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Using mathematical knowledge management to support integrated decision-making in the enterprise

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ABSTRACT

The basis of decision-making in the enterprise consists in formally representing the system and its subsystems in models which adequately capture those features which are necessary to reach consistent decisions. This work represents the elements of the enterprise which are included in mathematical models (i.e. decisions, parameters, constraints, performance indicators) in an ontology which captures the knowledge of the mathematical domain. Thus, this ontology relates the mathematical elements of the models to their corresponding semantic representation within the enterprise ontology. As a result, the mathematical symbolic abstractions of a given enterprise element in different models are directly linked to their actual unique meaning, and the integration of decisions in the enterprise is transparent and improved. The purpose of this work is illustrated in a case study related to capacity planning in the supply chain and scheduling problems.

1. Introduction

Nowadays, the application of analytical systems for decision-making has gained increased attention in enterprises since they can provide insights to find solutions that help businesses to remain competitive in the current environment of globalization of markets and fierce competition. The basis of decision-making consists in formally representing the system to be analyzed, in this case the enterprise and its subsystems, in a model which adequately captures those features that are necessary to reach consistent decisions. In general, models can be classified according to the way that information is represented. Therefore, a general classification distinguishes between qualitative and quantitative models. The former represent the physical and logic relationships among the elements of the system and describe the reality, such as conceptual or semantic models; whereas, the latter allow proposing decisions based on the analysis of actual data regarding the system, such as mathematical or statistical models.

Recent trends in process industries are shifting the focus from controlling the process plant as a stand-alone entity toward managing it as an integral part of a larger system (Klatt & Marquardt, 2009, March). 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. In fact, the border lines between the decision-making levels of the enterprise structure are often diffuse, and there are strong overlaps between planning in production, distribution or supply chain management and strategic planning. As a result, models adopted in enterprises are usually of high complexity. In addition, there is not a single valid model or model representation for each problem and their adoption depends on both the decision-maker preferences and the problem features (Hangos & Cameron, 2001). Hence, several models originally described with very different notations may be considered for representing a given problem. In this sense, semantic technologies can support a smooth integration of descriptive and optimization modeling in a single framework (Klatt & Marquardt, 2009, March). Indeed, semantic models enable the development and implementation of sophisticated tools for decision support, for example López-Arévalo, Bañares-Alcántara, Aldea, Rodríguez-Martínez, and Jiménez (2007) presented an approach for generating process alternatives using abstract models implemented in ontologies and case-based reasoning. The adoption of semantic technologies in industrial practice

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may facilitate the integration of existing process systems engineering (PSE) tools with information technologies (IT), and strengthen the role of engineers as developers for decision support and policy development (Bañares-Alcántara, 2010).

The development of knowledge based systems for the representation of mathematical models with engineering purposes has received increasing attention in the last 20 years. For instance, Top and Akkermans (1994) presented an ontological-based framework for structuring and automating model construction which is called 'evolutionary modeling'. The methodology encompassed the tasks of requirements specification, construction and assessment of tentative models. Three different ontologies with different methods and functions were proposed, which deal with generic physical components, physical processes and the mathematical structure. However, this work was mainly theoretical, and the proposed ontologies are not actually described. The paper focused on energetic–dynamic based systems.

A more general approach to mathematical modeling for engineering was presented by Gruber and Olsen (1994) in the so-called EngMath ontology. This ontology conceptualizes abstract algebra and measurement theory for mathematical modeling in engineering. As a result, it provides a formal language to represent mathematical expressions and translate them from any mathematical software tool. As a consequence, the ontology can be used as a conceptual foundation for developing other ontologies (e.g. the compositional modeling language (Falkenhainer et al., 1991, January)). Overall, the authors provided an accurate formalization of the algebraic domain for specifying the conceptual foundation of equations and avoiding implicit information. However, the correspondence of the equation elements and the represented items of the actual engineering domain was not considered. In addition, the authors only focused on representing the behavior of physical systems as a part of the conceptualization exercise.

Bogusch and Marquardt (1997) presented an object-oriented data model called VEDA for the formal representation of mathematical models of physico-chemical processes. The authors relied on the representation of behavioral modeling concepts to specify elementary objects such as variables, operators, units and the relationships that exist among them such as equations. These elementary objects were devised as the foundation for more complex modeling structures. Ontologies were proposed for the conceptualization of the domain. Subsequently, Bogusch, Lohmann, and Marquardt (2001) implemented the modeling environment ModKit which was built to support the development, maintenance, and reuse of chemical process models. This implementation included a taxonomy to structure model equations into balance, constitutive, definition and constraint equations. It also extended VEDA in order to support the creation of workflows to capture the methodology and the experience gained from the model development process. This work represents an important step toward the integration of process modeling in the engineering domain. However, two main points remain unclear: (i) the interrelation of the elements within the mathematical equations is not specified, and (ii) the sources of knowledge for establishing the operators and elements of the mathematical domain are not discussed, thus resulting in the use of a non-standardized language.

Suresh, Hsu, Akkisetty, Reklaitis, and Venkatasubramanian (2010) reported a conceptual framework, OntoMODEL, to assist in the process of mechanistic mathematical modeling associated with pharmaceutical product development. They proposed to separate the modeling into two parts, namely the declarative and procedural ontologies. On the one hand, the declarative ontology deals with the model equations, the information needed to solve them, and the results generated from them. On the other hand, the procedural ontology manages the components related to model solving. However, the connection between mathematical modeling and the represented domain is problem driven, which makes it difficult to be exported to other engineering domains.

Kuntsche, Barz, Kraus, Arellano-Garcia, and Wozny, 2011, November introduced MOSAIC, which is a web based platform to manage, share and evaluate model equations and their related information at the documentation level. They proposed a convention for symbolic mathematical expressions to facilitate their translation to common program languages. One of its novel features is that it allows transferring mathematical models into code suitable for the program chosen by the user. However, the engineering domain and the understanding of mathematical structures were not integrated in their work.

This work develops an ontology for semantically representing mathematical models in engineering. The ontology encompasses: (i) the mathematical entities themselves and their behavior (i.e. decisions, parameters, constraints, indicators); (ii) the relationships among these entities to build mathematical models; and (iii) the properties which allow to relate the mathematical entities to the semantic abstraction of the elements that they represent. Therefore, the entities of the mathematical models can be directly associated with the engineering concepts, which are unified/standardized into the classes, properties, and axioms of an existing ontology in the enterprise and process domain (BaPrOn, Muñoz, Capón-García, Lainez, Espuña, & Puigjaner, 2013). As a result, the links between the mathematical elements and the abstraction of the reality are explicitly formalized in the ontological framework. Therefore, although the modeler is still responsible for establishing such links, this framework stands for a tool for formalizing them, thus clarifying and unveiling the assumptions in the modeling process and the relations of the mathematical model to the real system. This approach is advantageous because it provides the possibility to integrate mathematical models from different decision levels into a single platform, and to easily incorporate other system aspects, such as the identification of mathematical elements (e.g. variables, performance indicators) that refer to the same engineering entity. Therefore, this work represents an additional step toward the development of an integration framework, which contributes to solve the data and information sharing among models and to facilitate a better understanding, structuring and modeling of processes for an effective transformation of information into knowledge.

With regard to the scope and domain, the mathematical modeling ontology is applied in this work to engineering problems related to process operational and strategic levels of the enterprise. The ontology describing the engineering domain in this work is the Enterprise Ontology Project (EOP) presented by Muñoz et al. (2013). Thus, the problems of supply chain (SC) strategic design-planning presented in the work of Lainez, Kopanos, Espuña, and Puigjaner, 2009, July and operational planning-scheduling described in Capón-García, Moreno-Benito, and Espuña (2011) are used to illustrate the capabilities of the proposed framework to represent mathematical models and its integration to the corresponding domain conceptualization.

2. Methodology

In this section, the knowledge management framework for the translation, interpretation and management of mathematical models is presented. The basis consists of a semantic model which relies on the Mathematical Markup Language (MathML), an XML application for describing mathematical notation (Ausbrooks et al., 2010, October). The semantic model deals with two key issues: (i) it captures both the structure and content of the mathematical expressions, and (ii) it relates the mathematical elements to the semantic representation of the reality.