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Invariant conditions in value system simulation models

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ABSTRACT

This paper presents a framework for the integration of supply chain (or logistics/distribution), value chain (or financial), and business process (or operational/manufacturing) simulation models, which should facilitate assessing the impact of supply chain and operational changes on an enterprise's financial performance. A Design Science approach is taken to demonstrate that the REA ontology, which provides a shared conceptual ground for these three model types, and its axioms, which describe invariant conditions for value systems, can help to build conceptually sound simulation models and identify the integration points between these models. It is further shown how these three types of simulation models can be integrated into one value system model for discrete event simulation, making use of the ExSpecT simulation tool. With this ontology-based framework, simulation model builders should be able to scope their models better and define integration points with other models, which is expected to promote the (re)use of simulation models for different purposes (e.g., simulating logistical, operational and financial performance).

1. Introduction

Information technology is important for acquiring competitive advantage in dynamic business environments [1]. When the cost of error is high, information technology provides practitioners with the information that is needed to develop conceptual models that provide a true and fair view of a future reality. These conceptual models are then used to simulate and analyze the predicted behavior of the future reality. For example, before an airplane prototype makes its maiden trip many simulation models have been made to study the predicted behavior of individual airplane parts and the plane as a whole. These simulation models support technology advances, while saving money and lives. Church and Smith [2] advocate and demonstrate the use of simulation models for managerial decisions, potentially saving money and jobs. Where most current approaches limit themselves to the simulation of logistical and manufacturing processes, considering only logistical and operational parameters such as production cost, service time, product quality and process flexibility [3–5], Church and Smith stress that business performance is mainly evaluated in terms of financial parameters (e.g., profit, net present value). Consequently, not only logistical and operational parameters such as operational cost but also financial parameters such as cost of capital should be taken into account when building simulation models for evaluating the future performance of alternative business process and supply chain designs. Integrating financial parameters in supply chain simulation models can help overcome financial sub-optimization[1] caused by the optimization of logistical and operational parameters without the assessment of their impact on financial parameters, as it allows for simultaneous optimization of operational performance and profitability [7].

Creating conceptual models for simulating business process, enterprise and supply chain performance is a challenging task, especially because – in practice – businesses form a small part of a much larger economic environment. As a result, conceptual models for the purpose of simulating business processes, enterprises and supply chains cannot be considered standalone artifacts, since "*today's highly complex systems require that simulation models developed by different teams in different domains interact with one another to serve a higher goal.*" [8] The simulation models developed by specialists with different domain expertise are often called *federates*, the aggregated simulation model that consists of interacting federates is often called a *federation*, and the approach is called *component-based simulation* [8]. The main challenge of component-based simulation is assembling federates, which may not have been developed with federations in mind, while preserving syntactical and semantic correctness [8].

The management of a virtual organization[2] is a typical situation in which the cost of error is high (i.e. the failure of one partner

[1] Sub-optimization: Independently optimizing the sub-systems of a given system will in general not optimize the performance of the system as a whole [6].

[2] A virtual organization is a synergetic alliance between separate firms that join their best-of-breed value-added activities (i.e. core-competencies) to take advantage of a market opportunity [9].

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might cause the whole virtual organization to fail) while financial, manufacturing and distribution processes have to be managed simultaneously because of their interdependence [9]. Many authors look at supply chain simulation models [5,10,11] or business process simulation models [2] as isolated artifacts. They build standalone simulation models, limiting the scope of their models to the supply chain, abstracting from the internal business processes of each supply chain partner, or limiting the scope to individual business processes, abstracting from the value and supply chain in which they are embedded. Other approaches that do map supply chain models with business process models only focus on operational evaluation criteria [5,12]. These operational approaches are prone to sub-optimization, since improved operational performance does not automatically lead to better financial performance [13]. A challenge of virtual enterprises is that operational and logistic processes have to be integrated across enterprise boundaries and financial performance is evaluated at the level of the individual supply chain partners (i.e. virtual enterprise components). Component-based simulation should be able to mitigate this challenge.

Although integration frameworks and methods exist, none of them integrates all dimensions needed for virtual enterprise management. For example, the supply-chain operations reference model (SCOR) [14] provides a framework for integrating operational and logistic processes but does not explicitly address the financial performance of individual supply chain partners. Where the e3-value ontology[3] [17] integrates financial and distribution processes, its conceptualization of manufacturing processes is too coarse grained for operational simulation models. Where Dietz' enterprise ontology [18] provides an excellent theory for modeling processes across enterprise boundaries, it explicitly renounces the existence of an "exchange layer" in which one actor gives something in return for something given by another actor [19]. This "exchange layer" is essential for components of a virtual enterprise as they need to be able to assess their own profitability as part of a virtual enterprise [20].

What is needed is a framework that is able to integrate simulation models for assessing the financial, operational and logistical performance of enterprises, the supply chains in which these enterprises are embedded and the business processes embedded in each enterprise. The framework should allow us to assess relevant performance parameters using individual simulation models (e.g. one business process or one enterprise in isolation), using simulation models as part of a federation of models (e.g. a business process as part of an enterprise that is part of a supply chain) and using a simulation model as a federation of lower-level models (e.g. a supply chain composed of several enterprises, which have their own business processes). The federation level is required to assess the performance of the entire virtual organization, as the business processes of the firms of which the virtual organization is composed need to operate as a single business process, while each participating firm needs to be profitable at the same time. In the remainder of this paper, this federation of simulation models will be called the *value system* simulation model. The abstraction levels identified within this value system simulation model will be referred to as *supply chain* (i.e. the level at which individual enterprises communicate and trade), *value chain* (i.e. the level at which individual enterprises or organizations balance logistic flows with mirroring money flows) and *business process* (i.e. the individual processes that use information to orchestrate logistic, operational and financial flows and produce information while orchestrating).

[3] Like modeling frameworks, ontologies can be used to represent structured and semi-structured information about a domain. For example, the constructs and axioms, which are defined as fundamental truths about a domain for which there is no counterexample or exception, of an ontology can be used to develop a domain-specific modeling language that can constrain modelers to develop case models that are a true and fair view of the domain [15,16].

Since the REA ontology [21] is – to the best of our knowledge – the only ontology that supports the modeling of individual business transactions and financial, distribution and manufacturing processes and supply chains, its level of abstraction is considered appropriate for providing the framework for the integration of federates. This paper demonstrates how the REA ontology can be used to create value system simulation models. The REA ontology describes enterprise economic phenomena using resources, agents and events as primitives and describing the necessary associations between these primitives with three axioms [22]. These axioms phrase fundamental truths for which there are no counterexamples or exceptions within the enterprise economic domain [16], which includes supply chains, value chains and business processes. Consequently, they represent invariant conditions that apply to the simulation model federates and federation (i.e. value system) introduced above, which is key to the integration solution presented below.

The following section addresses the research methodology employed for realizing our purpose. The third section discusses related work, and provides background on the REA ontology and discrete event simulation with Petri-nets. Section four rephrases the REA axioms at each value system abstraction level (i.e. supply chain, value chain, business process), to emphasize the integration points between the abstraction levels. In section five a value system simulation model that integrates the supply chain, value chain levels, and business process levels for an exemplar virtual organization (i.e., the beer game [23]) is built, and example simulation runs using the model are presented and used to illustrate the benefits of our REA ontology-based value system simulation modeling approach. Conclusions and directions for future research are given in the last section.

2. Research methodology

The research method applied in this paper is inspired by design science [24,25]. As opposed to behavioral science, which limits itself to developing and verifying theories that explain or predict human or organizational behavior, design science seeks to extend the boundaries of human or organizational capabilities by creating new and innovative artifacts. Unlike routine design, which applies existing knowledge to solve problems, design science research addresses previously unsolved problems in unique or innovative ways. Problems typically addressed by design science are characterized by (1) unstable requirements and constraints based on ill-defined environmental contexts, (2) complex interactions among subcomponents of the problem and its solution, (3) inherent flexibility to change design processes as well as design artifacts, and (4) a critical dependence upon human cognitive (e.g., creativity) and social (e.g., teamwork) abilities to produce effective solutions [24].

When designing value system simulation models, all these problem features can be recognized. "*The supply chain environment is dynamic, information intensive, geographically dispersed, and heterogeneous*." [26] The dynamism of the supply chain environment is inextricably bound with the unstable requirements and constraints in the simulation model articulation process. This dynamism also motivates the need for inherent flexibility to change the design process and artifacts (e.g., when existing approaches or models prove to generate unsatisfactory results due to new environmental conditions). Together with the dynamism, the information intensive character of the supply chain environment provokes ill-defined environmental contexts as it would be impossible or at least unreasonably costly to gather all relevant information. The geographic distribution of supply chain partners, which adds unpredictable transportation times due to traffic, different work conditions and legislation to the list of variables, interacts with other subcomponents of the problem and solution (e.g., the financial soundness of trading partners, business process, workplace and supply chain lay-out). Finally, the heterogeneity of the supply chain environment and the jargon for each (sub-) discipline challenge human social and