Journal of Industrial Engineering and Management

doi:10.3926/jiem.2009.v2n1.p90-113 JIEM, 2009 – 2(1): 90-113 – ISSN: 2013-0953

A simulation-enhanced lean design process

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Received March 2009
Accepted April 2009

Abstract: A traditional lean transformation process does not validate the future state before implementation, relying instead on a series of iterations to modify the system until performance is satisfactory. An enhanced lean process that includes future state validation before implementation is presented. Simulation modeling and experimentation is proposed as the primary validation tool. Simulation modeling and experimentation extends value stream mapping to include time, the behavior of individual entities, structural variability, random variability, and component interaction effects. Experiments to analyze the model and draw conclusions about whether the lean transformation effectively addresses the current state gap can be conducted. Industrial applications of the enhanced lean process show it effectiveness.

Keywords: lean manufacturing, simulation, process design

1 Introduction

Lean concepts for system transformation have become ubiquitous (Learnsigma 2007). However, lean concepts do not address one significant issue: providing evidence that a system transformation will meet measurable performance objectives before implementation. This lack of validation increases the risk the transformed system will not meet the performance objectives. The various existing lean processes address this deficiency by emphasizing their iterative nature: simply repeating all or a part of the process, including implementation, until the objectives

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are achieved. This approach is inherently oppositional to lean concepts as it unnecessarily extends the time and thus increases the cost of completing the transformation to a lean system.

Ferrin, Muller, and Muthler (2005) provide a perspective for addressing this lean deficiency: Simulation is uniquely able to support achieving a corporate goal of finding a correct, or at least a very good, solution that meets system design and operation requirements before implementation. Thus, these authors conclude that simulation provides a more powerful tool (a 6σ capable tool) than those commonly used in a lean process.

The objective of this paper is to develop an enhanced process for lean system transformation that includes kanban sizing, physical layout, and quantification of other parameters such that the risk of system performance objectives not being met by the first transformation activities is low. Developing such a process requires future state validation which can be accomplished by integrating simulation modeling and experimentation into a lean transformation process. Simulation is used to provide quantitative validation evidence that system requirements and objectives will be met by the first system transformation. Industrial applications are presented to demonstrate the effectiveness of the new framework.

2 Background and literature review

The term "lean production" in the literature has many definitions. Womack, Jones and Roos (1990) originally defined lean production as requiring "half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a product in half the time. Also, it requires keeping far less than half the needed inventory on site, results in many fewer defects, and produces a greater and ever growing variety of products." Shah and Ward (2007) defined lean production as "an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability". Hopp and Spearman (2004) focused on the buffering aspects of a lean production system and define lean as the production of good or services that minimizes buffering costs associated with excess lead times, inventories, or capacity.

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2.1 History

The road to transition American manufacturers into lean organizations has taken many decades of development. The origins of lean can be traced back to Kiichiro Toyoda's vision of just-in-time part delivery in the 1930's. The system of lean production was implemented by Eiji Toyoda and Taiichi Ohno at the Toyota Motor Company in Japan in the 1950's.

However, it wasn't until books such as Japanese Manufacturing Techniques by Schonberger (1982) and Zero Inventories by Hall (1983) were published that the concept of lean manufacturing was considered to be applicable to organizations outside the Japanese automobile industry.

When Womack et al. (1990) published The Machine that Changed the World, a new era in the approach to manufacturing systems design was launched. In the mid-1980's, in response to several governments concerns about the health of their automobile industries, the Massachusetts Institute of Technology created the International Motor Vehicle Program (IMVP). It was one of IMVP's researchers, John Krafcik, who first used the term "lean production" to describe the production system that used significantly fewer resources compared with the widely accepted system of mass production.

2.2 Lean and organizational structure

Lean production is defined by researchers based on either a philosophical view, identifying guiding principles, or from an operational view, identifying specific techniques or tools (Shah & Ward, 2007). Organizations converting to lean systems will give higher priority to operational issues compared to philosophical issues.

Lewis' (2000) analysis confirmed that organizations do not all follow the same path or employ the same tools in their efforts to develop a lean production system. White et al. (1999) compared the implementations of lean production techniques at small and large U.S. manufacturers. Results of the study showed that large manufacturers were able and more likely to implement these techniques than the small U.S. manufacturers. Although some of the techniques provided better results depending on the firm size, practices such as setup reduction, multifunction employees and Kanban system provide better organizational performance regardless of firm size.

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Warnecke and Hüser (1995) asserted implementing lean production was only one component of a corporate transformation to lean. A more precise term would be "lean management" or "lean industry". In this framework, lean initiatives would include product development, chain of supply, shop floor management, and after-sales service. Shah and Ward (2003) identified 22 lean practices and classified these practices into four main categories: just-in-time, total productive maintenance, total quality management, and human resource management. Principal component analysis examined the influence of plant size, plant age, and unionization on implementation of these practices. Results showed strong support for the influence of plant size on lean implementation, whereas the influence of unionization and plant age was less pervasive.

Competitive advantages that organizations achieve by implementing lean techniques include improved customer response time, decreased inventories and working capital as well as greater visual control (Hobbs, 2004). Over 60% of companies integrating lean manufacturing have seen reduced customer lead times, steady or reduced pricing and increase market share (Struebing, 1997). Koenigsaecker (1998) reported increases of 300% to 400% in productivity, 1000% in inventory turns, and decreases of 95% in lead times compared to batch production systems. Individual case studies have shown a wide arrangement of improvements including reduced product development time, increased operating profit, reduced manufacturing space, improved supplier quality, increased employee productivity and reduced cycle times (Standard, 1994; Womack and Jones, 1996).

2.3 Principles and tools

Womack and Jones (1996) further refined lean production's definition by proposing value, value stream, flow, pull and perfection as the five basic principles of lean production. The customer defines value for the organization based on needs, pricing, and timing for the product or service. The series of information management and transformation tasks form the value stream for the product creation. The value added steps in the organization identify the product flow for production. Customer's pull products from producers as opposed to these producers pushing product to the customers through material control mechanisms. The final principle integrates and perfects the system so the first four principles can be effectively implemented.

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There are various technical practices that manufacturers employ to implement lean manufacturing. Pavnaskar, Gershenson and Jambekar (2003) identified 101 lean manufacturing tools and developed a seven-level classification scheme to categorize these tools. Monden (1993), Karlsson and Åhlström (1996), Detty and Yingling (2000), Sánchez and Pérez (2001), Motwani (2003), Bhasin and Burcher (2006) and Shah and Ward (2007) discuss some of the more commonly implemented lean manufacturing tools. Table 1 identifies these tools and classifies them based on Womack and Jones' basic principles.

Lean Manufacturing Tools	Value	Value Stream	Flow	Pull	Perfection	Sources
Autonomation			•		•	b, d
Cellular manufacturing			•	•		a, d, e
Continuous Improvement /kaizen					•	a, b, c, d, e, f, g
Five S and visual Management					•	a, b, d
Kanban and JIT pull systems				•		a, b, c, d, f
Level production			•			b, d
Multifunctional and self-directed teams			•		•	c, e, f
Process and value stream Mapping	•	•				a, e
Seven wastes and waste elimination	•					a, c, e, f
Single minute exchange of dies (SMED)/ Set up reduction					•	a, d, g
Single piece flow			•			a, e, g
Standardized work			•			b, d
Supplier base reduction	•	•				a, c
Supplier development	•	•				a, e, f, g

Table 1. "Lean Manufacturing tools and their relationship to Womack and Jones' five principles". Sources: (a) Bhasin and Burcher (2006); (b) Detty and Yingling (2000); (c) Karlsson and Åhlström (1996); (d) Monden (1993); (e) Motwani (2003); (f) Sánchez and Pérez (2001); (g) Shah and Ward (2007)

Pavnaskar et al. (2003) reported that companies have misapplied lean tools and techniques during the conversion to a lean organization. The misapplications can be identified as "use of a wrong tool to solve a problem, use of a single tool to solve all of the problems and use of all the tools (same set of tools) on each problem". Applying lean tools incorrectly results in a waste of an organization's time and money as well as reduced confidence by employees in lean techniques and philosophy. Implementing the future state design without validating the design is a contributing factor in the poor performance in newly designed lean systems.

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2.4 Variability and simulation

As well as the benefits of lean production there are also several criticisms of the lean philosophy. Although manufacturing systems components often should be modeled as random variables, the design of lean systems is inherently a deterministic process. Random variation in addition to system component interaction can have a major influence of the performance of the future state. Criticisms include the inability to account for demand variability (Hampson, 1999; Hines, Holweg & Rich, 2004) as well as variability in process times, yield rates, staffing levels, etc. Undoing the effects of this variability requires creating inventory, capacity, or lead time buffers. Since variability buffering is a fundamental waste in the system, the ability to reduce variability is a basic requirement of lean (Hopp & Spearman, 2004).

Dhandapani, Potter and Naim (2004) showed how value stream mapping (VSM) was used in system design in the steel industry and determined that simulation was needed to identify the impact of variations, such machine reliability and material availability, on supply chain performance.

2.5 System component interactions and simulation

Lean system tools concentrate on each individual component of a production system and are unable to discover the interactions between these components. Khurana (1999) characterized complexity as technological, logistical, organizational, or environmental. Production processes are influenced by either logistical complexity or technological complexity. Logistical complexity is due to high volumes of tasks while technological complexity is due to the inherent complexity of the system as well as the multiple interactions between the components. Disney, Naim and Towill (1997) described that a total system model could be created that exceeded an individual’s capacity to comprehend all the system’s details. The system model, which integrated simulation and genetic algorithms, resulted in increased performance of the production control function by understanding the interaction between factory order and inventory levels.

Detty and Yingling (2000) described several studies where simulation identified the values for specific parameters of the lean system (e.g. number of kanbans, container size, batch size). Simulations enabled decreases in inventory, order lead time, and system flow times as well as reduced variability in supplier demand in an

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assembly process for a consumer electronic product. Schroer (2004) showed that simulation techniques could be used to facilitate understanding of the basic concepts of lean manufacturing such as kanban inventory control, push versus pull manufacturing and process variability reduction. Turner and Williams (2005) proved that supply chains, whose complexity included product variety, demand seasonality and consumer behavior, could be successfully modeled.

Hung and Liker (2007) used simulation to study the effect of batch sizes on production lead time in a multi-stage assembly operation. The study indicated the interaction of quality capabilities, logistical polices, and equipment reliabilities have a significant impact on pull system responsiveness and failure to consider these interactions will result in suboptimal performance of the pull system. Kumar and Phrommathed (2006) used simulation to model a sheeting operation at a pulp and paper manufacturer where simulation reduced the possibility of ineffectively redesigning a critical process. Zahir, Vlayka, Lynne and Peter (2000) discuss how a lack of tools for evaluation business process changes leads to their failure. As processes have become more complex, the ability for simulation to analyze this complexity allows for the effective implementation of business process improvements. Kumar and Nottestad (2006) reported that although capable, simulation often ignores higher order interactions of mechanical systems. Integrating design of experiments with simulation allows for a better understanding of the system. McDonald, Van Aken and Rentes (2002) used simulation to address questions that couldn’t be addressed by the static view provided by a VSM, specifically when parallel processing steps or product complexity existed. Comm and Mathaisel (2005) studied a lean manufacturing application of a labor-intensive industry in China. Simulation improved the use of VSM by addressing the complexity and number of the process steps in the system analysis. Other studies that used simulation to analyze the impact of component interaction include Adams, Componation, Czarnecki and Schroer (1999), Byrne and Heavey (2006), Comm and Mathaisel (2005), Detty and Yingling (2000), Mehra, Inman and Tuite (2006), Pfeil, Holcomb, Muir and Taj (2000), and Schroer (2004).

2.6 The future state and simulation

A fundamental process in lean system design is the use of a VSM to identify the future state of the system. The VSM does not include any variability information or mechanisms for validating performance of the system. Some software exists for

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translating the VSM into a simulation model, SigmaFlow for example (SigmaFlow, 2006).

There have significant number of case studies that identify the use of discrete event simulation as a key component in validating the system design before implementation. Abdulmalek and Rajgopal (2006) describe the integration of VSM and simulation to manage uncertainty in the system and create a dynamic approach for evaluating different future state maps. Lian and Van Landeghem (2007) addressed limitations in VSM by integrating simulation into the procedure and identified additional benefits of using simulation as a training tool besides quantifying the benefits of the improvements. McClelland (1992) identified simulation as a method firms could used to evaluate the impact of implementing a new manufacturing strategy or analyzing possible alternatives being considered by the firm. Other studies that used simulation to validate the future state include Adams et al. (1999), Detty and Yingling (2000) and Zahir et al. (2000).

3 The lean process

Typically, firms will launch their transition efforts to lean manufacturing with an initial assessment of the organization. During this phase a steering team is organized and trained in lean techniques and philosophy. The team evaluates the product offerings based on the organization’s competitive strategy and marketing objectives. The production operations are reviewed with the perspective of creating a lean operation. The next phase in the program requires the organization to document the current state of the operations. Manufacturing processes are verified and the value streams are identified. A value stream represents all the steps in a process that transform raw materials into a finished good and will include flows of information and materials throughout the process (Tapping, Luyster and Shuker 2002). A VSM of the current state is created and opportunities for waste elimination are evaluated. The next phase of the program is devoted to designing the future state using lean principles and techniques. An overall concept of how the facility should ideally operate is developed and expressed in the future state VSM. The process flow defined by the future state VSM leads to a detailed production system design that incorporates lean techniques such as kanban controls on inventory and a cellular organization for production. The future state design is evaluated by additional production personnel including the process owners. The last phase of the program is the implementation on the factory floor. Throughout

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the implementation phase the performance of the production system is reviewed. Commonly, during this phase, operational issues are addressed and policies and procedures are adjusted to promote lean operations (Feld, 2001; Hobbs, 2004; Conner, 2007).

The various processes for lean transformation are significantly different from one another. For example, Hobbs (2004) discusses the "methodical and disciplined" approach to lean (Figure 1).

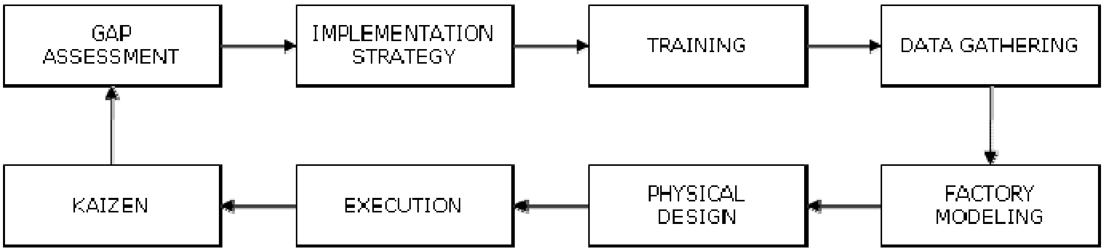

Figure 1. "Hobbs' Disciplined Approach to Lean Manufacturing". Source: Hobbs (2004)

This approach starts with a gap assessment and progresses through several steps until kaizen events reevaluate the performance of the system and the cycle repeats. Gap assessment determines current state gap, the difference between the current performance of the system and the desired performance of the system. The approach includes factory modeling as an input to the physical design but does consider the iterative process that should occur between the physical design and modeling of the system. The author does not further develop the idea of factory modeling. Kaizen is a Japanese word for improvement. Thus, the desire to continuously improve system performance leads repeating the gap assessment step.

Feld (2001) proposed a streamlined road map to lean manufacturing. This approach identified four phases in implementing a lean manufacturing program (Figure 2).

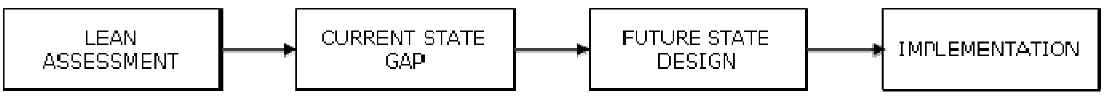

Figure 2. "Feld's Streamlined Approach to Lean Manufacturing". Source: Feld (2001)

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As with Hobbs' approach, the initial phase was an assessment of the organization's capabilities and progressed from an analysis of the current state gap directly to future state design and implementation. This methodology did not specifically consider modeling the future state prior to implementation or reevaluating the system after implementation.

Lean assessment includes a performance assessment of the system as it is currently operating (current state) as well as an assessment of the current market for the product produced by the system. In practice, these assessments are more descriptive than analytic and more qualitative than quantitative. A VSM of the current system is developed and a root cause analysis to identify why system performance is less than desired conducted. In practice, the root cause analysis is more likely the product of discussions and consensus building than objective analysis.

Future state design involves an overall concept design as well as a detailed design that are premised to result in the desired performance of the system. These designs include a VSM of the future state as well as effective communication with management and the plant.

The next step is implementation whose details are beyond the scope of this paper.

4 An enhanced lean process

We propose an enhanced lean process based on Feld's streamlined approach to lean manufacturing, which has five steps (Figure 3).

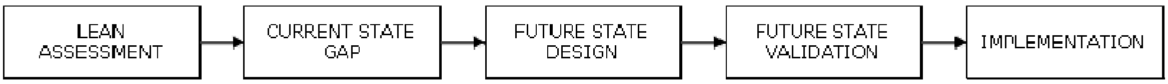

Figure 3. "Simulation-Enhanced Approach to Lean Manufacturing".

The Future State Validation step has been added before implementation. The step may be performed using discrete event computer simulation as was previously discussed. The validation step must help ensure that the future state design effectively addresses the current state gap.

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4.1 Enhancing the VSM with simulation modeling

A VSM is a static representation of the system. It is a descriptive model in that no inferences about system performance can be drawn from it by mathematical analysis or computer experimentation. Changes in the system over time are not represented.

A simulation model of the same system enhances the VSM model in several ways.

- The model can be analyzed using computer based experiments to assess system performance under a variety of conditions.
- The dimension of time can be included in the model so that dynamic changes in system behavior can be represented and assessed.
- The behavior of individual entities such as parts, inventory levels, and material handling devices can be observed and inferences concerning system behavior made.
- Variability, both structural and random, are commonly included in simulation models and the effects of variability on system performance determined.
- The interaction effects among components can be implicitly or explicitly included in a simulation model.

Simulation experiments can be conducted to help quantify system operating parameters answering questions such as whether on-time delivery to customers improve if the number of kanbans is increased. The number of kanbans is input to the simulation model and the percent of customer shipments made on time is measured. Such assessments are supported by computing and reporting performance measures specific to a particular system in the model. For example, suppose a production process has three steps performed in sequence with the middle step outsourced to a nearby plant. The number of parts at the nearby plant could be computed and reported as well as the finished goods inventory.

Including time in a simulation model means the dynamics of system behavior can be considered. Continuing with the example in the preceding paragraph, the effects of changing when and how often parts are transferred between the two

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plants can be assessed. In plants making multiple part types, a comparison between making every part every day or some parts on one day and some parts on another to help reduce setup time can be made. How to coordinate production between two flow lines in the same plant when one produces parts for the second can be examined and analyzed.

Simulation models support examining the behavior of individual entities in detail. The flow of an individual part through a production system can be traced, which can be particularly important when alternative pathways exist. Daily changes in inventory levels can be reported and examined, including the number of units added to and taken from the inventory. Events which caused stepwise changes in behavior can be reported, for example events that change the flow in a continuous production chemical plant.

Simulation models allow individual entities to be distinguished from one another using attributes. Thus, conditional logic based on these attributes can be used to affect entity behavior such as flow and processing times. Including such details allows simulation models to more closely conform to system behavior.

Variability is commonly included in simulation models so the effects of reducing it can be quantified. Random variation including that due to machine and process reliability (internal variability), raw material availability (supplier reliability), and customer demand (customer variability) can be taken into account.

Structural variability occurs when a system component does not do the same activity in the same way every time. For instance, the processing time on a machine could be 2 minutes for parts of type A and 3 minutes for parts of type B. A product could be shipped every day to a customer but produced only on Mondays and Thursdays to minimize the number of setups. Both structural and random variation contributes to the need for inventory, excess capacity, and increased production lead times (Hopp & Spearman, 2007). Lean activities tend to focus on identifying and reducing random variation. Structural variation is often ignored or not identified since all operations can appear to be deterministic when only this type of variation is present.

Simulation models can accommodate voluminous data and the results of the analysis of this data. For example, shipping data for a product can act as a substitute for customer demand. The distribution of shipping volume can be

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determined and used in the simulation model. For example, examination of the shipping data for each part type for a plastics parts company showed the number of pallets shipped per day followed as discrete distribution. The shipping strategy for a chemical company was such that the particular load spots available for each product as well as the days of the week when the product was shipped were input to the simulation model.

Lean tools lack the ability to analytically determine the effects of changes made to a single component on other components or overall system performance. This deficiency makes validating lean transformations before implementation almost always difficult if not impossible.

For example, it is well known that target inventory levels depend only on the variability of the process that adds items to the inventory and the variability of the process that removes items from the inventory. Thus inventory levels are dependent on the behavior of other system components. Lean techniques treat inventory levels as independent variables. Often in practice, lean transformations initially set inventory levels too high and gradually reduce them in time until all unneeded inventory is removed. This approach systematically requires too much inventory at least for a significant time period and thus seems oppositional to lean concepts.

Alternatively, simulation models can include how system components interact. These interactions likely affect the ability of the system to meet its performance objectives. Changes made in the operations of one component likely effect the operation of other components as well as the overall performance of the system. Simulation modeling and analysis has been shown to be effective in the same domains, such as manufacturing where lean is most often applied. Thus, simulation is a primary tool for validating lean transformations, the future state, before implementation.

Examples concerning the need to assess component interaction and the use of simulation to do so are presented in Standridge (2004) as well as Standridge and Marvel (2006).

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4.2 Improving the future state design

Analytically validating the future state may result in multiple possible future states as well as determining which of the possible future states meet system performance objectives. Lean procedures assume the one future state developed by the lean transformation team will be effective and proceed to implementation without validation or identifying and assessing alternatives. The use of simulation modeling and analysis for validation overcomes this deficiency.

Validating the future state helps determine its operating parameter values, such as the number of WIP racks required to minimize inventory while meeting throughput targets. Simulation experiments can be used to help determine the values of multiple parameters concurrently. Component interaction effects suggest that parameter values not be set one at a time. Lean techniques assume the transformation team can set the parameter values for implementation using only deterministic, and likely simple, computations.

Maas and Standridge (2005) as well as Grimard, Marvel, and Standridge (2005) give examples of using simulation for future state validation and parameter value setting.

5 Industrial examples

Lean transformation projects using the new five steps enhanced lean process and emphasizing validation of the future state have been performed. Two of these projects are described below.

5.1 Industrial example of a tier one automotive supplier

A tier one automotive supplier discovered that a lean transformation that did not include a simulation based validation of the future state was ineffective. A simulation model was developed for future state validation of the lean implementation and then utilized in production planning to evaluate schedules and the impact of new product introductions (Standridge and Marvel, 2006).

The lean system design converted a process layout to a production flow lane layout. Based on a value stream analysis, the new facility layout supported processing most of the products in a single flow lane. Initially, the manufacturer

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evaluated product flow by determining gross capacity, using a static spreadsheet analysis, of each piece of equipment in each flow lane. This approach was inadequate for several reasons including:

- The effect of structural variability on system performance was not assessed. Due to equipment processing and capacity limitations, some products needed processing in more than one product flow lane. Some, but not all, of the operations on some subcomponents were outsourced, including plating at an outside vendor. The various pieces of equipment used to fabricate and assemble the subcomponents and final products operated with different processing speeds and capacities.

- The effects of interactions between system components were not assessed. The assignment of product to the product lanes was based on gross capacity and did not consider the dynamics of the production system such as the interaction between the processes. Due to equipment processing and capacity limitations, some products needed processing in more than one product flow lane.

- The effects of random variation in processing times and customer demands were not considered.

Use of the simulation model helped the lean transformation team meet system performance objectives during the first implementation instead of using a trial and error method of system improvement after implementation. Simulation experiments identified when the assembly process had to be halted or modified due to a lack of subcomponents as well as assessing the impact of decisions made on the production floor to adapt to these shortages. Identifying the root causes for the subcomponent shortages allowed the manufacturer to identify equipment or processes that needed improvement.

5.2 Industrial Example of a Tier Two Automotive Supplier

A tier two automotive parts supplier developed a lean system design as a closed-loop supply chain (Marvel, Schaub & Weckman, 2008). The poor performance of the current system, the current state gap, caused a system redesign. The supplier produced customized products for stamped and fabricated metal product industry customers. Long-term contract with the suppliers created most of the high volume

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customer demand and product delivery due dates but some short term contracts generated sporadic low volume demand for some products. An initial step in the lean design process classified all the product offerings as either high volume or low volume products. These parts were assigned to part families based on similarities in the processing characteristics. The facility layout was designed as a multiple flow lane facility with part families assigned to each flow lane. The major production issues were considered to be the sequencing of products and the gross capacity of the flow lanes.

A complicating factor in the system design was determining the number of customer specific product containers (which can be viewed as kanbans) that moved between the supplier and each customer. These containers were used to ship the product between the supplier and each customer and were returned empty by the customer to the supplier. The supplier could not ship product to a customer in alternate containers and the number of containers provided was negotiated between the supplier and customer during the contract stages. The standard method to estimate the number of containers provided by each customer was based on static performance analysis. The availability of kanban containers at the supplier had a significant impact on the overall supply chain and system performance (Figure 4).

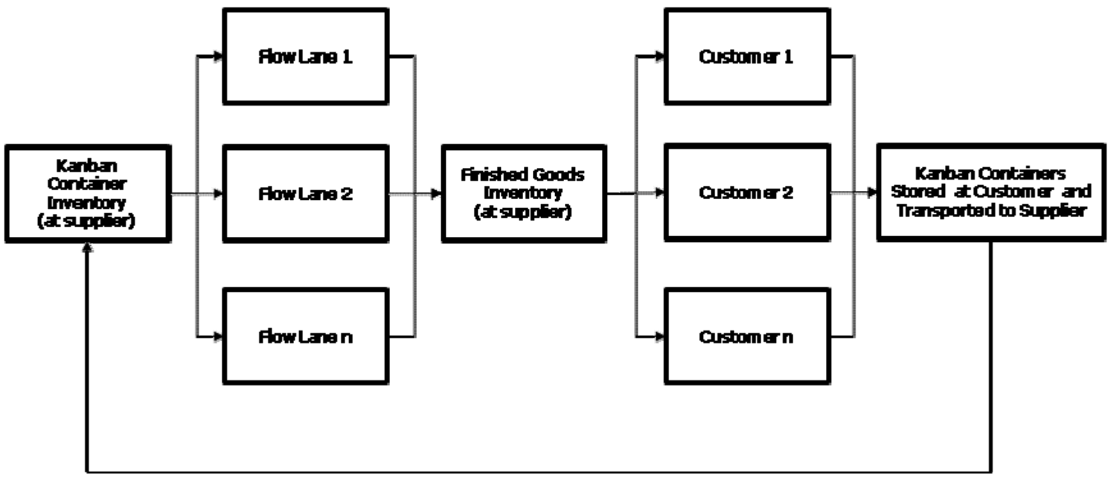

Figure 4. "Kanban Container Flow through Supply Chain. Source": Marvel et al. (2008)

A simulation model was employed to validate the new system design (future state) as well as a planning tool to evaluate new product contracts as well as changes to the production schedule (Figure 5). The simulation model was able to incorporate logistical constraints of the customers, as well as transportation efficiencies and

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material availability. The model identified potential customer service issues and well as impacts of future system improvements.

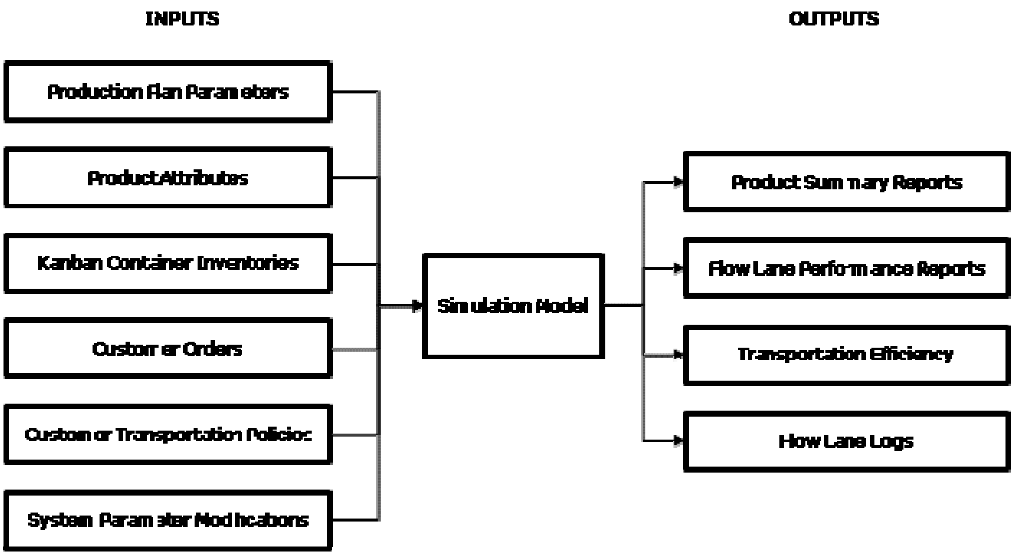

Figure 5. “Simulation Model Inputs and Outputs”. Source: Marvel et al. (2008)

Development of the simulation model required modeling the kanban container returns from the customer. Analyzing the return data, including fitting a distribution function, showed the availability of customer containers was a much more significant problem than originally considered. The variation in container returns resulted in production being starved, which caused greater delays than the sequencing of products or the availability of capacity for noncritical products which were produced only in gaps in the production schedule.

The use of the simulation model showed the interaction of system components cannot be adequately assessed by breaking the system into its elementary components and evaluating each individually, as is done in a static lean analysis. The simulation model was able to address the following four specific concerns of the supplier regarding the future state design that could not be identified by the traditional lean process.

- Are there enough kanban containers in the system, considering logistical constraints, to meet the market demand requirements?
- Is there enough capacity in the system to meet the demand for the sporadically manufactured products?

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doi:10.3926/jiem.2009.v2n1.p90-113 ©© JIEM, 2009 – 2(1): 90-113 – ISSN: 2013-0953

- How does the sequencing of the products impact system performance?
- How efficient are the schedules for product transportation to the customers?

The simulation output summary provided to the user (Figures 6 and 7) addressed these concerns by 1) identifying when the current production plan would be interrupted by having an inadequate number of kanban containers; 2) identifying the number of instances in which the production plan was unable to satisfy customer orders which was the second concern of the supplier; and, 3) analyzed truck shipment efficiencies that would result from the current customer shipment policies. Only by using the enhanced lean process and validating the future state could alternatives that met customer service expectations be identified and implemented.

Product	Scheduled Flowlane	Planned Cycle Days	Adj. Cycle Days	Planned Kanban (lin. Ft.)	Adj. Kanban (lin. ft.)	Planned Run Rate (ft/hr)	Adj. Run Rate (ft/hr)	# of Times Spool Shortage Caused Skipped or Delayed Run	# of Times Unable to Fill Customer Order (Backorder)	# of Times Production Cycle Skipped due to Amount of FGI	# of Complete Cycles
1021				200		100		0	0	0	
1298				14000		325		0	0	0	
2370	2	5	8	0		200		0	0	0	11
2999				984		100	54	0	0	0	
3119				0		213		0	0	0	
4581	4	15		2000	1312	250		0	0	0	3
6131				7720		213		0	2	0	
6768	1	5		0		150	136	0	0	0	11
8220				0		250		0	0	0	
9001	3	10		35000	42360	410		7	2	0	5
9932				0		176		0	0	0	

Figure 6. "Simulation Output Summary". Source: Marvel et al. (2008)

CUSTOMER	AVG TRUCK EFFICIENCY DURING SIMULATION RUN	# OF SPOOLS SHIPPED DURING SIMULATION RUN
CustomerA	83.3%	152
CustomerB	62.5%	30
CustomerC	11.9%	63
CustomerD	38.3%	46
CustomerE	87.5%	42
CustomerF	75.0%	60
CustomerG	58.3%	28
CustomerH	8.3%	2
CustomerI	60.4%	86
CustomerJ	8.3%	2
CustomerK	16.7%	44
CustomerL	58.6%	146
CustomerM	15.4%	37

AVG WEIGHTED TRUCK EFFICIENCY DURING SIMULATION RUN
56.85%

Figure 7. "Customer Shipment Efficiencies". Source: Marvel et al. (2008)

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6 Summary

An enhanced lean process adding the idea of validating the future state using simulation modeling and experimentation before implementation is presented. This validation helps ensure the future state effectively addresses the current state gap. Systems issues that are often overlooked in traditional lean assessments such as component interaction, structural variability, random variability, and time dependencies are considered in the validation step by using a simulation model. Industrial applications of the new process show its effectiveness in validating proposed future states and identifying alternatives needed to deal with component interaction and variability effects that could not be identified by traditional lean assessments.

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