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LOGISTICS SYSTEMS MODELING AND SIMULATION

George Thiers
Leon McGinnis

The Georgia Institute of Technology
School of Industrial & Systems Engineering
Atlanta, GA 30332-0205 USA

ABSTRACT

Modern logistics systems are much more than simply networks of material flow. They involve collaboration between firms that are also competitors. The supply chain can be a key consideration in product design, with its design and operations influenced by concerns about uncertain energy costs, sustainability, economic security, and other complex issues. Because of these and other considerations, the contemporary practice in which an analysis model is the first "formal" model of the logistics system is no longer feasible. Rather, what is required for a sustainable practice of simulation in logistics is a model-based approach which begins with a formal language for capturing a defining description of the logistics system itself. This formal language must be sufficiently accessible to the logistics systems stakeholders so that they can validate the resulting system description. The resulting descriptive model will be the basis for subsequent analyses, including simulation. In this context, we address the requirements for such a formal language, describe our initial progress in developing such a language for logistics systems, and place it in the context of prior work on "reference models."

1 INTRODUCTION

Global supply chains (GSCs) are complex socio-technical systems, and a key feature of modern civilization. GSCs can link many firms, involve many locations and transportation channels, concern thousands of part numbers, and be responsible for hundreds of thousands of shipments on an annual basis. Stakeholders include the firms involved in producing the goods, the customers for the goods, and all the firms involved in moving and storing the goods. The cost of GSCs is significant; for example, recent logistics costs in the US have ranged between 7.7% and 9.3% of GDP (Zhao 2010). Even small improvements in GSCs have potentially large benefits to society. This helps to explain the sustained strong interest in logistics systems modeling and analysis.

The research literature on global supply chains is dominated by OR models, particularly optimization and simulation models. Optimization models generally answer questions of the form, "Where should we produce, where should we have warehouses, how much inventory of which parts should be kept in each warehouse, how often should shipments be made, and what should be the origin and destination for shipments in order to satisfy the requirements of our customers at minimum expected logistics costs?" Optimization models are "normative" in that they assume all facts are known, and produce a "best" answer to those questions given those facts. Simulation models, in contrast, assume that the answers to the questions are known but recognize uncertainties associated with some of the facts, and attempt to produce a more realistic picture of what the performance will really be in terms of measures such as customer service and cost.

Contemporary research on GSCs admits two possibilities for significant enhancement in their design and analysis: (1) modern GSCs introduce issues not captured in legacy modeling approaches; and (2) modern GSCs often are so large and complex that no single stakeholder can fully understand and describe the entire system. The thesis of this paper is that addressing these two needed enhancements will require a new approach to GSC modeling, and that approach must begin with the development of a formal language for describing the GSC in its own terms.

The situation for GSC modeling is analogous to that of software engineering in the early 90's. The scope and scale of software projects had grown to the point that software engineers needed a way to articulate the problem to be solved (the code to be developed) at a level of abstraction accessible to the problem's stakeholders, i.e., well above the code level abstraction. The ultimate result was a formal language—UML or the Unified Modeling Language (see, e.g., www.uml.org)—along with a suite of tools to support creation of high level problem descriptions that could be understood by and vetted by the problem stakeholders. In the case of GSCs, we argue that what is needed is a similar high level language for describing the GSC problem, in terms and in a format accessible to the GSC stakeholders, so they can validate the "problem statement" in advance of creating analytic models—which in most cases are not directly accessible to the problem stakeholders.

In the software engineering domain, formal modeling has been complemented by formal model transformation tools, tools which partially or largely automate a translation from the formal problem model (in some cases called the platform independent model, or PIM) to the code (in some cases called the platform specific model, or PSM). A very clear discussion of PIM-to-PSM transformation can be found in (Monsieur *et al* 2011). An analogous approach to modeling and analyzing GSCs is also possible, translating formal problem models into analysis models, including simulations (see, e.g., related work in the manufacturing domain (McGinnis et al 2010)).

In this paper, we focus on the modeling problem *per se*, and in particular on the development of both a formal semantics for GSCs and a modeling approach that addresses not only the legacy issues of logistics costs but also the enterprise context within which the logistics problem must be solved. We use a relatively new systems modeling language, OMG SysML™ (see, e.g., http://omgsysml.org), because it provides a rich set of fundamental abstractions, leads to models on which computations are easily performed, and provides a set of mechanisms for customizing the language for a particular domain. After briefly introducing SysML, we give a short discussion of the GSC context, both in terms of the domain and how we might think about the domain from a modeling perspective. Then we give specific examples of using a formal language to model the GSC context and to model the traditional supply chain components. We conclude with a discussion of how this approach can impact the future practice of GSC modeling and simulation.

2 OMG SYSML™

SysML is implemented as a profile of the UML, thus incorporating many of the UML's abstractions—block, activity, state machine, port, object flow, and control flows are particularly relevant for modeling GSCs. While the formal model constructed using SysML is captured in a *containment tree* with an underlying XML realization, multiple graphical views of the model can be created using various *diagram* types. In this paper we focus on *block definition* and *internal block definition* diagrams, used to define semantic relationships and represent system structure, and on the *activity diagram*, usable to describe processes including decision making.

The interested reader can find a wealth of information about SysML at the OMG SysML website, www.omgsysml.org.

3 GSC MODELING CONTEXT

The context for contemporary GSC problems is incompletely defined by traditional logistics costs factors such as material acquisition, transportation, and warehousing. The context is also defined by factors such as:

- Local content requirements—products sold in a region or country must have a minimum content value created in that region or country

- Design for manufacture—product designs must accommodate requirements to distribute production in a way that satisfies local content and sourcing requirements
- Product evolution—as a product changes over time, for example by adding or deleting options, decisions about sourcing may also change
- Sourcing—decisions about how many sources to have, where they should be, and perhaps the level of investment required to stand up a new source
- Governance—behavior of the GSC is determined through the interactions of independent legal entities, whose manner of interaction may or may not be defined in contracts
- Risk mitigation—sustaining GSC operations at an acceptable level requires early identification of potential risks and developing appropriate risk mitigation strategies

Any approach to GSC simulation that attempts to support enterprise-wide decision making must consider these kinds of factors.

A common situation is one in which the GSC consists of several or many firms and is led by a "prime systems integrator" or PSI. As an example, a global manufacturer of wind turbines does not actually produce all the components of the wind turbine. The sourced components may include the blades, the hub, the gearbox, the generator, the tower, and the controls, any of which may come from several different producers. Some of these components may be sourced within the PSI's corporation, and simultaneously from external suppliers who are also competitors. Components may be shipped from one continent to another, involve both sea and land transportation and choice of a port of entry. New sources may need to be developed, for example to produce new blade designs. Decisions about whether or when to introduce new products, such as blades, generator options, and tower options, will impact both marketing and the logistics system. Marketing decisions such as whether or not to bid jobs with restrictive local sourcing requirements will likewise impact the logistics system.

As another example, consider the production of the Joint Strike Fighter, designated the F-35 (see, e.g., (Wikipedia 2011)). Lockheed Martin Aerospace is the PSI, with partners and suppliers in countries around the world, as the intent is to sell the airplane to many different allies in addition to the US Air Force, Marines, and Navy. The F-35 represents a major departure from legacy production approaches. Previous aircraft such as the F-16 were assembled almost completely under one roof, and most suppliers were first-tier with whom LM Aero contracted directly. In contrast, manufacturing the F-35, like manufacturing the Boeing 787, involves integrating entire completed sections of the airplane that are produced by partners and suppliers. In addition to creating new engineering and manufacturing challenges, this approach to airplane production creates new supply chain issues such as lack of visibility by the PSI into large parts of the supply chain (suppliers of the first tier partners and suppliers), shipping complications for subassemblies too large for a 747 freighter, taxes and tariffs, and planned integration of previously-independent production and sustainment supply chains. LM Aero knows how to build airplanes, but F-35 requires the company to develop new competency in global supply chain management.

A GSC is a special case of a discrete event logistics system (DELS), and has much in common with other DELS including warehouses, factories, transportation networks, financial service networks, etc (see, e.g., (Lendermann et al 2010)). A fundamental concept in DELS is the notion of resources acting in particular roles. Resources for a DELS are any asset, including people, real estate, facilities, material, budgets, consumables, and various forms of capital including capital equipment, intellectual capital, and public capital. A useful way to think about DELS is to partition roles as "plant" and "control." Plant roles include transforming (with special cases transporting, storing, and packaging), and measuring. Control roles include receiving and handling messages and storing and retrieving information; "handling" a message may involve decision logic which leads to "command" messages to the plant. Semantics needed to describe arbitrary DELS also include geometry, location, time, schedules, requirements, performance measures, and abstractions such as 'network' and 'flow'.

The previous semantics may seem too general to be useful. They become useful when specialized to a particular DELS such as a GSC. 'Material' becomes any part with a SKU number – anything worthy of tracking. 'Facility' in a GSC context includes any supplier, production, sustainment, or warehouse facility with a shipping and receiving dock. 'Capital equipment' includes high-value containers, forklifts, trucks, ships, and aircraft, all recorded as assets on some enterprise's balance sheet. 'Public capital' resource includes transportation channels, whether road, sea, or air. All of these resources will act in particular roles, for example forklifts and trucks in a transport role and warehouse facilities in a storage role. 'Role' in a more abstract form may be called 'function' in the sense of a functional-flow diagram (Weilkiens 2008).

The following two sections describe, respectively, modeling the GSC organization, and modeling the traditional GSC logistics functions. The perspective taken in these modeling examples is that of "design" rather than simply analysis. In the organizational context, the process we use consists of successive elaborations of a functional flow diagram until a level of detail is reached allowing assignment of resources into roles. In this process, SysML language internal block definition diagrams are used until a level of detail is reached allowing activity diagrams to be used to describe behaviors represented by resource capabilities. In the traditional logistics function context, we present semantic constructs needed to define an appropriate schema for the data necessary to perform a traditional logistics system optimization or simulation analysis.

4 MODELING THE GSC ORGANIZATION

At the highest level, any enterprise may be represented by a single functional block as in Figure 1.

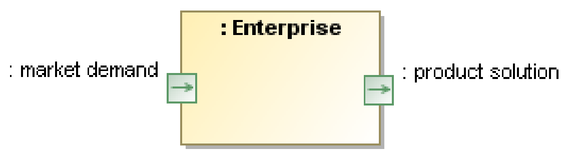

Figure 1: Enterprise Function

From the perspective of a GSC, the 'enterprise' function can be elaborated as in Figure 2. This is, of course, a highly simplified presentation of the essential functions, showing only a few examples of their interactions. It does illustrate, however, the intuitive nature of the graphical aspect of the SysML language - diagrams which are easily grasped by the GSC stakeholders, who can readily identify errors or omissions in the descriptive model.

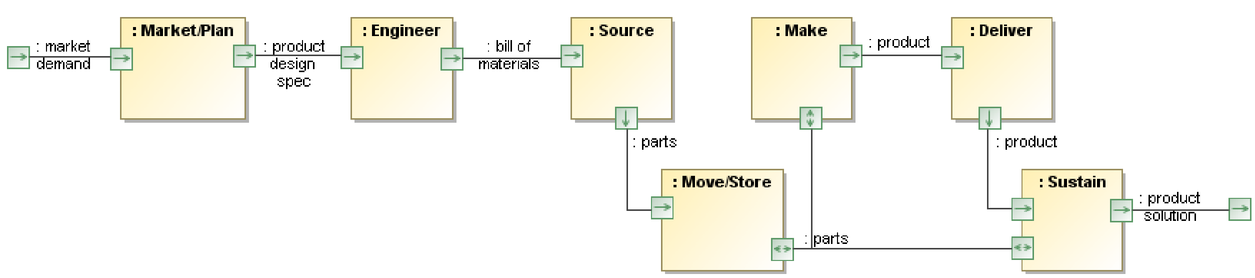

Figure 2: Major GSC Functions

Traditional supply chain study concerns the 'Source', 'Move/Store', 'Make', and 'Deliver' functions, with the most attention paid to 'Move/Store'. To illustrate functional elaboration, consider the source function, which can be elaborated as in Figure 3.

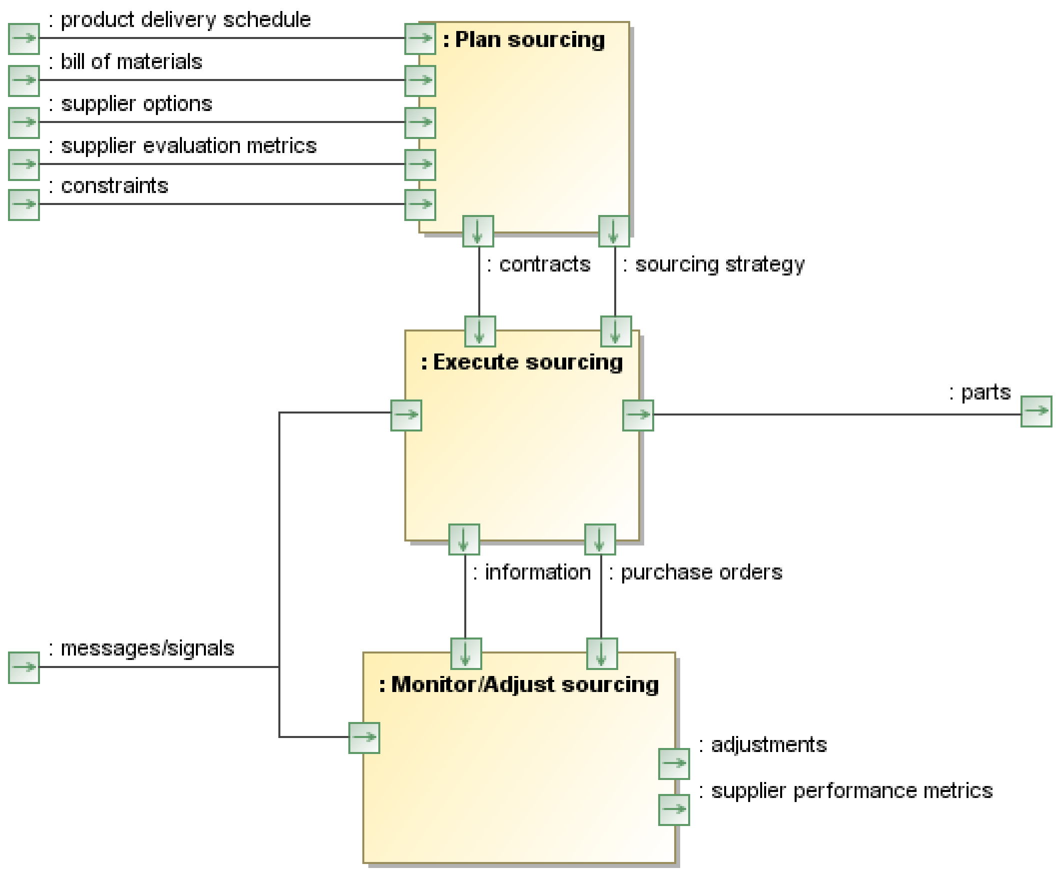

Figure 3: Sourcing Function

In Figure 3, the ‘Execute sourcing’ block represents the “plant” for sourcing, i.e., the physical aspects of sourcing. The “control” for sourcing has two sub-functions: ‘Plan sourcing’ is a periodic activity, perhaps quarterly or monthly, while ‘Monitor/adjust sourcing’ is a continuous function. As the function is refined in definition and takes the form of specific roles, we can begin to specify other characteristics such as constraints, specific resources to be assigned, and individual responsibilities.

SysML internal block definition diagrams are an effective means to show the structure, inputs, and outputs for organizational functions. At some point in the design process, we need to begin to describe how the function actually transforms its inputs to its outputs. A SysML activity diagram can show the internal dynamics of blocks as illustrated in Figure 4 for the ‘Plan sourcing’ block:

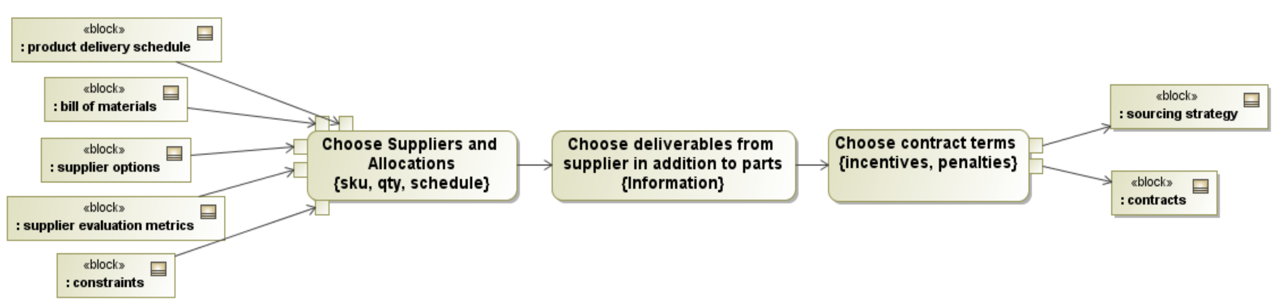

Figure 4: Internal operations of 'Plan sourcing' function

Planning involves choices, and choices are made by stakeholders, often with supporting analysis. In SysML, the actions depicting choices in Figure 4 are implemented as “call behavior actions”, linked to behavior of stakeholders acting in particular organizational roles. In general, a ‘plan’ subfunction is mostly about choices and links to behaviors owned by person resources. An ‘execute’ subfunction mostly links to behaviors owned by capital resources. A ‘monitor/adjust’ subfunction may involve both automated tuning and human intervention, and links to behaviors owned by both persons and capital.

Using a formal modeling language like SysML to describe the GSC context has a number of advantages over the typical org-chart and document approach. First, the SysML models help to clarify the definitions of and relationships between GSC functions, providing valuable support to those responsible for designing the organization. In particular, it enables a representation of the organization that makes clear who makes which decisions, and allows a careful assessment of the relative needs for decision support. In addition, the formal semantics developed for the GSC context can be carried over into formal modeling of the traditional supply chain decisions, as illustrated in the next section.

5 MODELING THE GSC LOGISTICS FUNCTIONS

Traditionally, a major focus of modeling and simulation in the supply chain context has been on the processes associated with logistics, i.e., on transportation and warehousing. Consider the move/store function, from the GSC context in Figure 2, which can be elaborated as in Figure 5.

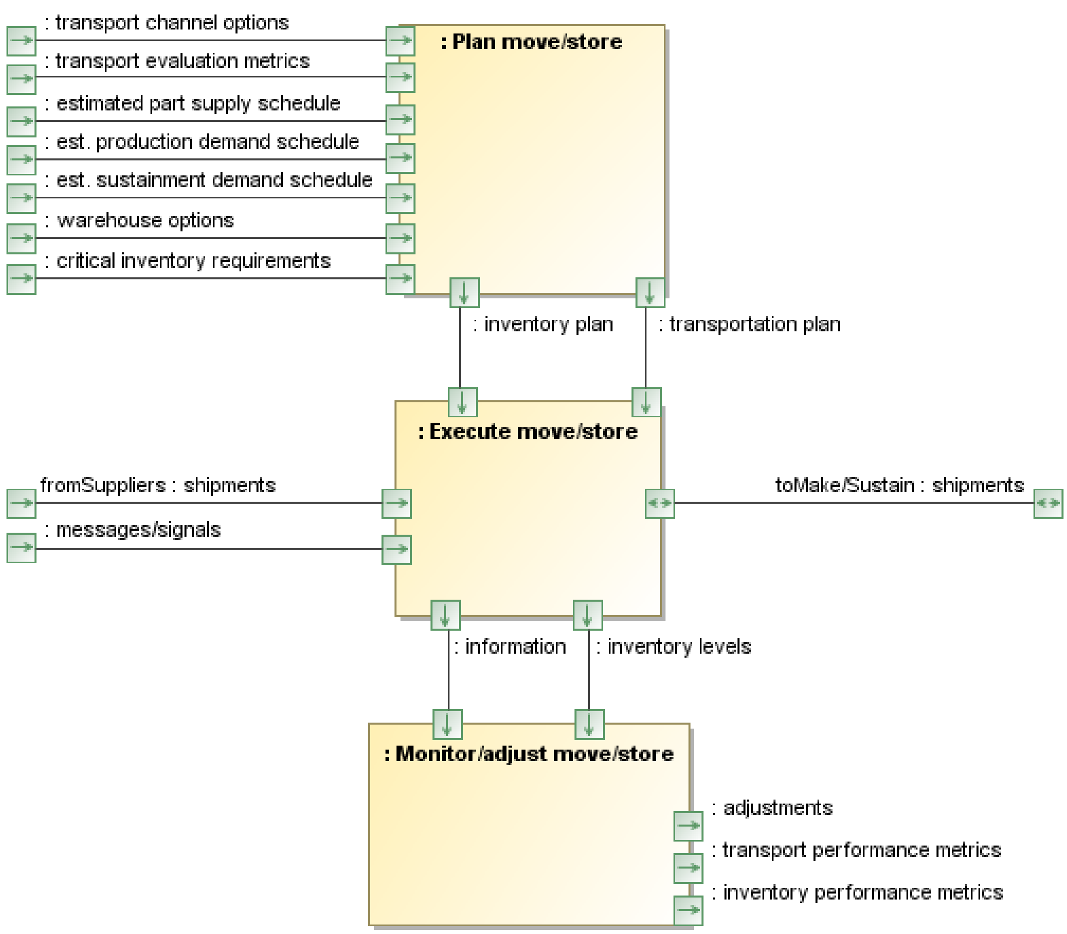

Figure 5: Elaborated Move/Store Function

As before, a SysML activity diagram can show the implementation of the 'Plan move/store' block; Figure 6 illustrates one way in which the planning function might be implemented.

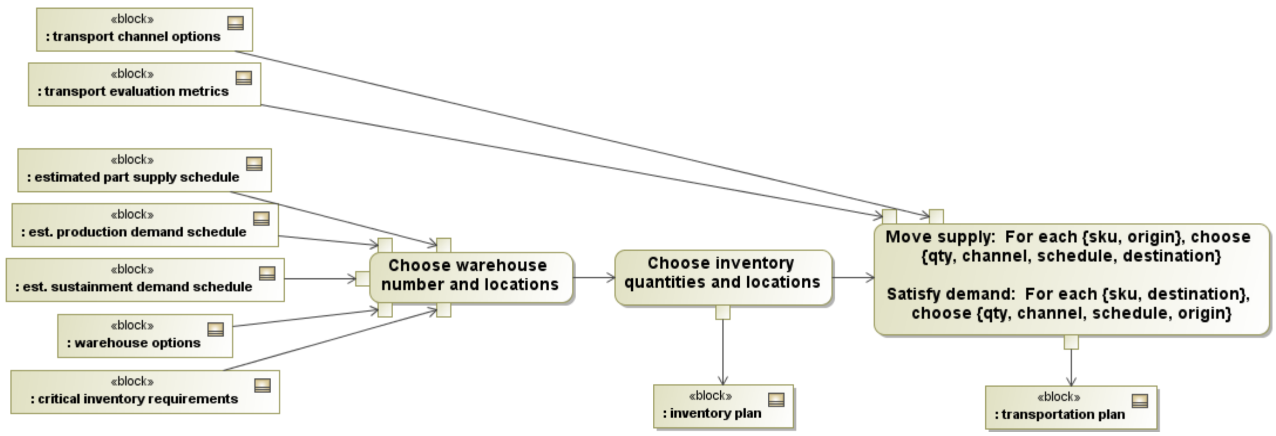

Figure 6: Planning Implementation for Move/Store

In Figure 6, the action that creates the 'transportation plan' corresponds to the traditional OR analysis of logistics systems. This analysis might involve both a network flow optimization model that determines flow rates, and an associated simulation model that evaluates the plan with regard to uncertainties and risks. These kinds of models—network optimization and network simulation—require a mathematical representation of the transportation network itself. The semantics of this network model can be defined using SysML.

Figure 7 illustrates one way in which the semantics for our GSC network might be defined. Here, a 'channel' corresponds to a particular (origin, destination) pair and a particular shipment mode, and perhaps even to a particular shipper. The boxes labeled 'supplier', 'warehouse', 'production facility', and 'sustainment facility' each correspond to a particular location, which may be either an origin or a destination. The semantics defined in Figure 7 leads directly to corresponding lists of facilities, locations, and channels to which the GSC stakeholders can easily relate.

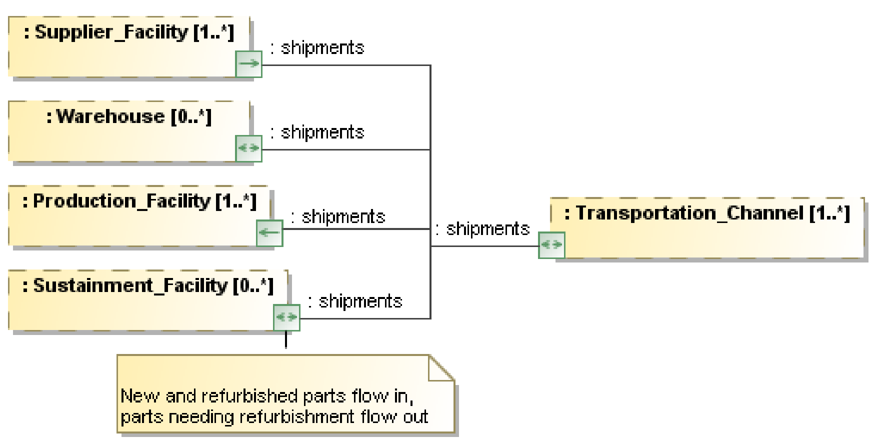

Figure 7: Logistics Network Semantics

The network semantics in Figure 7 can be mapped directly into a traditional network formulation with nodes and directed arcs. Each block in Figure 7 has corresponding instance data; for transportation channels, data for access (size and weight limits) and performance (transit time mean and variability) should be available, and can be mapped to attributes of directed arcs in the corresponding network analysis model. Once a sourcing strategy and contracts exist, estimates for supply or demand of certain SKUs at certain rates at any facility should be available, and can be mapped to attributes of nodes in the corresponding network analysis model.

In Figure 7, the semantic 'shipment' needs elaboration. While production and consumption rates may be stated in units of "parts/time", in reality parts themselves do not traverse transportation channels. Parts move in containers. Containers move in other containers (a box nested in a pallet) or in mobile resources (push carts, forklifts, trucks, ships, trains, aircraft). Only mobile resources can traverse transportation channels. Some of these semantics are introduced in Figure 8, although to thoroughly track parts nested in containers nested in mobile resources traversing transportation channels, the notion of 'Location', both relative and absolute, needs definition.

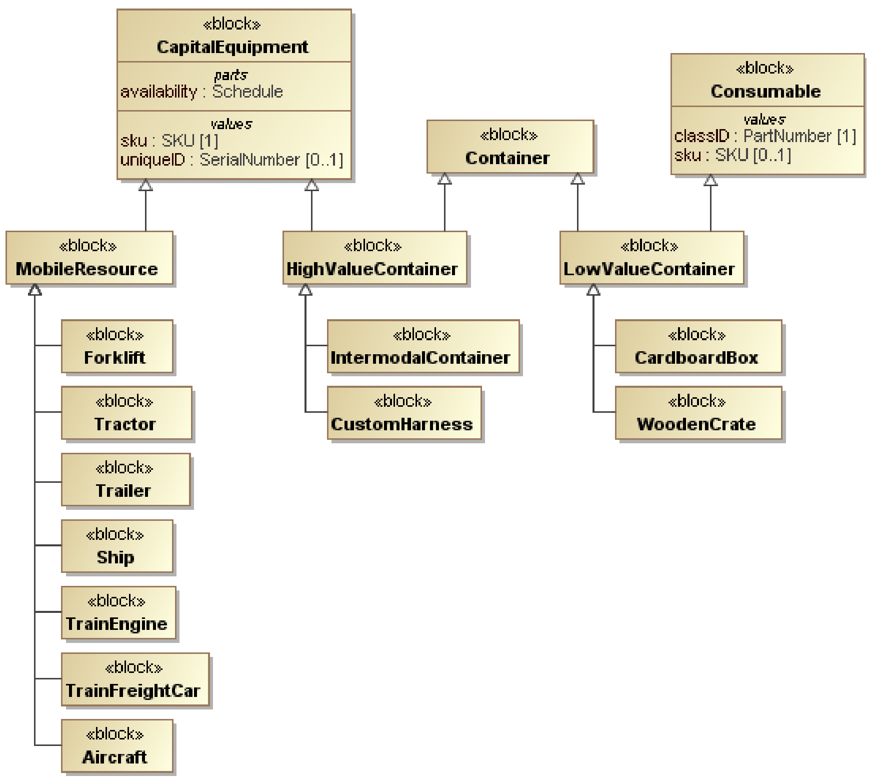

Figure 8: Other GCS Concepts

Continued elaboration of these semantics should motivate why an investment in a GSC context model is preferable to legacy modeling approaches, as complex questions not addressed by traditional logistics analysis become apparent. Partnership agreements or outsourcing of entire subassemblies introduce questions such as: Who will invest in and own which capital equipment and facilities? Who owns each part at any time and when does money change hands? Is it possible and desirable among partners and suppliers of major subassemblies to manage a single supplier list and logistics operation? Does a novel GSC organization introduce major risks that are everybody's problem but have no owner?

6 LEVERAGING FORMAL GSC MODELS

As illustrated by the figures, using a formal language such as SysML confers a significant benefit in making explicit what often is hidden in large-scale complex supply chain modeling applications, namely, the semantics of both the context for designing and managing the GSC, but also the intimate details of the GSC itself. Especially for an enterprise that engages many different entities, this benefit alone might justify formal GSC modeling. However, there is at least one other significant benefit.

In software engineering, the field of model driven architecture (MDA) has developed around the concept of describing an application in a high level language, such as UML, and then automating the generation of the corresponding code for a given software/hardware platform (see, e.g., http://www.omg.org/mda/ for detailed descriptions of MDA and applications). In systems engineering, a rapidly emerging body of research amply demonstrates the feasibility of transforming system models expressed in SysML into analysis models. For example, (Peak et al 2007) discuss direct analysis of system models expressed in SysML; (Kwon and McGinnis 2007), (Huang, Ramamurthy and McGinnis 2007), (Huang, Kwon and McGinnis 2008), (McGinnis and Ustun 2009), and (McGinnis et al 2010) all address modeling manufacturing systems in SysML and translating the SysML model to simulation; (Paredis and Johnson 2008) discuss using SysML models to support simulation in engineering design; and (Paredis et al 2010) discuss a standard for translating SysML models to Modelica models.

It seems clear that in well-defined domains, there is great promise for the approach of using formal languages, like SysML, to model both the context and the specific decision problems, and model transformation technology to automate the generation of computational decision support models. Not only does this approach capture and archive both systems and analysis knowledge in a reusable form, it may also dramatically impact the time and cost to perform complex systems analyses. An order of magnitude reduction in modeling time was reported in (Batarseh and McGinnis 2011) for modeling electronic assembly systems.

7 FUTURE RESEARCH

The concepts presented here represent a significant departure from the traditional approach to modeling and simulating supply chains. We recognize that this approach is limited to domains that are sufficiently well understood so that new modeling concepts do not have to be "invented". Even when new concepts must be developed, this approach provides a mechanism for archiving that knowledge and making it available for future problem modeling and analysis. Thus, we believe the growing body of evidence supports the assertion that this will become common practice in the coming decade.

Nevertheless, there are significant remaining research challenges, including:

- Developing a consensus of standard GSC semantics—today there is no such standard, but it will be essential for the realization of a formal modeling approach
- Developing libraries of standard concepts and their instances—for example, the concept "pallet" is realized in a bewildering array of pallet standards; all these options must be available to the GSC problem modeler
- Identifying and formally defining opportunities for decision support across the GSC organization (as illustrated in Figure 2), identifying the kinds of analysis models needed to support these decisions, and formalizing the semantics of these models
- Developing the theoretical basis and engineering tools for creating model transformation automation
- Understanding and resolving issues associated with integrating this kind of modeling and decision support capability with existing and future enterprise information systems.

In many ways, this list of research challenges echoes the challenges identified by (Lendermann et al 2010) for discrete event logistics systems.

Modeling *per se* always has been a challenge for the OR community. It may well be that the secret to meeting that challenge lies in adapting the formal modeling ideas from software engineering to the unique challenges of modeling and simulating large-scale complex systems like global supply chains.

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AUTHOR BIOGRAPHY

GEORGE THIERS is a graduate student in the Stewart School of Industrial and Systems Engineering at Georgia Tech. Before returning to school he was employed by the Mathworks in Natick, MA and received a masters degree in mechanical engineering from the University of Michigan, Ann Arbor. His email address is gthiers3@gatech.edu.

LEON F. MCGINNIS is the Gwaltney Professor of Manufacturing Systems at Georgia Tech, where he is a member of the faculty in the Stewart School of Industrial and Systems Engineering and the Woodruff School of Mechanical Engineering, founder of the Keck Virtual Factory Lab and Associate Director of the Manufacturing Research Center. He is internationally known for his leadership in the material handling research community and his research in the area of discrete event logistics systems. A frequent speaker at international conferences, he has received several awards from professional societies for his innovative research, including the David F. Baker Award from IIE, the Reed-Apple Award from the Material Handling Education Foundation, and the Material Handling Innovation Pioneer award from Material Handling Management Magazine. He is author or editor of seven books and more than 110 technical publications. At Georgia Tech, Professor McGinnis has held leadership positions in a number of industry-focused centers and multi-disciplinary programs, including the Material Handling Research Center, the Computer Integrated Manufacturing Systems Program, the Sustainable Design and Manufacturing Program, and the Tennenbaum Institute for Enterprise Transformation. His current research explores the use of formal systems modeling methods to support systems engineering of discrete event logistics systems. Professor McGinnis is a Fellow of the Institute of Industrial Engineering. His e-mail address is leon.mcginnis@gatech.edu.