detailed and abstract knowledge. Such models allow the identification of process sections, their functions, objectives and relationships. As a result, alternative views of the process can be generated automatically and organized in a hierarchy of different levels of abstraction.
The waste treatment system stands for a key utility in the enterprise site. Its goal consists of temporarily storing and processing all the waste generated by the production plants without being a constraint for the production processes. In addition, the whole system should operate under existing environmental legislation and keeping the lowest operating cost. Therefore, a major issue consists of adequately modeling and optimizing the waste treatment, while considering the whole enterprise environment.
Once the waste management system is adequately understood, it is necessary to tackle the integration problem. In general the different parts of a company, and in particular the waste treatment management of a site, require different types of information about resources, products and production processes in order to carry out their functions. The first step toward such integration consists of the sharing of information, which can be achieved with

modern information technology tools. These tools allow the instantaneous flow of information along the various systems in a company (Grossmann et al, 2008). Hence, adequate information structures are necessary for effectively transforming available data to information, and this into knowledge. In this line, several standards are used in enterprises in order to improve their efficiency and flow of information.

Finally, the interoperability among different decision support tools is a critical aspect in the daily operation of waste management systems, and the enterprise in general. Thus, databases are usually used to store the values related to specific and relevant aspects of the enterprise environment and the system dynamics. For this reason, it is important to consider the relationship between transactional systems which contain data, and the analytical models which help in the decision making process. By improving the communication between these two elements, decision support tools will benefit from higher data availability and their subsequent interpretation as information quality.

This work aims to provide a general and systematic representation of the waste management system within a production site, in order to later apply optimization approaches for decision-making. For this reason, in order to unify different conceptual waste management elements within an integrated production site, this work provides a platform, which encompasses the most important features of production processes and supply chain management, for the consideration of integrated process waste management. This platform includes the different decision levels and functions within the enterprise allowing potential information integration. In this sense, semantic technologies seem to offer an appealing way to capture knowledge and integrate information, for supporting a smooth integration of information and mathematical modeling in a single modeling framework (Klatt and Marquardt, 2009).

Therefore, this work focuses on providing a semantic model, namely an ontology, which deals with diversity in waste management problem representation and allows effective data sharing and information flow. Specifically, this model aims to adequately provide the necessary data which will be used by the optimization tools and the decision maker. Thus, the decision maker has the opportunity of creating high information quality and reaching better solutions, in terms of shorter time of response and choices. As a result, an effective data-information cycle can be performed. Indeed, the use of an ontological model for representing a waste treatment plant has been detected as an opportunity for providing decision makers with new technologies to assess and evaluate the plant performance using information quality.

In the following sections, the benefits of knowledge management technologies are introduced. Next, the waste management problem is described, and the proposed approach is presented. Finally, a case study illustrates the expected results of this framework.

2. Knowledge management

One of the major current business commitments to ensure the competitiveness and success in performance refers to its ability to manage knowledge. It refers to the development and exploitation of the organization's tangible and intangible knowledge. It consists in the definition and application of the correct tools in order to capture, share and exploit the corporate knowledge as well as corporate historical practices. Organizational knowledge management is concerned with realizing the value of this "intellectual capital", which exists as: tangible assets (such as patent licenses and information held in databases on customers, suppliers, products and competitors, etc.) and intangible assets (such as the skills, experience and knowledge of people within the organization) (Apostolou et al., 2008).

This work proposes the development and application of semantic technologies for knowledge management, knowledge sharing and information support, as bases for the development of an enterprise information system. Increasingly, companies realize that their corporate intra-nets are valuable repositories of corporate knowledge. However, due to the size, amount and diversity of information this task of transforming information into useful knowledge has become a major problem. Knowledge management is about leveraging corporate knowledge for greater productivity, value, and competitiveness. Knowledge management tools can be based on several technologies such as distributed databases, ontologies or networks maps. Knowledge management usually considers the knowledge representation organized in five principles: i) a surrogate; ii) a set of ontological commitments; iii) a fragmentary theory of intelligent reasoning; iv) a medium for efficient computation; v) a medium of human expression. Knowledge management systems benefit from ontologies that semantically enrich information and precisely define the meaning of various information artefacts (Davis et al., 1993). In addition, the support for information and knowledge exchange is a key issue in the enterprise information system exploitation. The exponential growth of on-line information on intranets and the web leads to information overload. To cut down on the time wasted in searching and browsing, and reduce associated user frustration, much more selective user interaction, accurate and powerful deliverable information quality is needed. Most information in modern electronic media is mixed-media and rather weakly structured. Finding and maintaining information is a hard problem in weakly structured representation media

Ontology engineering is an important emerging discipline that has a significant potential to improve information organization, management and understanding. It plays a crucial role in enabling content-based access, interoperability, and communications. Ontologies are increasingly seen as a key semantic technology for addressing heterogeneities and mitigating the problems they create and for enabling semantics-driven knowledge processing. Finally ontology engineering refers not only to the development of semantic models, but also the application and exploitation of knowledge base in those models.

Ontologies are formal structures enabling acquiring, maintaining, accessing, sharing and reusing information. The usefulness of ontologies as a general means of conceptualizing and formalizing the content of a subject area has been widely acknowledged. Ontologies conceptualize and formalize knowledge to facilitate knowledge sharing and reuse, by providing: i) a shared and common understanding of a domain; this domain can be communicated among people and across application systems, ii) an explicit conceptualization that describes the semantics, iii) use/reuse and share across software application and groups of people, and iv) captures consensual knowledge of different groups of people.

3. Waste management

The industrial waste management usually stands for an end-of-pipe problem involving effluents, which contain contaminants originated from industrial activities. Waste streams must meet discharge constraints imposed by environmental regulations before being disposed of in the environment. However, both industrial and municipal waste can be considered as an energy and material source via efficient energy recovery and material recycling technologies. In this context, waste-to-energy (WtE) technologies pursue to convert, transport, manage, and recover or reuse energy from any type of waste, while maximizing the synergies with material recycling technologies and satisfying all constraints imposed by legislation. The application of waste-to-energy (WtE) technologies has the advantage of increasing heat recovery and electric efficiency, reducing the overall emissions and enhancing energy storage among others.

Waste treatment plants comprise several technologies, such as incineration, wet-air oxidation, per-oxidation, catalytic incineration, or biological treatment (Chakraborty and Linninger, 2002), whose objective is the removal of contaminants from the industrial effluents. The production planner is responsible for generating operating plans of the whole network, while considering the constraints on waste management system. Recently, Wassick (2009) presented the benefits of using systematic modeling and optimization in the waste management and plant integration. He also highlights the importance of exploiting the synergies of integration and diversification. Specifically, the waste management problem is closely related to the production planning, as well as to the energy and water management systems. In this area, process systems engineering is a well established discipline which covers a set of methods and tools to support decision-making for the creation and operation of the process supply chain from a holistic approach.

Waste minimization, material recovery and utilities rationalization have been traditionally dealt as integral parts at the design stage of process plants (Barbosa-Povoa, 2007; Chakraborty and Linninger 2002). However, once the production process is established, the management of the generated wastes and its coordination with the production processes and utilities systems have a crucial role in the optimal plant resources allocation from economic and environmental perspectives.

In practice, treatment allocation decisions are usually taken based on company-specific selection criteria, since the choice of the adequate option for an entire manufacturing site with hundreds of ever changing effluents becomes an overwhelming task (Chakraborty and Linninger, 2002). In the literature, this problem has been tackled as a design problem of wastewater treatment network, which is part of the water network problem involving mass exchange concepts. Therefore, the adequate standardization and modeling of the waste management system, along with the systematic organization of data are crucial activities to handle waste management and optimization problem. Next, the main features of waste management systems are described.

3.1 Waste system description

In general terms, the waste treatment system can be characterized by waste generating production plants, storage tanks, a complex network of piping and headers, waste treatment units, and loading stations for rail tank cars and tank trucks (Wassick, 2009). Therefore, production plants produce waste streams which can be transferred either to short-term storage tanks, to rail cars, or to tank trucks. These units serve as raw material storage for the waste management facilities. Thus, the piping network connecting production plants to storage tanks and to waste treatment units, may provide the production planner flexibility to handle exceptional situations at the cost of increasing the number of options. The adequate information describing the plant stands for the main input to the optimization process, in order to obtain successful production plans for mid-term planning and short-term scheduling (Figure 1).

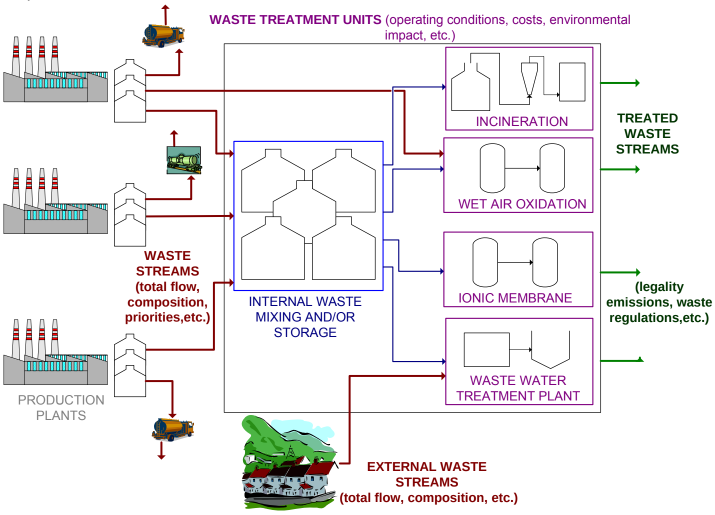

Figure 1: Information scheme in a waste management site, considering production plants, storage facilities and treatment units

Each entity of the waste treatment network holds a set of specific operational aspects and is characterized by a set of associated parameters, as described next.
The amount of waste generated by production plants is usually a function of their production rate. Therefore, based on the demand forecast, loads over the waste management system can be estimated. Thus, the chemical properties of waste influence the total treatment load on the capacities of the treatment units. Depending on composition of wastes, they can be mixed downstream before the treatment units.
In addition, storage tanks usually have a maximum and safety inventory capacity. In case there are multiple downstream receivers from a given storage tank, the number of simultaneous transfers may be limited. In addition, there may be different storage policies in the tanks, such as shared storage or exclusively dedicated storage of waste. The maximum flow rate for the transfers can also be limited by the pumping or piping elements. Thus, safety issues, such as maximum storage time for specific wastes, may have influence on the final applicable waste treatment policy.
Storage tanks may be connected to treatment units by means of shared transfer headers. Thus, tank trucks may be used to transfer some wastes to on-site treatment units, which are not accessible by pipelines. In this case, there is usually a limit on the number of on-site shipments per week. However, tanks trucks may also be used as additional intermediate inventory capacity with specific cost. They are held on site and then moved to the adequate treatment unit and emptied. Plant logistics may impose limitations over the number of trucks used.
In case, there is not enough capacity on site, rail tank cars may be used to transfer some waste out of the system for off-site treatment. There may be limits on the amount, which can be loaded in a single day. Costs derived from storage, transportation and treatment should also be considered.
Finally, waste treatment units are the most complicated units in the network. They may have several operating limits such as the number of streams that they can simultaneously receive, the concentration of certain species in the treated waste, or the overall amount of material they can process. There is a cost associated with the treatment of each waste within each unit. This cost may have a complex structure. Thus, certain units may recover valuable chemicals from the waste, which can be reused.

4. Methodology

This work adopts a methodology based on continuous improvement for the development of ontologies proposed by Muñoz et al. (2010). It consists of a sequence of stages related to the Plan, Do, Check/Study and Act Cycle

(PDCA or PDSA), which embeds the principles of two ontology development methodologies, namely "Methontology" (López et al., 1999) and "On-To-Knowledge" (Sure & Studer, 2002). As a result of combining the previous two methodologies, the PDSA methodology presents an ordered sequence of steps, which are easy to understand and track. Each phase or activity of the PDSA cycle involves a reflective process based on the scientific method, and ensure improvement efforts are carried out by the success to be achieved. Figure 2 shows the summary of the methodology for a better comprehension.

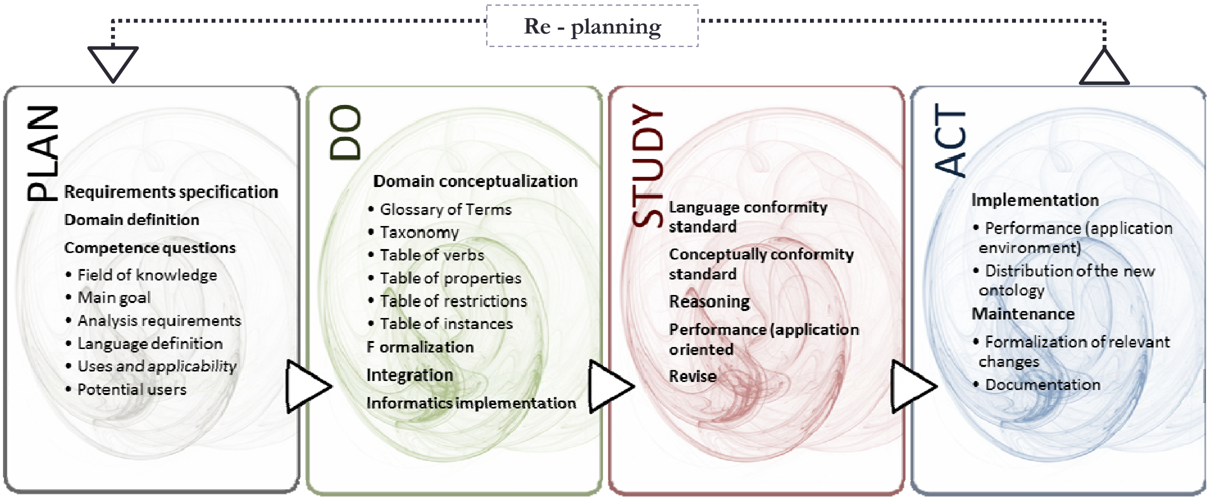

Figure 2: Continuous improvement methodology for ontology development and use

The development of the Process Model Ontology aims to have a common terminology and structure for processes. As a result, the proposed framework is capable of capturing and homogenizing the structure of processes in an organization, as well as standards and models of process improvement. Muñoz et al. (2012) extended an ontology containing an integrated representation of the entire enterprise structure, ranging from SC management to the scheduling function and comprising activities related to operational, tactical and strategic functions in order to further consider the environmental issues. The original model is based on the understanding and management of operational concepts (physical models, procedures, functions and processes) provided by ANSI/ISA-88 and ANSI/ISA-95 process standards (International Society for Measurement and Control, 2007) and complemented by other handbooks and reviews (Chopra and Meindl, 2004). The main contribution of the whole framework and the model is greater efficiency in communication and coordination procedures within the enterprise in order to assess its environmental issues.
On the one hand, the ANSI/ISA-88 (International Society for Measurement and Control, 2007) defines standards and recommended practices for the design and specification of batch control systems as used in the process control industries. Unlike others, the ANSI/ISA-88 standard is not a compliance standard, and it is defined as a guideline which contains the preferred term for systems and software based on batch process requirements.
On the other hand, the ANSI/ISA-95 defines the functions associated with the interface between control functions and enterprise functions. Even more it functions as a definition of the information which is shared between control functions and enterprise functions.
Figure 3 illustrates an extract of taxonomy of the ontology, which organizes the classes related to process and supply chain information.

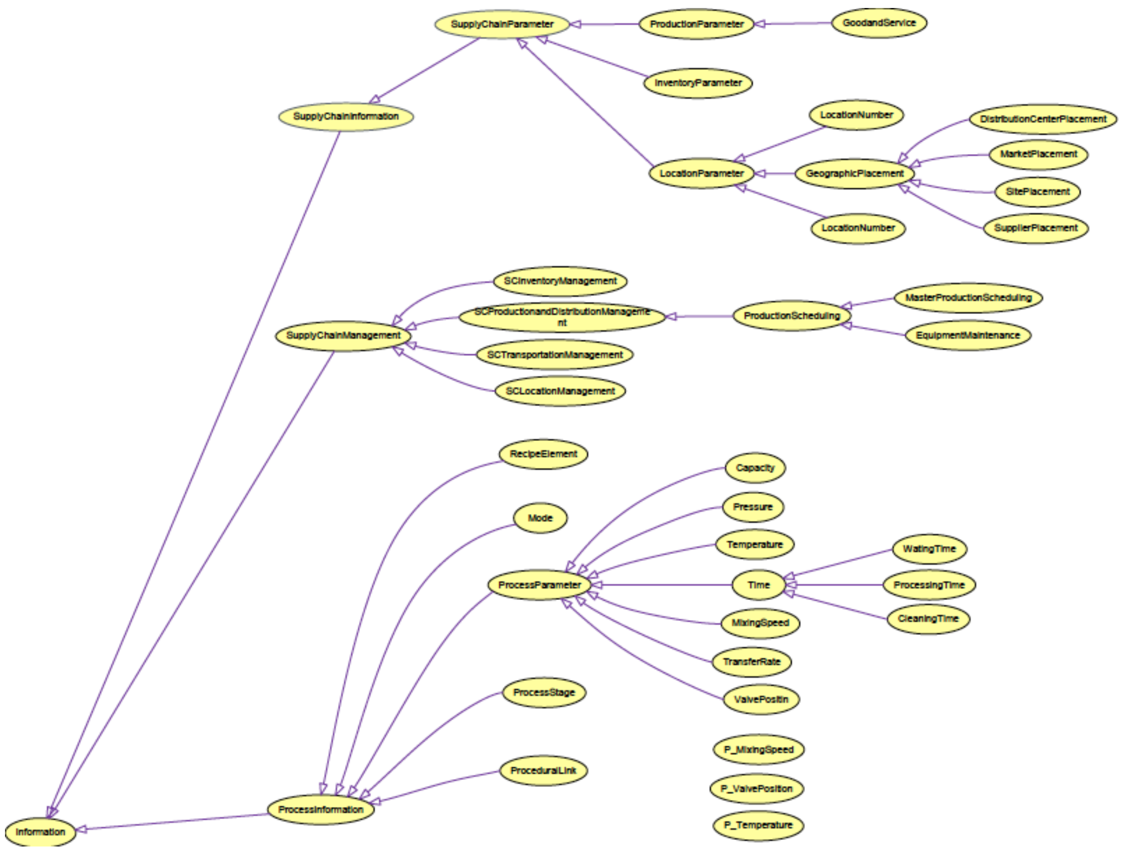

Figure 3: Extract of the taxonomy of the ontological model presenting the information related to process and supply chain levels.

This paper adopts this previous ontology and demonstrates its re-usability in the domain of industrial waste management. This re-usability is possible given that the ontology is based on process standards, which are able to improve enterprise efficiency and flow of information. Therefore, in this work, the data introduced in the decision support systems are directly problem instances of the ontological model, whose dynamic values (those which are frequently updated) are read from different databases. Even more, an automatic order of the net of databases, which many times are spread along the different hierarchical decision levels, is achieved since every database is adequately related to the corresponding part of the ontological model. Each relationship between the dynamic value, e.g. demand data property in the ontology, and its corresponding numeric value stored in the data base is easily programmed in Java language.

5. Case study

The case study considers a real waste treatment plant, whose relevant processes and policies for waste treatment are described in this section (Figure 4). The main concern in that plant is to optimize decisions related to waste stream management in order to increase the economic yield and reduce the environmental impact of its operation. Since there are a huge number of waste streams with different properties, such as air demand and heat of combustion, the scheduling of the treatment is not a trivial task, and information should be stored and managed efficiently.

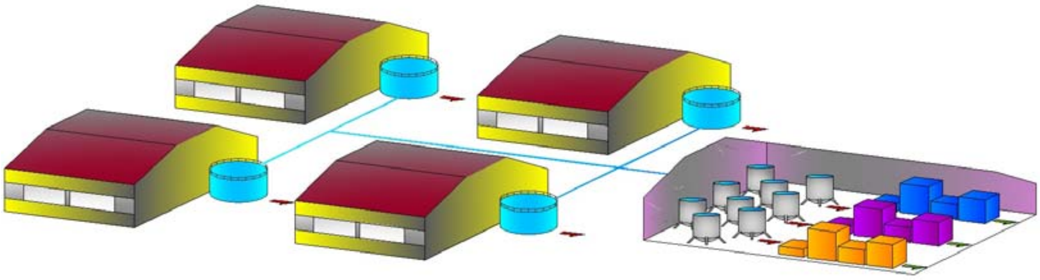

Figure 4: General representation of the case study, including production plants, storage tanks and treatment units

The waste treatment plant treats 50 different waste streams stemming from 50 independent external storage tanks located close to the production processes of different enterprises in the same site. There are two main types of waste streams, namely combustibles and mother liquors, which are classified based on their water content. Combustibles are organic wastes exhibiting less than 10% water content, whereas the water content of mother liquors ideally exceeds 75%. Their different composition leads to different properties, such as net calorific value and air demand, which are highly relevant for the combustion process, in the waste treatment process. Thus, waste streams are divided in four so-called campaigns, depending on their composition in organic compounds, namely fluorine, chlorine, bromine and phosphorus. This classification is necessary because specific constraints regarding the campaigns are relevant for waste mixing and treatment. Finally, there are incompatibilities among different mother liquors, which indicate that such streams cannot be injected simultaneously to the treatment units.

The industrial waste treatment plant has 28 tanks, which store the waste streams previously to the waste treatment units. In these tanks, waste streams can be mixed and stored before the treatment. Based on their connectivity to the treatment units, some internal tanks can only contain mother liquors or combustibles. A pipeline network allows the transfer of waste from the external to the internal tanks. This is possible in three different ways, namely via the so-called direct transfer, the so-called indirect transfer and via transfer wagons for tanks which have no connectivity with pipeline. Using the direct transfer, waste can be transferred between directly connected tanks under the condition that every external tank can only pump waste to one internal tank at the same time. In addition, each internal tank can only receive waste from one external tank at a time. Using the indirect transfer, only a single one to one connection is possible at the same time, meaning that waste can be transferred from one external tank to one internal tank, where both tanks have to belong to the "indirect transfer group". Additionally, waste can be delivered in trucks from outside the plant if there is free treatment capacity. The waste delivered by trucks is directly pumped into the internal tanks from one of the five truck stations. On the other hand, waste can be exported from the site directly from the external tanks to other companies if the treatment capacity of the site is exceeded.

Regarding waste mixing policies, mother liquors can never be mixed, whereas combustibles of the same campaign can be mixed in the internal tanks. Therefore the properties of the mixtures in the internal tanks are linear combination of the contained components. If the mother liquor stored in an internal tank is to be changed, the tank has to be fully emptied and cleaned with fresh water for a period of about two hours.

There are three different industrial waste treatment units in the waste treatment plant, namely two similar constructed incinerators with different capacities (larger capacity incinerator 1 and smaller capacity incinerator 2) and a burner. The incinerators are used to treat both combustibles and mother liquors of all campaigns whereas the burner is only able to treat combustibles of the fluorine and chlorine campaign. The two incinerators show three main differences: upper limits of the mother liquor throughput, connections from the internal tanks, and the ability to use oxycombustion, since only in incinerator 1 pure oxygen can be injected simultaneously with air.

Each incinerator is equipped with three combustible, three mother liquor and three air injection lances. Every group of three lances has a different connectivity to the internal tanks whereas the connectivity of the lances is identical within a group.

An important constraint on the operation of the incinerators is that temperature has to be kept within certain intervals to guarantee a proper combustion and to avoid destroying the construction material. Moreover, the flow rate of fumes is limited to a certain value because of the capacity of the steam generated in the heat exchangers

located downstream. For the burner, there is also a limitation of the fumes flow rate and injection rate, whereas it is assumed that the temperature limitation is not an issue.
The instantiation of this example results in 1,220 instances, and the time for checking their consistency with the reasoner is 1.745 CPU s in a successful compilation. Figure 5 contains some instances of some classes relating the physical models related to the inventory and location management of the waste management enterprise, the processing sites supplying waste and the transportation links among the different enterprises. In this figure, the classes are represented in bold on top of the boxes, the properties are written on the arrows relating classes and the instances are listed in the boxes. In this example, the processing plant of enterprise “Proc_PA01” is located in the site “Site_PA01”, and has two supply chain management policies related to the location and inventory of the site. The location management policy “SCLocationManagement_Site1” has a location parameter related to the site placement, whereas the inventory management has storage resources, which in this case is the unit “Residue_tank_PA01” related to the storage of the residue, and has inventory of the residue produced in the site. The unit has several properties, such as the minimum and maximum level, the identification name, or the residue that it processes. In this case, “Residue_PA01” can be stored in the aforementioned tank, and the level of that residue in the tank is defined in the “SCInventoryManagement_Site1” of the enterprise. Thus, the residue is transported by means of a transportation link, namely a pipelined identified as “TR_Pipe”, between the processing plant and the industrial waste treatment plant, whose location parameter is “SP_IWTP”.

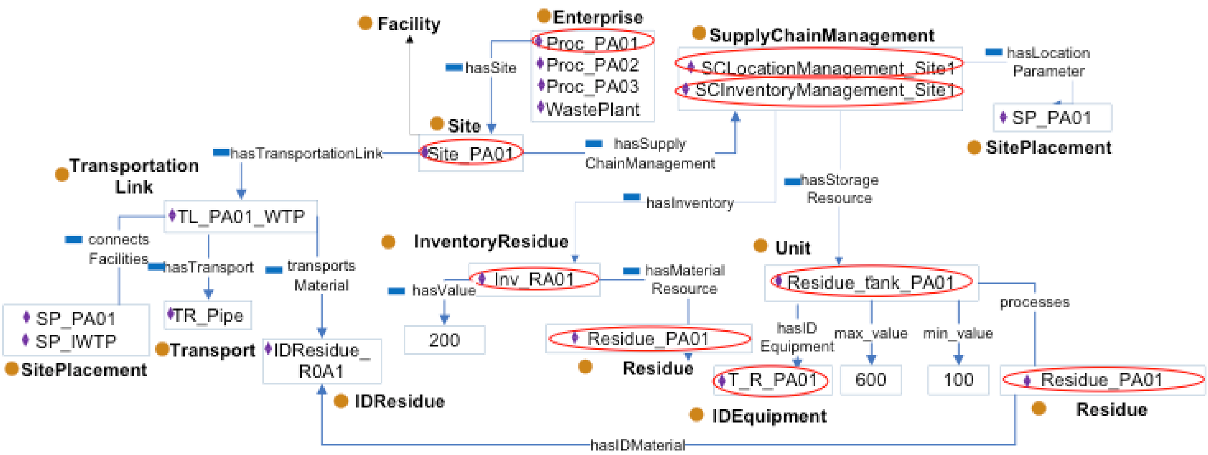

Figure 5: Scheme of classes and instances relating sites and environmental impacts of transport resources

Once the problem is successfully represented, the analytical optimization models must be provided with the necessary data and information, which is managed by the ontological model. The required input data, coded in .txt files, is generated using the Java application and they can be called from the optimization models.

6. Conclusions

In this work, the enterprise wide ontology representation is re-used to support decision-making of companies devoted to industrial waste management. The various elements within the hierarchical structure of the supply chain associated with waste management are successfully represented. As a result, this work allows improving the data communication from the transactional systems to analytical models. Overall, the main contribution consists of providing greater efficiency in communication and coordination procedures in waste management systems.
The ontology can provide decision-makers with improved data for the waste management related activities. Specifically, the ontology supports decision-making by streamlining information and data integration by an integrated and structured model that captures the activities carried out in the site.
Thus, this work intends to promote transversal process-oriented management to enable crossover among the different functional silos in which businesses have typically been structured. Such structures can recognize the existing trade-offs and the impacts of the available alternatives at the various information aggregation levels. By updating the decision-making/optimization model according to the current enterprise status, non-significant effects can be discarded. Additionally, the ontological model optimizes the way in which the databases are distributed

along the informatics structure of the enterprise. As a result, databases can be well located so that their data can easily be accessed and transformed into valuable information.

Specifically, this work represents a step towards supporting the integration of various software tools applicable to the management and exploitation of plant data. As a result, the entire process management structure is enhanced to aid the automatic design and operation of more waste management systems based on the exploitation of information quality.

Finally, the modeling of a real industrial waste management plant has been performed within the ontological framework, resulting in an effective and complete model of the existing plant.

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