MODELING LEAN, AGILE, AND LEAGILE SUPPLY CHAIN STRATEGIES

by

Thomas J. Goldsby
University of Kentucky

Stanley E. Griffis
Air Force Institute of Technology

and

Anthony S. Roath
The University of Oklahoma

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INTRODUCTION

An unprecedented number of companies are pursuing lean management and agility to reduce costs, improve customer service, and gain competitive advantage. "Lean thinking" embraces the elimination of waste in its various forms. Activities that consume resources but generate no redeeming value in the eyes of customers are wastes that must be eliminated in the "lean" paradigm (Womack and Jones 1996). Agility, on the other hand, emphasizes flexible, timely action in response to rapidly changing demand environments (Christopher and Towill 2002).

Lean management has been the subject of best-selling business books over the past decade and the focus of many management training programs as managers seek to make the "lean leap." Agile management, meanwhile, has enjoyed its own share of attention as the mantra espoused by many leading consultancies and technology vendors. Academics have embraced both paradigms as well, with special issues commonly appearing in leading journals dedicated to each philosophy. Beyond indications of passing interest, entire journals are dedicated to the advancement of theory and practice in leaness and agility (e.g., Lean Construction Journal, International Journal of Agile Management Systems).

Though the "lean" and "agile" philosophies are anchored with relatively simple premises, their complexity becomes apparent during implementation. The very requirements and performance outcomes associated with the two approaches are often called into question. It appears that
neither paradigm is particularly well understood—even by companies considering their respective adoption and implementation. The ambiguity of the paradigms raises the challenge of determining whether one approach or the other would serve as an appropriate basis for adopting a supply chain strategy. When should a company and perhaps an entire supply chain pursue lean management or agility, and must the question be an either/or proposition? Answering these questions is critical given the significance of aligning the company with its up and downstream supply chain trading partners support of business strategy and key supply chain objectives.

The purpose of this paper is to further the understanding of lean, agile, and hybrid (or so-called “leagile”) supply chain strategies, with particular interest directed toward the dynamics and trade-offs associated with each of the strategies. This objective is achieved by operationalizing the three strategies in a real-world case setting. Simulation research is used to examine the operationalization of the different strategies and to measure the respective performance associated with each, identifying the similarities and differences among strategic inputs and outcomes. The application of simulation to supply chain settings is well established given the stochastic nature of supply chains, where decisions in one area have impact on the others (Bhaskaran 1998; Closs et al. 1998; Disney, Naim, and Towill 1997; Towill 1996; Waller, Johnson, and Davis 1999). Simulation provides a basis for comparison among alternative strategies and, in turn, enhanced managerial decision-making.

This paper first describes the three supply chain strategies and introduces the research hypotheses. The paper then details the research setting and method, reviewing the operationalization of the strategies in the simulation models. Finally, the paper presents the results and implications for managers and researchers.

A REVIEW OF THE STRATEGIES

This section describes the three supply chain strategies of interest: lean, agile, and leagile strategies. Each is described in turn.

Lean Supply Chains

Womack, Jones, and Roos (1990) introduced the business world to the premise of lean production in their seminal book *The Machine That Changed the World*. The book chronicled the operations found in the automotive industry, capturing the dramatic differences in approach and ensuing performance found among the world’s leading automakers. In particular, the book examined how the techniques employed by Japanese automakers, namely Toyota, outpaced the performance achieved by U.S. and European competitors. Much has been written in the academic and popular business press about Toyota’s much envied competitive weapon, the Toyota Production System (TPS).

As the architect of TPS, Taiichi Ohno believed that fundamental for any company’s success was the elimination of waste (or “muda” in Japanese). Ohno (1988) developed a list of seven basic forms of muda: 1) defects in production, 2) overproduction, 3) inventories, 4) unnecessary processing,
5) unnecessary movement of people, 6) unnecessary transport of goods, and 7) waiting by employees. Womack and Jones (1996) added to this list with the muda of goods and services that fail to meet the needs of customers. The term “lean,” originally coined by MIT researcher John Krafcik, applies because the lean company uses “less of everything compared with mass production — half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time” (Womack, Jones, and Roos 1990, p. 13). Womack, Jones, and Roos add that in comparison to a mass production approach, a lean company calls for far less inventory and incurs fewer defects while providing greater variety in products.

The potential offered by lean principles has been embraced by practitioners and researchers alike. An Industry Week survey of U.S. manufacturers in 2004 found that almost 36% of plants reported implementation of lean principles in some fashion (Rio 2004). Beyond manufacturing, lean principles have also found application in logistics (Disney, Naim, and Towill 1997; Jones, Hines, and Rich 1997; Wu 2002), product development and launch (Bowersox, Stank, and Daugherty 1999), purchasing (MacDuffie and Helper 1997), accounting (Ahlstrom and Karlsson 1996), and even office environments (Hyer and Wemmerlov 2002; Tapping and Shuker 2003).

In the follow-up to their seminal book, Womack and Jones (1996) extended their original conceptualization of lean operations to the broader enterprise. They contend that the lean enterprise is one that identifies the value inherent in specific products, identifies the value stream for each product, supports the flow of value, lets the customer pull value from the producer, and pursues perfection. It is through this holistic, enterprise-wide approach to lean implementation that the theory extends beyond functional strategy to a broader supply chain strategy employed by the company.

It is important to note that while “pull” replenishment is a principle of the lean enterprise, the question arises: pulling from where? Womack and Jones speak of the “customer” but ordinarily lean systems do not pull from the end customer. Rather, manufacturing responds to the demand signal emitted by the next-stage customer, which is rarely the end user. This is true even at Toyota, the “epitome of lean,” where manufacturing reacts to a combination of dealer orders and sales forecasts provided by Toyota Motor Sales (Goldsby and Martichenko 2005). Despite talks of the ten-day car, auto manufacturers generally believe that cars must be readily available at dealer lots in anticipation of prospective car buyers, for it is believed that U.S. car buyers would rather drive away immediately with vehicles that may not perfectly match their criteria than wait ten (or more) days for a car that exactly meets their requirements (Holweg and Miemczyk 2003).

Given the “I want it now” assumption, automakers serving the U.S. market (including Toyota) typically manufacture vehicles in advance on a make-to-stock (MTS) basis and speculate what will be sold. This planning-based production method more readily supports level scheduling of production (or “hei-junka” in Toyota-speak) and pull-based kanban ordering upstream for parts to support manufacturing. Yet, it is clear that demand does not always equal supply — auto dealers must speculate regarding final consumer demand. Therefore, while lean seeks to minimize waste in its various forms, the planning basis essential for serving end customers with immediate product
availability means that inventory will be produced in advance, similar to mass production. The key difference between a "lean push" and a "mass production push" is that lean typically relies on a much shorter forecast horizon (often two weeks or less) and an ability to adapt should production schedules need to be changed. The challenge with any push-based system rests ultimately with accurately anticipating the quantities, qualities, and allocation of products that will match consumer demand. Improved performance in this area calls for greater focus on the customer. The strategy that embodies an effort to respond to end-user demand on a real-time basis is agility, which is described next.

Agile Supply Chains

While lean management emphasizes the pursuit of process efficiency – generating the greatest outcome from the least input through the minimization of wastes, agility refers to effective, flexible accommodation of unique customer demands (Christopher 2000). Naylor, Naim, and Berry (1997) suggest that the agile company is one that “[uses] market knowledge and a virtual corporation to exploit profitable opportunities in a volatile marketplace” (p. 108). Instead of relying on speculative notions of what might be demanded, the quantity of demand, and the location of that demand, agility employs a “wait-and-see” approach to demand, not committing to products until demand becomes known. Therefore, while lean management typically calls for make-to-stock replenishment driven by short-term forecasts, agile supply chains employ make-to-order provisions, producing only what has already been sold or committed in the marketplace.

Key to providing agile response is flexibility throughout the supply chain. In manufacturing, this would call for the ability to produce in large or small batches, minimizing the “pain” associated with setups and product changeovers, often cited as a critical component of lean manufacturing. Agility might also call for a flexible workforce with members cross-trained, or able to fulfill a variety of tasks as dictated by the demand situation. Product designs should also reflect an ease of assembly that provides for quick conversion of materials from a raw to completed state. Beyond the capabilities of the focal firm, the rest of the supply chain must be responsive as well for agile market accommodation. In fact, response-based supply chains are often characterized as "short," with few or no intermediaries. Supply should be located nearby, and information sharing among the parties must be open and frequent (Christopher 2000; Christopher and Towill 2001).

As is the case with lean management, advocates for agility have established a strong voice in practice and research. Many companies are realizing that the costs and risks associated with holding speculative inventories are too great. This is particularly true with products that have short life cycles (such as personal electronics) or erratic demand (like fashion apparel), where the risks of obsolescence are high. Toyota's supply chain represents a lean strategy in its production of high-quality, affordable automobiles, but there are few, if any, agile manufacturers of automobiles who would employ true make-to-order (MTO) accommodation of customer demand on a large scale. However, other product categories – both complex and simple in product composition – do employ agile, MTO response to the market.
A much heralded example of agile market accommodation is practiced by Dell in its direct-to-consumer business model. The computer maker holds inventories of component parts such as hard drives, processors, memory storage media, monitors, speakers, and a host of other supplies at each of the company’s three assembly plants in the U.S. Many Dell suppliers are located near the Dell assembly plants, providing parts in a just-in-time manner, some replenishing parts as frequently as every 90 minutes (Hoffman 2004). Dell then quickly configures the components into finished desktop and laptop computers that meet customer-specific orders. The make-to-order approach does call for the consumer to wait, as opposed to pre-positioned finished goods inventories found in make-to-stock operations. Dell and other agile companies bank on customers’ willingness to wait for products that meet their specific requirements.

Another example of agility is found at TaylorMade adidas Golf (TMaG) which produces high-performance golf clubs specific to a customer’s needs. TMaG maintains inventories of the various club heads, shafts, and grips that compose the finished product. They can readily mix and match materials and produce a product that meets the customer’s needs in terms of club length, weight, angle, and performance attributes, depending upon how they formulate the semi-finished subassemblies and process them (Bowman 2002). Like Dell, TaylorMade’s basis for these customized clubs is to produce only what is demanded when it is demanded to accommodate customer orders perfectly.

In essence, demand pulls supply all the way back to the point of production in agile supply chains. The manufacturer reacts to the demand signal emitted directly from the end customer. The weakness of this model is that finished goods inventory cannot be made in advance and, hence, every order essentially enters into a backorder situation.

Though "lean" and "agile" strategies are often pitted as opposing paradigms, they share a common objective: meeting customer demands at the least total cost. It is on the nature of that demand and the basis of meeting customer demands in which the two approaches differ (Goldsby and Garcia-Dastugue 2003). Researchers in recent years have suggested that the two approaches need not necessarily represent opposing points of view. Rather, they may be merged in a variety of ways to create so-called "leagile" approaches.

Leagile Supply Chains

Naylor, Naim, and Berry (1997) coined the term “leagile” to refer to hybrids of the lean and agile approaches. Building on the concept of the blended strategy set forth by Naylor et al., Christopher and Towill (2001) conceived three distinct hybrids. The first hybrid approach embraces the Pareto (80/20) Rule, recognizing that 80% of a company’s revenue is generated from 20% of products. It is suggested that the fast-moving products that make up the dominant 20% of the product line can be produced in a lean, make-to-stock manner given that demand is relatively stable for these items and that efficient replenishment is the appropriate objective. Meanwhile, the remaining 80% should be produced in an agile, less anticipatory manner, perhaps even employing make-to-order production to generate supply for only those items ordered when they are ordered. This strategy is often referred to as a mixed-model approach in manufacturing environments (Goldsby and Garcia
Dastugue 2003). It is common for manufacturing facilities to be designed so that some lines are designated for efficient processing of fast-moving product while others are designated as small-batch lines with quick, frequent changeovers in support of the slower-moving items.

The second lean-agile hybrid involves having temporary capacity to meet the needs of peak demand. Most companies experience a base level of demand over the course of the year. This base level of demand can be accommodated in a lean manner, using the company’s own resources to employ heijunka (smooth production) principles to maintain highly efficient operations. However, when demand spikes over the course of peak seasons or heavy promotion periods, outside capacity is procured to meet the heightened demands of these distinct time windows. The procurement of outside capacity for coverage in these situations is viewed as the agile component of this hybrid approach. Many companies engage in leagile supply, manufacturing, and logistics to support seasonal demands.

The third hybrid, perhaps the most intriguing of the three, calls for form postponement. Form postponement refers to delaying the final form of a product until an order is received from customers dictating the quantity and qualities of the goods demanded (Feitzinger and Lee 1997; Zinn and Bowersox 1988). This approach works best when goods can be developed from common materials into a near-finished state with final touches to the product providing for a diverse assortment that accommodates distinct customer needs. The premise calls for lean operations in the production of generic, semi-finished product, and agile accommodation in the customization process (Mason-Jones, Naylor, and Towill 2000). It is on the basis of accommodating diverse needs efficiently that many refer to such an approach as “mass customization” (Feitzinger and Lee 1997).

An example of leagility at work is found at Toyota – the very company regarded as the inspiration for “lean thinking.” Scion, a splinter division of Toyota, is dedicated to serving a distinct segment of today’s automotive market: the 18–25 year-old “Generation Y” segment. Toyota caters to this market through marketing mechanisms that avoid the mainstream media, choosing instead to sponsor local sporting events, concerts, and enthusiast clubs (Oser 2004). Pervasive in this marketing strategy is an emphasis on individuality when selecting and owning a car. After logging on to Scion’s website, Toyota encourages visitors to modify one of the three base Scion models (the xA, xB, and tC), saying, “Build your Scion: We relinquish the power to you.” Customization of the vehicles involves selection among 40 different “menu” options, including vehicle color, wheels, interior and exterior styling, and stereo system, among others.

The base vehicles are produced in a lean manner in Japan and shipped to the U.S. Some vehicles are delivered directly to dealer locations, where they may be used for showroom and demonstration purposes along with supplying the dealer with a small inventory for general sales. Customization calling for cosmetic features and accessories can often be accommodated at dealer locations. These accessories range from exterior features like spoilers, custom lighting, and body graphics to interior items like steering wheels and sport pedals. The remaining vehicles are maintained at distributor facilities near U.S. receiving ports, where more substantive customization can take place. These more substantive, port-installed modifications include stereo installation, side-impact airbags, and performance elements like sport mufflers and struts/shocks. Therefore, base vehicles
may be produced in a lean manner, leaving the agile accommodation of customer-specific needs for the port facility or the dealer.

Whether the customization is small or significant, the point is that the final form of the product is delayed and ultimately committed at a location near the final customer – in the U.S. rather than in Japan – allowing for cycle time compression, or quicker accommodation of customer-specific demand (Mason-Jones, Naylor, and Towill 2000). This method of mass customization is sometimes referred to as “forward-positioned postponement” (Pagh and Cooper 1998). The approach is similar to that long employed by Hewlett-Packard in the bundling of power supplies and users’ manuals with computer peripherals for distribution within diverse regional markets, but on a broader, more complicated scale (Davis 1993; Lee and Sasser 1995). This final form of leagility is that which is modeled in the current analysis.

Given these characterizations of the three supply chain strategies, this research will examine three broad aspects of supply chain performance. The first aspect examines the expected level of customer service attainable by each model. A common measure of service is average order-to-ship time. This metric captures both on-hand inventory availability and backorder response time. When inventory of the right product is available at the right place upon order receipt, then order-to-ship time should be minimal, consisting only of the time required to fill the order from existing inventory. The model that is expected to perform best on this measure of performance is the lean model since it is the only one of the three to preposition finished goods inventory in the distribution channel in advance of customer orders. Hypothesis 1 therefore states:

**H1:** Customer service, as measured by order-to-ship time, will be best in the lean system.

This hypothesis should hold true as long as sufficient quantities of the right inventory are on-hand at the appropriate stockkeeping locations. If backorders exist in the lean system, considerable time may be required to acquire supplies and realign production priorities.

A second aspect of interest is inventory. The measure of enterprise-wide inventory across the three strategies captures the speculative nature of the supply chain. More inventory in various states of completion in different locations translates into greater inventory holdings and higher inventory carrying costs. The least speculative strategy of the three models is the agile system. By employing make-to-order production, only raw materials are acquired in advance of demand. Therefore, the second hypothesis states:

**H2:** Enterprise-wide inventory will be lowest in the agile system.

To add to this hypothesis, the agile model should prove to be second in order of inventory minimization, given that it does not build finished goods in advance but rather engages in postponed production of finished goods.

The third aspect of interest is total cost. The enterprise-wide total cost of each strategy is an exploratory dimension of the current analysis. Total cost consists of the focal company’s costs of material acquisition, inbound logistics, manufacturing, and outbound logistics. Inbound and outbound logistics include the costs of transportation, warehousing, and inventory carrying costs. Post hoc
analysis will compare the models on a total cost basis, examining the cost trade-offs that exist among the models in the base case scenario as well as varying cost conditions. The paper continues with a discussion of the base case environment and operationalization of the lean, agile, and leagile supply chain strategies.

**RESEARCH SETTING AND METHOD**

The operational environment chosen to demonstrate the lean, agile, and leagile strategies was that of a component manufacturer supplying the heating, ventilation, and air conditioning (HVAC) manufacturing industry. The modeled component is a pressure switch used in HVAC equipment to detect pressure levels in the heating and cooling systems of residential and commercial buildings. The component is essentially a generic assembly that can be configured into several distinct switches by using different calibration settings and mounting brackets. The buyers of the switches (HVAC manufacturers) typically have unique requirements regarding the attributes of the final assembly. Within any given family of switches, the manufactured product is ultimately customer specific because of the uniqueness of the calibration setting requested and the mounting bracket applied to the unit.

The case company produces components in the Maquiladora zone of northern Mexico and maintains two U.S. distribution centers (DCs), one in Southern California and one in Kentucky. A depiction of the material flows associated with the current operation appears in Figure 1. The eight parts that make up the final component assembly are all sourced from U.S. suppliers and flow, for tariff reasons, through the distribution center in Southern California to the Mexico production facility. One Mexican supplier is used, providing the packaging materials for the finished assemblies and they are the only supplier to deliver directly to the Mexico production facility. After items are produced in Mexico, all are transported to the Southern California distribution center where they are either stored as finished goods inventory or transported to the Kentucky distribution center for storage. The HVAC manufacturers subsequently draw inventory from the closer DC.
The base case scenario depicts a lean system. The company has embraced lean management techniques for more than five years. Consistent with the lean description above, the company employs a forecast-based planning approach to establish pre-positioned inventory levels at the DCs. When customer orders are placed, the finished goods inventory at the appropriate distribution center is checked. If the order can be filled immediately, it is, and the distribution center processes an order to replenish its finished goods inventory. When an order cannot be filled immediately, a build signal is sent to the production facility in Mexico, and the order is backordered until production occurs and the replenishing supply is shipped to the requesting distribution center. No attempt at transshipment between distribution centers is possible because each stockkeeping unit (SKU) at the distribution centers is unique. Therefore, customers are served from one DC or the other, not both.

The materials flows for the agile model are the same as lean on the supplier side of the operation with inbound materials being mixed at the Southern California facility on their way to Mexico, but differ with regard to production and outbound distribution. Instead of two outbound distribution centers, the agile model uses only the Southern California DC. No finished goods inventory is held at the DC, and customer orders are communicated directly with the production facility as demand occurs. Upon receipt of the order, parts are inducted into the manufacturing process and finished components are then routed through the Southern California DC and on to the customer. The agile environment is depicted in Figure 2.
The agile model, as its name implies, incorporates elements of both the lean and agile operations. Both DCs are utilized, but they hold no finished goods inventory. Instead, each holds semi-processed, generic assemblies that can be made into any of the SKUs. When a customer order is received, light manufacturing tasks are performed to customize the assemblies into final SKUs to fill a specific customer's order. At the same time, the distribution center places an order for replacement of the generic assemblies to resupply those used to fill customer orders. In this arrangement, both distribution centers must house production machinery and labor to support the forward-positioned postponement operations.

Model Parameters

Numerous data inputs were necessary to reflect the stochastic nature of the three supply chain strategies of interest. Direct observation of the manufacturing and logistics operations by the researchers, interviews with senior management of the Mexico facility, sales forecasts, and demand data resulted in sufficient input to support the modeling effort. Table 1 outlines the operations parameters used in the models.
Supplier parts are delivered daily to the Southern California DC. This facility serves as an inbound mixing facility for the Mexico plant. Transportation across the U.S./Mexico border also occurs daily and takes between 22 and 26 hours, with a most likely time of 24 hours. Upon receipt in Mexico, parts are stored in the warehouse until needed on the production floor. Parts are released to the production floor based upon demand and move through production in a time that is triangularly distributed with a minimum of 2.4 hours, a mode of 3.0 hours, and a maximum of 4.2 hours for the lean and agile production models. Leagile production took place in two distinct steps with subassembly processing at the Mexico plant with a triangular (0.6, 1.2, 1.8 hours) distribution and final processing at the DCs occurring with another triangular distribution (2.4, 3.0, 4.2 hours).

Upon completion of production, assemblies are shipped to the Southern California DC for either storage or immediate delivery to the DC in Kentucky. All assemblies crossing the border do so according to the same distribution as the U.S.-to-Mexico border crossing. Assemblies destined for the Kentucky DC are delayed in Southern California for a triangularly distributed period of time (minimum = 2, likely = 8, maximum = 24 hours) before continuing on to Kentucky according to a triangularly distributed time (minimum = 4 days, likely = 4 days, maximum = 5 days). Assemblies then enter the warehouses of the respective DC either to immediately fill demand or to await customer orders. Order wait time is accrued whenever demand is not immediately met due to insufficient inventory on the shelf.

Several modeling assumptions were necessary to bound the research problem. These assumptions address various design factors of the model and were carefully selected to improve the model's internal validity while maintaining external validity. Key model assumptions are shown in Table 2.
Foremost among these assumptions is the nature of demand under which the three strategies were tested. Demand is modeled as a scaled factor of the case company’s annual demand. Mean daily demand is consistent over the course of the modeled time horizon, reflecting the company’s practice of lean management and the smoothing of demand. Despite this “smoothing” effort there was still variation in demand as depicted by a built-in degree of variance (15% standard deviation) around the mean order size. Negative order values were controlled for as all normal distributions can potentially return a negative value. In addition, variation resulted from the timing of customer orders. The timing of orders generated variation since SKUs are unique to each of the customers. Therefore, even though demand volume might be fairly consistent over time, the composition of demand involves disparate SKUs. Each customer’s share of the case company’s annual sales drove the frequency with which individual customers placed orders for their particular SKUs.

**TABLE 2**

<table>
<thead>
<tr>
<th>Category</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockkeeping units (SKUs)</td>
<td>Seven different items are produced in the models to cater to seven customers; each customer buys a distinct SKU; SKUs are based upon a standard platform configuration, using common raw materials that are customized in final processing.</td>
</tr>
<tr>
<td>Finished goods assembly processing</td>
<td>Finished goods assembly is a two-step process; the production of generic (pre-customized) assemblies is consistent across the three models; customization is consistent in the lean and agile models and 25%-43% longer at the DCs in the agile model due to increased variability associated with additional process steps.</td>
</tr>
<tr>
<td>Production resources</td>
<td>Production assets do not have a designed failure rate.</td>
</tr>
<tr>
<td>Transportation capacity</td>
<td>Transportation capacity was unconstrained for modeling purposes.</td>
</tr>
<tr>
<td>Transit times</td>
<td>Transit times are consistent across the models.</td>
</tr>
<tr>
<td>Customer demand</td>
<td>Customer demand is a scaled factor of actual aggregate demand – due to size limitations of the modeling software.</td>
</tr>
<tr>
<td>Demand forecasting</td>
<td>Annual demand was disaggregated into daily batches.</td>
</tr>
<tr>
<td>Inventory positioning</td>
<td>Raw materials feed the Mexico plant approximately daily based on disaggregated annual demand.</td>
</tr>
</tbody>
</table>

The model as described was developed with Arena simulation software (Rockwell Software 2003), resulting in a large and complex model containing hundreds of modeling elements, 80 different queues, and 14 different state variables. The output was compared to the actual system being modeled to assess model validity. Output from the simulation indicated that the model’s performance was consistent with that of the real system, providing evidence that a valid model had been developed.
To determine how many simulation runs were required, a model for each of the three strategies was run for thirty replications of one and one-half year each, a period deemed consistent with product lifecycles. Run calculations indicated that 2,684 replications of each model were required to achieve sufficient power of analysis at the 0.05 level of significance (per Banks, Carson, and Nelson 2000). Additionally, variance reduction techniques suggested by Law and Kelton (2000) were followed, including the use of common random numbers.

RESULTS

Table 3 provides a summary of the model results on the focal areas of performance. Mean values and standard deviations are reported for order-to-ship time and inventory levels across the three models. Hypothesis 1 implied superior customer service performance, as measured by order-to-ship time, by the lean model given the presence of pre-positioned inventories at stockkeeping locations. This hypothesis finds support given the considerably lower mean value for the lean model (34.08 hours), compared to the leagile (99.96) and agile (254.44) alternatives. This implies an ability to support customer demand more quickly with forecast-driven supply. The response-based systems found in the leagile and agile models must process materials and semi-finished assemblies into finished assemblies before filling orders. The results indicate that leagile and agile models will take more than 4 and 10.5 days, respectively, to serve the customer under modeled conditions. While the lean model takes just under 1.5 days on average to accomplish the same task, it should be noted that orders are not always filled immediately, demonstrating that the lean model is also susceptible to delay.
TABLE 3

SIMULATION MODEL RESULTS

<table>
<thead>
<tr>
<th>Customer Service</th>
<th>Lean</th>
<th>Agile</th>
<th>Leagile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order-to-ship time (hours)</td>
<td>34.08&lt;sup&gt;A&lt;/sup&gt; (24.75)</td>
<td>254.44&lt;sup&gt;C&lt;/sup&gt; (46.94)</td>
<td>99.96&lt;sup&gt;B&lt;/sup&gt; (64.69)</td>
</tr>
</tbody>
</table>

Inventory

<table>
<thead>
<tr>
<th></th>
<th>Lean</th>
<th>Agile</th>
<th>Leagile</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. CA mixing facility</td>
<td>96.23&lt;sup&gt;A&lt;/sup&gt; (23.49)</td>
<td>97.66&lt;sup&gt;B&lt;/sup&gt; (23.14)</td>
<td>96.40&lt;sup&gt;A&lt;/sup&gt; (23.11)</td>
</tr>
<tr>
<td>Mexico raw materials</td>
<td>53.75&lt;sup&gt;B&lt;/sup&gt; (18.03)</td>
<td>53.96&lt;sup&gt;B&lt;/sup&gt; (18.34)</td>
<td>23.09&lt;sup&gt;A&lt;/sup&gt; (11.58)</td>
</tr>
<tr>
<td>Mexico work-in-process</td>
<td>5.12&lt;sup&gt;B&lt;/sup&gt; (2.73)</td>
<td>5.09&lt;sup&gt;B&lt;/sup&gt; (2.77)</td>
<td>1.81&lt;sup&gt;A&lt;/sup&gt; (0.38)</td>
</tr>
<tr>
<td>Mexico finished goods</td>
<td>29.09&lt;sup&gt;C&lt;/sup&gt; (6.52)</td>
<td>13.57&lt;sup&gt;A&lt;/sup&gt; (0.36)</td>
<td>14.05&lt;sup&gt;B&lt;/sup&gt; (9.04)</td>
</tr>
<tr>
<td>DC totals (S. CA and Kentucky)</td>
<td>76.75&lt;sup&gt;C&lt;/sup&gt; (18.41)</td>
<td>9.54&lt;sup&gt;B&lt;/sup&gt; (0.29)</td>
<td>8.24&lt;sup&gt;A&lt;/sup&gt; (2.15)</td>
</tr>
<tr>
<td>Total Inventory</td>
<td>260.94&lt;sup&gt;C&lt;/sup&gt; (25.74)</td>
<td>179.82&lt;sup&gt;B&lt;/sup&gt; (23.58)</td>
<td>143.58&lt;sup&gt;A&lt;/sup&gt; (22.46)</td>
</tr>
</tbody>
</table>

Mean values are reported in the table with standard deviations in parentheses. Inventory volume is expressed in finished-good equivalent units. Unique letters designate significant differences at the .05 level.

In particular, the lean model is susceptible to under-forecasts, leading to significant backorder times in the absence of sufficient inventory. The results suggest that extended backorders were not prevalent under the modeled demand conditions. Inventory is likely to build up, however. The inventory figures in Table 3 support this expectation, showing that the lean model results in considerably more inventory than the agile and leagile models. The second hypothesis contends that the agile model will experience less inventory than either of the other two models. This hypothesis is not supported given that the leagile model experiences fewer final assemblies’ worth of inventory than the agile model on an enterprise-wide basis.

Though statistically significant differences exist between the leagile model and the other two models at various locations, the most substantial difference appears to be at the raw material level at the Mexico plant. The leagile model holds less raw material inventory as a function of producing generic sub-assemblies on a rather consistent basis, reflecting an operational benefit of the portfolio effect. The agile model, on the other hand, takes product from the raw material state to final
assembly only upon demand. As a result, raw material inventory will sit for a longer period of time, on average.

The finding that the lean model results in substantially more inventory than either the agile or leagile strategy might be surprising to some given lean management’s emphasis on inventory reduction. Yet lean’s premise is to rely on forecasts rather than actual demand to drive replenishment. What must be kept in mind is that the lean approach operates with much less inventory than a conventional mass production approach, which is not presented in the current analysis. The agile and leagile approaches employ less speculative inventory in various states of completion; hence, the agile and leagile approaches appear to be more lean than the “lean” model depicted in this research.

**POST HOC ANALYSIS**

In addition to the two stated hypotheses, detailed post hoc analysis of the model output was conducted with regard to enterprise-wide costs found in the base case. Additionally, analysis was conducted on the cost data to assess the sensitivity of the supply chain strategies to varying cost conditions. The enterprise-wide cost characteristics across the three strategies will be examined first.

**Base Case Cost Analysis**

Cost data were collected for the base case scenario, supporting the calculation of enterprise-wide costs for the three supply chain strategies. Costs were determined for raw materials acquisition, manufacturing, and inbound and outbound logistics for the product family of interest. The manufactured cost for an item in this product family totaled $5.50 and the applicable inventory carrying cost was 15%. A review of the total costs listed at the bottom of Table 4 indicates that the lean approach represents the least-cost alternative among the three strategies. On this basis, the case company appears to have selected the appropriate strategy for production and distribution of its products.
TABLE 4

BASE CASE SCENARIO COST COMPARISONS

<table>
<thead>
<tr>
<th></th>
<th>Lean</th>
<th>Agile</th>
<th>Leagile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Materials Acquisition</td>
<td>$ 2,472,386</td>
<td>$ 2,494,996</td>
<td>$ 2,491,986</td>
</tr>
<tr>
<td>Inbound Transportation</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>9,777,002</td>
<td>9,693,485</td>
<td>12,421,226</td>
</tr>
<tr>
<td>Interfacility Transportation</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Warehousing (space and handling)</td>
<td>456,589</td>
<td>368,780</td>
<td>555,538</td>
</tr>
<tr>
<td>Outbound Transportation</td>
<td>124,800</td>
<td>551,866</td>
<td>124,800</td>
</tr>
<tr>
<td>Inventory Carrying Cost</td>
<td>75,718</td>
<td>25,029</td>
<td>19,985</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$13,056,495</strong></td>
<td><strong>$13,284,156</strong></td>
<td><strong>$15,763,535</strong></td>
</tr>
</tbody>
</table>

Closer examination of the categorical costs illustrates the strategies' relatively similar costs for raw materials acquisition and identical costs for inbound transportation and interfacility transportation. Inbound and interfacility transportation costs are uniform on the basis of the twice-daily shuttles that run from the Southern California mixing facility to the Mexico production plant and back in all three scenarios. Manufacturing costs are lowest under the agile approach given that only ordered products are manufactured, while the lean model produces volume that is not always demanded. Manufacturing costs for the leagile strategy are demonstrably higher given that production takes place in two distinct phases with the latter stage (i.e., customization of the item) occurring in the U.S.-based distribution centers, where labor costs are higher. This manufacturing premium alone is enough to make the leagile approach uncompetitive in the current analysis. All other costs remaining unchanged, leagile manufacturing could incur only a 1.7% premium, compared to its current 27.0% premium, to match the total cost for the agile strategy. Manufacturing costs would actually have to be lower in the leagile operation than in the lean operation in order for the leagile strategy to match the lean strategy – which again is very unlikely. Warehousing costs that are substantially higher given the additional handling and space required to support the product customization activity at the two distribution centers further erode the competitiveness of the leagile option for the relatively low-cost item.

Outbound transportation costs are dramatically higher in the agile environment given the delivery of expedited, small-quantity shipments directly to customers. If the company were to use less timely means of ground transportation, it is likely that the agile strategy would prove to be the least-cost alternative though the longer and more variable order lead time might offset such a cost advantage. OEM customers in the base case scenario seem to reflect this sentiment, preferring to have certain supply in a short amount of time and a willingness to support the supplier's inventory carrying costs to enjoy such provision.
These observations illustrate the total costs as well as the trade-offs found among the categorical costs in the base case scenario. Additional analysis is required to assess the cost dynamics of the strategies under varying conditions. The sensitivity analysis in the next section provides further insight regarding the relative strengths and weaknesses of the three strategies under different assumptions for two key variables: product value and inventory carrying-cost percentages.

Sensitivity Analysis

To evaluate the models’ sensitivity to varying product values and carrying costs, the results were evaluated in light of 15 different possible scenarios. The finished goods range in value by ten-fold orders of magnitude and the carrying cost levels range within values commonly cited in the literature (Stock and Lambert 2001). With three finished good values ($10, $100, $1,000) and five carrying-cost percentages (ranging from 10 to 50%) across the three supply chain strategies, 45 possible design points were developed for the analysis.

To assess the resulting enterprise-wide costs associated with these design points, the outputs from the three simulation models were referenced and average inventory at the various levels across the enterprise noted. These values were then used to calculate total enterprise-wide costs for each model. These costs appear in Table 5.

**TABLE 5**

ENTERPRISE-WIDE TOTAL COSTS

<table>
<thead>
<tr>
<th>Finished Goods Value</th>
<th>Carrying Cost Percentages</th>
<th>Model</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10</td>
<td>10%</td>
<td>Lean</td>
<td>23,094,114</td>
<td>23,185,225</td>
<td>23,276,336</td>
<td>23,367,446</td>
<td>23,458,557</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>Agile</td>
<td>23,261,718</td>
<td>23,291,917</td>
<td>23,322,116</td>
<td>23,352,315</td>
<td>23,382,514</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>Leagile</td>
<td>27,969,414</td>
<td>27,993,558</td>
<td>28,017,701</td>
<td>28,041,844</td>
<td>28,065,987</td>
</tr>
<tr>
<td>$100</td>
<td>10%</td>
<td>Lean</td>
<td>224,351,288</td>
<td>225,255,047</td>
<td>226,158,807</td>
<td>227,062,566</td>
<td>227,966,326</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>Agile</td>
<td>222,979,841</td>
<td>223,280,297</td>
<td>223,580,752</td>
<td>223,881,208</td>
<td>224,181,664</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>Leagile</td>
<td>272,220,193</td>
<td>272,460,738</td>
<td>272,701,282</td>
<td>272,941,826</td>
<td>273,182,370</td>
</tr>
<tr>
<td>$1,000</td>
<td>10%</td>
<td>Lean</td>
<td>2,236,923,028</td>
<td>2,245,953,274</td>
<td>2,254,983,519</td>
<td>2,264,013,764</td>
<td>2,273,044,009</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>Agile</td>
<td>2,220,161,067</td>
<td>2,223,164,091</td>
<td>2,226,167,115</td>
<td>2,229,170,139</td>
<td>2,232,173,162</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>Leagile</td>
<td>2,714,727,984</td>
<td>2,717,132,538</td>
<td>2,719,537,093</td>
<td>2,721,941,648</td>
<td>2,724,346,203</td>
</tr>
</tbody>
</table>

Bold cells highlight the least-cost alternative.

Unlike the base case model analysis where there is a ‘best’ option, there are differences in which model performs best as the result of the varying per-unit costs and carrying costs incurred.
The lowest-cost items, those with a finished goods value of $10, experience the lowest enterprise-wide cost under a lean system at the lower carrying-cost values (i.e., those below 40%). However, as the carrying costs rise, the agile model begins to outperform the lean model. This is consistent with expectations of the two systems given that inventorying carrying costs rise as a function of both carrying-cost percentages and the value of the inventory. Although lean systems seek to eliminate waste, they still populate the supply chain with inventory at all stages, albeit less than a mass production approach.

In contrast, agile supply chains accommodate customers by pulling inventory only upon order placement. Raw material inventory incurs less inventory carrying cost than finished goods (Lambert and Bennion 1982). In addition, the agile strategy employed a direct-to-customer distribution strategy once products arrived at the Southern California DC, eliminating the cost associated with the Kentucky DC. Though the agile model calls for small-quantity shipments of finished goods direct to customers, the increased carrying costs found in the lean model begin to offset the total cost savings enjoyed by the lean system. The break-even point between the lean and agile models occurs at a carrying-cost percentage of approximately 33.4% for $10 items. The medium-priced ($100) finished goods and high-priced ($1,000) goods exhibit results consistent with the observations involving higher carrying-cost percentages given the higher inventory holding costs. The agile model, by holding very little finished goods inventory and only one distribution center, is able to offset its premium transportation costs and incurs a lower enterprise-wide total cost across all carrying-cost levels with these goods of higher value.

The leagile model generates the highest enterprise-wide cost across all modeled scenarios despite incurring the lowest inventory holdings, as noted in the discussion of our second hypothesis. Although its order-to-ship time is better than agile, it is worse than lean. From a total cost perspective, it consistently lags when compared to lean and agile. The reason for this appears to be the manufacturing cost premium associated with producing semi-finished assemblies and then reintroducing them to the manufacturing process closer to the customer. In the leagile model, a 25% manufacturing cost premium was charged for this two-stage production. Although with careful operations planning and development this disadvantage could be significantly reduced, the manufacturing premium would need to be reduced to a 1.7% premium noted in the base case to allow the leagile model to be competitive against the lean and agile models on a cost basis.

IMPLICATIONS AND CONCLUSIONS

This research yields several implications for the manager and the researcher. One primary purpose for the research was to provide meaningful descriptions of three much debated supply chain strategies. By modeling the strategies, the research effectively characterizes the strategies in tangible terms. The simulation method supports the operationalization of the strategies, taking each from hypothetical concept to a functional, working model. Therefore, the valid development of models is important not only in the generation of results but also in the very illustration of the strategies as they might be practiced. Simulation serves as a valuable tool for the manager to address
"what if..." questions, allowing one to compare alternatives and to understand the realities associated with a strategy before committing significant resources.

The operationalization of the models demonstrates the key differences that exist among the strategies in terms of customer service commitments, forecasting approach, manufacturing philosophies, logistics network design, information exchange, inventory planning, and transportation methods, among other strategic and operational decisions. These supply chain strategies therefore reflect not only the management of physical flows among entities in the supply chain but also the very method by which products are developed, procured, manufactured, marketed, and sold as well as the relationships among internal and external parties that make the implementation of supply chain strategy possible.

The research suggests that there is an appropriate time and place for each of the three strategies. That is, each strategy holds merit and proves advantageous under specific market and economic circumstances. The lean strategy demonstrated the best customer service performance, as measured by order-to-ship time. This will hold true so long as demand is smooth and can be predicted with a relatively high degree of accuracy. This finding is consistent with the observations of Mason-Jones, Naylor, and Towill (2000) and Christopher and Towill (2002). The lean strategy accumulates more enterprise-wide inventory than the other two approaches, with the most demonstrative differences in the accumulation of finished goods inventory. This, too, is caused by the production of finished goods in advance of demand, as opposed to the wait-and-see approach of the other two strategies. Despite this seemingly "non-lean" result, a direct comparison to mass production (not presented as part of this study) would reveal that the lean approach far outperforms mass production in keeping inventories down.

Post hoc analysis showed that despite lean management’s higher inventory investment, the case company was correct in its determination to employ a lean strategy given that it not only resulted in the highest service level to customers but also the lowest enterprise-wide costs. Subsequent analysis suggested that this holds true under conditions involving low-value finished goods ($10) at lower inventory carrying cost percentages (30% and below). However, the agile strategy proved to be the low-cost approach in all other modeled scenarios.

This research also supports the contention of several authors that the lean and agile strategies can be combined into a so-called "leagile" hybrid. The modeled approach reflected the lean production of generic base units that were then positioned closer to customers in the distribution channel for subsequent customization. While this operationalization of forward-positioned postponement did not prove to be the least-cost approach for the base case or other modeled scenarios, leagility might prove advantageous with products and manufacturing scenarios where the manufacturing premium associated with disjointed operations is minimal.

There may also be instances similar to the Toyota Scion example, where customers are willing to wait a short period of time and perhaps pay somewhat more for a customized product. In still other circumstances, delayed processing might actually be welcome in order to allow semi-
finished product to cure, age, or ferment, before final processing or packaging. The delayed action may therefore be significant or minimal, like that found in package-to-order operations where sold product might be distinct in packaging only. Regardless, the combination of lean production and the provision of postponed tailoring of products in support of mass customization remains an area for further exploration and assessment.

Other extensions of the current research are abundant. The current analysis focused on the operations of a tier-1 supplier to the HVAC manufacturing industry. The same three strategies could be examined in a host of other industries and at different levels of the supply chain. In addition, the current analysis limited its scope to the service rendered by the focal company and the costs incurred by this company. A significant benefit of simulation research is the ability to model entire supply chains to understand better the dynamics that transpire among multiple companies. Therefore, rather than focusing on a single company, researchers might broaden the scope for system-wide implications across the supply chain. The simulation might also be expanded to encompass additional product families, more accurately reflecting the full array of products manufactured and distributed in the supply chain. With the incorporation of more products, a more complete analysis of potential benefits associated with pooling inventory and measurement of the portfolio effect would be feasible. With expanded scope in analysis, however, the researcher must often trade internal validity for added external validity.

Subsequent research should not necessarily be limited to broadened scope, however, given that the models may be refined for added insight within the focal company’s operations. Further analysis might be directed toward different demand scenarios to assess the robustness of the strategies given various demand characteristics – either more stable or more erratic demand than that reflected in the base case scenario. The level of analysis might also be honed to focus on the intricate activities taking place within specific facilities in the focal company’s domain. These “black boxes” found in the current analysis (e.g., manufacturing) could be examined in much greater detail for the sake of in-depth investigation of optimal work design at the activity level. For example, how are the “black boxes” altered as a result of improved information flow across the enterprise, and how does improved information flow influence the physical flow of material and goods? Studying such issues in greater detail can enhance our understanding of complex interactions among activities in the supply chain.

Beyond further refinement, assessment, and selection of the modeled strategies, there must be consideration for the implementation of a chosen strategy. Methods aside from simulation will continue to be tapped to determine how companies can coordinate activities to achieve supply chain integration and desired outcomes. In fact, simulation can be combined with other empirical methods (e.g., survey research) and qualitative methods (e.g., case research) to capture more fully the complexities of supply chain interactions. The experimental designs of simulation research should therefore seek to incorporate the critical behavioral, non-operational elements of supply chain management. The current analysis used established decision-making logic with perfect rationalization of its actions.
Further research should seek to capture the realities of disparate motives, information asymmetry, channel power, perceived risks and rewards, and a host of other behavioral attributes associated with industrial dynamics and supply chain management. In addition, research might consider how supply chains should be designed to respond to disruptions such as those caused by inclement weather, natural disasters, work stoppages, or operations failure. Analyses might also examine possible contingency strategies around management-driven initiatives such as mergers/acquisitions, product-line expansions, or the adoption of new technologies like radio frequency identification (RFID). Inclusion of these considerations, while difficult to model, will substantiate understanding of both the inputs and outcomes associated with coordinated effort, helping convert the supply chain vision into reality.

NOTES


Rockwell Software (2003), *Arena 7.01*, Selwickly, PA.


**ACKNOWLEDGMENT**

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**ABOUT THE AUTHORS**

**Thomas J. Goldsby** (Ph.D. Michigan State University) is an Associate Professor of Supply Chain Management, Gatton College of Business and Economics, The University of Kentucky. Dr. Goldsby has held previous faculty appointments at Iowa State University and The Ohio State University. He received a BS in Business Administration from the University of Evansville, and an MBA from the University of Kentucky. His research interests focus on logistics customer service, supply chain integration, and the implementation of lean and agile supply chain strategies. He is co-author of a book titled *Lean Six Sigma Logistics: Strategic Development to Operational Success*.

**Stanley E. Griffis** (Ph.D. The Ohio State University) is an Adjunct Professor in the School of Engineering and Management at the Air Force Institute of Technology (AFIT) in Dayton, Ohio. His research interests primarily focus upon logistics performance measurement, lean supply chains, and reverse logistics and its role in customer satisfaction.

**Anthony S. Roath** (Ph.D. Michigan State University) is an Assistant Professor of Marketing and Supply Chain Management at the Price College of Business, The University of Oklahoma. His research interests include international supply chains, relational management/governance, and logistics modeling and simulation.