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Critical evaluation of paradigms for modelling integrated supply chains

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ABSTRACT

Contemporary problems in process systems engineering often require model-based decision support tool. Among the various modelling paradigms, equation-based models and agent-based models are widely used to develop dynamic models of systems. Which is the most appropriate modelling paradigm for a supply chain? In this paper, we seek to address this important question through a well-structured benchmarking process. First, we demonstrate that in the space of models, 'equations' and 'agents' are concepts of a different order, the former referring to the system description elements in the model while the latter emphasises the model elements. Thus conceptually, the two paradigms are not mutually exclusive. Next, in a case study different dynamic models of an oil refinery supply chain are developed, using different tools and approaches. By performing detailed experiments with two different models, it is demonstrated that the models are equivalent when compared using model definition, numerical results and recommended decisions. However, the modelling process itself is different and results in different model structures. By analysing the effort required to expand the models, allowing new scenarios to be tested, and re-use of model components, we identify the strengths of the two paradigms in the context of supply chain modelling.

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1. Introduction

Contemporary problems in process systems engineering (PSE) often require a model of the process, product, or system for their solution (Cameron & Ingram, 2008; Cussler & Moggridge, 2001; Hangos & Cameron, 2001). There are many ways to model a system depending on the problem characteristics, purpose of modelling, functional specifications, available information, etc. (Cameron, Fraga, & Bogle, 2005). In contrast to traditional process systems where artifacts with physico-chemical interactions are the key constituents, supply chains (SCs) are best thought of as socio-technical systems where complex production technologies interact with distributed, intelligent, autonomous entities—each with their own dynamics, goals, desires and plans.

There is a significant challenge in modelling such systems that function in dynamic, stochastic, socio-economic environments with intra-organisational and inter-organisational complexity. Numerical modelling, traditionally the paradigm of choice in PSE, could be adopted to represent such complex socio-technical systems. One subset of these, optimisation-models, have been widely used, especially when the scope of the problem is limited to selected supply chain functions such as planning (Nilay, 2005) or scheduling (Mendez, Cerda, Grossmann, Harjunkoski, & Marco, 2006). Simulation models were envisaged for supply chains as far back as the 1950s (Forrester, 1958), however it is only more recently that dynamic simulation-based decision support are attracting widespread attention, especially in the PSE community (Bose & Pekny, 2000; Perea-Lopez, Ydstie, & Grossmann, 2001; Ydstie, Perea-Lopez, & Grossmann, 2003).

Supply chain dynamics can be modelled through balance equations (for inventory, orders, etc) similar in structure to those used to model chemical processes (Pantelides, 1988). The socio-technical nature of supply chain problems, however, motivates an alternative modelling paradigm: agent-based models. These take an actor-centric perspective instead of the activity-based one. The actions of each actor – represented as an agent – and the interactions between them are explicitly represented in such models, and in consequence the behaviour of the entire system emerges.

Agent-based models are now widely considered to be a promising approach for decision support in supply chains (Gjerdrum, Shah, & Papageorgiou, 2000; Julka, Karimi, & Srinivasan, 2002; Julka, Srinivasan, & Karimi, 2002; Mele, Guillen, Espuna, & Puigjaner, 2005; Siirola, Hauan, & Westerberg, 2003; Ydstie, 2004). A detailed comparison of the advantages and disadvantages of the equation-based and agent-based modelling paradigms that can be used for supply chains is called for. By building different models and looking, for example, at how they are built and how they can be

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expanded, we can come to a well-founded justification of the choice of modelling paradigm, recommendations and guidelines on which paradigm is more suitable for which application or problem.

Others, including Van Dyke Parunak, Savit, and Riolo (1998), Borshchev and Filippov (2004) and Tang, Parsons, and Sklar (2006), have attempted to perform a similarly motivated comparison between equation-based models (EBMs) and agent-based models (ABMs). However, in all these papers a clear definition of what is being compared is missing. Inconsistency in the definitions of modelling paradigms has led to a situation where conclusions from one author are used as an unfair justification for the choice of a certain modelling paradigm by others.

Van Dyke Parunak et al. (1998) were the first to compare ABMs, then a very new field of research, with the traditionally used EBMs. They write that "understanding the relative capabilities of these two approaches is of great ethical and practical interest to system modellers and simulators". The case study they use is that of the (relatively simple) Forrester supply chain. In their study, the EBM uses differential equations, while the ABM is more detailed comprising different classes of agents (e.g. company agents representing the different companies in the supply chain, shipping agents used to model transport with uncertainty and delays, etc.).

After performing a comparison between the models, they conclude that ABMs can be applied to all domains that traditional models have been previously used in, and that there are some advantages such as a more natural fit, ease of construction, support for more direct experiments, and the ease of translation back to practice. Perhaps some of these benefits do accrue, but good measures or indicators to establish them have been hard to come by. Even though it does not compare two models made for the same purpose, the article's conclusions (fuelled by the fact that the term EBM used in the title is much broader than the system model examined in its body) are often used to justify the application of the agent-based paradigm.

Chatfield, Hayya, and Harrison (2007) discussed the use of different formalisms combined, to take advantage of strong points of each: "Forcing modelers to conform their understanding of a subsystem to an unnatural viewpoint may lead to added model building difficulty. For example, agent-based concepts are easily mapped to some supply chain entities and actions, such as basic supply chain participants (retailers, warehouses, etc.) and their behaviours, but are not suited for other areas of the supply chain, such as process items (materials, orders, etc.)"

Macal and North (2005) and Macal and North (2002) developed an agent-based implementation of the beer game (a frequently used case study for research on supply chains), based on the original System Dynamics model. They claim that their results "exactly duplicate" Sterman's EBM (Sterman, 1989) which once again demonstrates that dynamics of an EBM can be captured by an ABM. While insightful, the results from these comparisons are obtained without resorting to a well-defined approach and without clear definitions of what is compared, making it difficult to generalise the findings.

We would like to stress that comparing modelling paradigms based only on the conceptual model specifications is not enough; rather a well-defined benchmarking process and the execution of experiments are required. In this paper, we present a strategy for executing benchmarking studies of modelling paradigms. A benchmarking exercise is executed for two models (each motivated by a different paradigm) of an oil refinery supply chain. The lessons learnt will be applicable for modelling supply chains, but can be generalised to other socio-technical systems, for example in the infrastructure domain.

The rest of this paper is structured as follows. First, in Section 2 we will discuss the differences between modelling paradigms and stress the importance of clearly defining the label used for a paradigm. The corner-stone of this paper is the detailed benchmarking process described in Section 3. After a description of the oil refinery supply chain in Section 4, three different models of this system are presented in Section 5. The benchmarking process is then applied to the refinery supply chain models and conclusions from the exercise are drawn and recommendations for the use of the different modelling paradigms are given in Section 6. Finally, in Section 7, the paper is summarised.

2. Modelling paradigm spectrum

Many researchers use different definitions of ABMs. Statements made about the advantages of the approach are too easily generalised to models that fall outside the definition. The same pitfall could be observed when the term EBM is used. This inconsistency has led to a situation where conclusions from one author are used as a justification for the choice of a certain modelling paradigm where this is not suitable.

To identify commonality among the various perspectives on agent-based modelling, a small survey was designed and sent to a group of researchers with a strong interest and contribution to the agent-based systems area (see Acknowledgements). It became clear that the concept "agent" has a different meaning when used in "agent-based models" and "multi-agent system". When talking about multi-agent systems, characteristics following, for example, definitions by Wooldridge and Jennings (1995) are common. When used in an ABM context, it appears to be more a metaphor – or way of thinking – towards modelling the behaviour of individuals, rather than a strict definition with minimum requirements.

One conclusion that we can draw is that there is not a clear line between agent-based and non-agent based models. The concept is not black-and-white, rather there is a continuous scale (or a spectrum in the modelling space) where a model can be more agent-based or less so. There are two main axes in which models can differ: The *model elements* axis and *system description elements* axis. The former deals with *what* is modelled and the constituents of the model, the latter with *how* their structure and behaviour is formally described. After an attempt to define these concepts an illustrative example will follow.

First, we will consider *what* is being modelled. The model elements can range between *system observables* and *individuals*. System observables are the flows and states that can be observed in the real system, without taking into account who or what caused them (and why). On the other end of the spectrum, a focus on individuals means that the system is modelled by capturing the behaviours of exactly these decision making and executing entities. The behaviour of an individual leads to actions that, together with the actions of all other individuals, cause system level behaviour, which can be observed in the model.

Next, there are different ways to formalise the structure and behaviour (or in other words, *how* the model is built). Various description elements such as *equations* or *algorithms* can be used. An equation is a mathematical statement that two terms on either side of the equals sign are equivalent. Algorithms are well-defined sequences of instructions.

ABM and EBM are *labels* used to describe a model and they can be characterised by their use of these model elements and system description elements. As for ABMs, in general they are characterised by a focus on individuals as model elements. EBMs, on the other hand, focus on system observables modelled predominantly using equations. An essential point to be noted in this context is the following. Once any model has been constructed it has to be simulated or solved. The presence of algorithms in the model description is qualitatively different from those being used in the solution procedure. Both ABMs and EBMs would require algorithms in the solution

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