Investigating the Impact of the Dynamics Associated with Increasing Responsiveness Level on Leanness

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Abstract

Lean manufacturing is a powerful philosophy in our limited resources global environment. In the last few decades, many organizations around the world strive to apply lean innovation but some encounter failure. Among the reasons for such failure is the lack of an appropriate tool to measure the degree of leanness as well as the high dynamic nature of lean implementation. This paper presents a new model to evaluate lean performance and the dynamics associated with lean implementation using a system dynamics approach. The model examines the performance of a multi-stage production system through variable stochastic system parameters such as cycle time, and machine availability. In addition, the model captures the dynamics associated with increasing the responsiveness level of manufacturing firms. The Leanness score proposed is based on overall work-in-process (WIP) efficiency, overall service level, and overall equipment effectiveness (OEE). The model provides decision makers with the status-quo of their organizations regarding leanness level, a visible explanation about which factors can affect their leanness score, a metric to track lean implementation and finally the opportunities for continuous improvements.

Keywords
System Dynamics, Leanness Measurement, Responsiveness level, Uncertainty

1. Introduction

In nowadays highly competitive environment, many companies around the world try to survive by establishing the “Lean manufacturing concept” in their enterprises. According to the Delaware Valley Industrial Resource Center (DVIRC), an estimated 60 percent of US manufacturers have gone lean.

Lean is a Japanese management approach that focuses on cutting out waste, while ensuring quality. This approach can be applied to all aspects of business – from design, through production to distribution. It aims to cut costs by making the business more efficient and responsive to market needs. It is all about producing more and more with less and less [1].

Lean manufacturing and other improvement techniques have been popularized over the last two decades to give a competitive edge for the corporations. Despite this vastly diffusion of lean, failed implementations are common, and there is significant “confusion and inconsistency” in how lean production works and how it is best implemented [2]. A survey of 100 business executives highlighted some problems with lean and six sigma implementations including: 70% of organizations reported a less than 5% improvement in manufacturing costs as a result of lean; 60% said their previous lean improvements were not sustainable [3].

It is becoming clear that companies need to better understand how going lean can be achieved in today’s complex, dynamic business environment. Too often, companies plan and adjust their activities on the assumption that they will operate in a largely stable environment. By taking action without first understanding their dynamic conditions — the uncertainty and sudden change that often drives waste to accumulate in the first place—companies risk falling far short of their goals. This paper measures the leanness of a multi-stage production and examines the dynamics associated with increasing the responsiveness level. The research is based on a system dynamics approach to model a multi-stage manufacturing system and explore the impact of implementing lean policies on the leanness score. System dynamics (SD) approach proved to be appropriate for studying the dynamic behavior of complex manufacturing systems.
2. Literature Review
The interest in lean production is raised since its identification by [4]. Many researchers address deeply lean systems, philosophies, tools and techniques. Analytical approaches to study lean manufacturing systems included the work that presented a group of qualitative and quantitative rules to implement lean manufacturing [5]. The approach focused on how to change the current mass production operation of industries to a lean operation with a nine different design rules for that transformation.

Simulation of lean system performance comprises a significant share of lean dynamics literature. An analysis of the performance of just-in-time production systems was conducted with exploring the effects of operating policies on system performance measures [6]. A further work was done by examining the performance of multi-item, multi-line, multi-stage JIT and the impact of some factor settings on some performance measures via simulation with SLAM II [7]. The use of discrete event simulation was demonstrated as a tool to assist organizations with the decision to implement lean manufacturing by quantifying the benefits achieved from applying lean principles [8]. An assessment of current and future value stream map (VSM) via simulation with Arena was developed by [9].

The need for lean assessment is apparent as a consequence of the divergence among authors in identifying lean production which lead to confusion in the theoretical level and problematic issues in the practical level. So, each organization want to implement lean production should select tools, concepts, techniques that satisfy its own needs [10]. A checklist including 36 indicators gathered from a survey is developed to assess the changes towards lean manufacturing. A qualitative model to evaluate the degree of leaness of firms was developed [11]. The current status and performance of lean production in china was assessed by [12]. Data Envelopment Analysis (DEA) technique was used by [13] to measure the overall leaness of a value stream mapping (VSM) considering cost, time and output value. To assess the enhancements achieved through the application of lean tools and techniques, a cost-time profile (CTP) tool was developed for monitoring the accumulation of cost in the manufacturing of a product through time [14]. The impact of lean production on working conditions was assessed by [15]. An adaptive lean assessment approach was used as a guide to the lean implementation by recognizing web-based program for each user to evaluate the current status of organization and the opportunities for improvement [16]. Fuzzy membership functions were developed as an approach to evaluate the lean performance of manufacturing systems [17].

An approach to dynamically model and analyze manufacturing systems, and especially their different planning and control policies, is system dynamics (SD) introduced by [18]. SD has distinctive performance when considering strategic issues in manufacturing companies [19]. Furthermore, SD models have proven their applicability to analyzing strategic scenarios as well as simulation of policies and operations in manufacturing systems [20]. Application of SD in manufacturing systems to date focused mainly on pure inventory dynamics and supply chain where the objective was to study how the system can be designed and analyzed to respond to unanticipated demand with maximum stability and minimum cost [21-25].

A dynamic model for capacity scaling was developed in reconfigurable manufacturing systems (RMS) and was analyzed based on control-theoretic approaches to indicate the best design for the scaling controller [26]. A proposed SD single stage model for capacity scalability in make-to-order manufacturing was presented [27]. It used various performance measures to examine the best scaling policy under different demand scenarios. SD was also used to analyze the complexity and the stability of manufacturing systems and identify an index of Manufacturing Execution Complexity Index, MECI [28]. SD model was built for discussing the issue of network configuration for the needs of complex realization of non-standard orders [29]. Also, SD was used to compare between traditional supply chain and agile supply chain [30]. The impact of dynamic disturbances in manufacturing process on the production planning and control (PPC) in job-shop manufacturing was investigated [31]. It used system dynamics to analyze the system response under different arrival patterns for customer orders and the existence of various types real-time events related to customer orders and machine failures. It also evaluated the shop performance by measuring the backlogged orders, WIP inventories, and tardy jobs. Comparing between two models for a supply chain under two conditions of supply disruptions, without backup supplier, and with a contingent supplier was done by SD [32]. Building SD model to investigate the dynamics associated with single lean manufacturing cell was developed. It showed that although lean cell is expected to be responsive to external demand with minimum waste, however, this was not the case under the considered uncertain conditions [1].

From the previous review, utmost effort focused on the rules and recommendations to apply lean manufacturing or the different approaches to improve many aspects of lean manufacturing tools. Although the literature offered tools,
models, and techniques to assess the leanness degree of manufacturing systems, few work study the lean systems from a dynamic perspective. Such dynamic analysis in today’s uncertain environment is fundamentally critical to understand and thus better manage lean manufacturing systems and keep competitive advantage for firms. This paper presents a system dynamics approach to assess the degree of leaness of manufacturing systems under dynamic conditions. The approach presented is considered an initial attempt to explore more and more the dynamics associated with different aspects of this excelling manufacturing paradigm.

3. Dynamic Manufacturing System Model
A system dynamic model is developed as shown in Figure 1 to measure the monthly leanness score of a production system. The production system is composed of four components which are production system, quality system, backlog system and leanness score evaluation system. The production system involves four stages, three of them are concerned with manufacturing and the fourth is the finishing stage. The four stages are controlled by stochastic cycle time for each stage. The quality system is based on sampling techniques at the end of the manufacturing process and is controlled by inspection time. The backlog system is an indication of the delay between the placement and delivery of orders. In lean context, such indication is an important reflection of the level of responsiveness. Finally, the leanness score system is composed of three metrics which are Overall Equipment Efficiency (OEE), Overall Work-in-process (WIP) Efficiency, and Overall service level.

3.1. Model Notations
B (t): the backlog level at time t.
WIP_t (t): the WIP level at time t at station i.
PIR (t): the production input rate at time t.
PR (t): the production rate at time t.
CT_i (t): the cycle time at time t at station i.
TCT: the theoretical cycle time.
COT: the changeover time.
FR (t): the finishing rate at time t.
FGI (t): the finished goods inventory at time t.
SR (t): the shipment rate at time t.
TWIP: the monthly total WIP.
MSR (t): the maximum shipment rate at time t.
DSR (t): the desired shipment rate at time t.
MOPT: the minimum order processing time.
TDD: the target delivery delay.
PE: the monthly performance efficiency.
NOT: the monthly net operating time.
NAT: the monthly net available time.
SPT: the monthly scheduled production time.
PDT: the monthly planned downtime.
UPDT: the monthly unplanned downtime.
MA: the monthly machine availability.
IOP: the monthly ideal operating time.
OEE: the monthly overall equipment efficiency.
DR (t): the demand rate at time t.
FOR (t): the filled order rate at time t.
B_0 (t): the initial backlog at time t.
DT: the delay time (due to quality).
D (t): the number of defects at time t.
QC (t): the quality control level at time t.
QCSR (t): the quality control start rate at time t.
QCOR (t): the quality control output rate at time t.
IT: the inspection time.
LOT: the monthly lost operating time (due to quality).
QR: the monthly quality rate.
AQL: the acceptable quality level.
QS: the quality signal.
4. Dynamics of the Modeled Manufacturing System

4.1. Production System

A manufacturing system in which several production activities have been functionally aggregated into different production stages is considered. There are many reasons for wanting to aggregate production activities into stages. First, in most manufacturing systems (e.g., semiconductors, automotive and assembly industries) production activities are naturally grouped into well-identifiable production stages. Second, when dealing with multi-product systems, changing of setups to switch from one product to another are often performed on major sub-systems of machines (e.g., on a production line) rather than on individual machines. Controlling the production of each individual machine may, therefore, not be appropriate in such cases. The multi-stage production system considered is a WIP-based control system where the WIP level is observed and controlled by varying the production rate as shown in Equation (1):

\[
WIP_t = \text{INTEG} (PR_{t+1} - PR_t, 0)
\]  

(1)

Production rate equations as seen in equations (2 and 3):

\[
PIR(t) = DR(t)
\]  

(2)

\[
PR_i = \left(\frac{1}{CT_i}\right) \times \frac{MA}{100}
\]  

(3)

To reflect the uncertain environment surrounding the manufacturing systems nowadays, the WIP levels are controlled via a stochastic cycle time. Cycle times for each stage are expressed in random normal distribution functions (see Equation 4):

\[
CT_i = \text{RANDOM NORMAL} (\text{Min}, \text{Max}, \text{Mean}, \text{SD}, \text{Seed}) - \text{COT}.
\]  

(4)

Since the manufacturing system is a multi-product system, it is assumed for simplicity that the manufacturing system is producing products in the same family so changeover time is constant for all stages.
4.2. Backlog System
Order backlog indicates that there is a delay between the placement and delivery of orders. In lean context, such indication is an important reflection of the level of responsiveness (see Equation 5, 6, and 7).

\[ B(t) = \text{INTEG} (\text{DR}(t) - \text{FOR}(t), B_0) \]  
\[ \text{FOR}(t) = \text{SR}(t) \]  
\[ \text{SR}(t) = \text{MIN} (\text{DSR}(t), \text{MSR}(t)) \]  

Every time a product is shipped to a customer, the backlog is reduced by one unit as well. While the shipment rate and filled order rate are supposed to be numerically equal and both have same units (product/hour), they are two different concepts. The shipment rate is the rate by which physical product leaves the organization, while the order fulfillment rate signifies information flow.

The desired shipment rate is the rate of shipments that will confirm orders are filled within the target delivery delay as shown in Equation 8. The target delivery delay reflects the acknowledgment of the manufacturing firm that there will always be a time span between placement and receipt of orders due to different internal processes [21]. In lean context, firms would strive to minimize such a delay. The actual delivery delay will equal the target when the shipment rate equals the desired shipment rate:

\[ \text{DSR}(t) = B(t)/\text{TDD} \]  

To make sure that the model initiates in a balanced equilibrium, the initial backlog must equal the target delivery delay of incoming orders (see Equation 9):

\[ B_0(t) = \text{TDD} \ast \text{DR}(t) \]  

The maximum shipment rate depends on the firm’s current inventory level and the minimum order processing time as indicated by Equations 10 and 11.

\[ \text{MSR}(t) = \frac{\text{FGI}(t)}{\text{MOPT}} \]  
\[ \text{FGI}(t) = \text{INTEG} (\text{FR}(t) - \text{SR}(t), B_0). \]  

The minimum order processing time is determined by the firm’s order fulfillment process, the complexity of the product, and the proximity of customers to the firm's distribution centers. It represents the minimum time required to process and ship an order [21].

4.3. Quality System
The quality control is an integral part of the workflow and it can be the bottleneck section. The maximum output rate at the testing station is constrained by labor, productivity and inspection time. These constraints are reflected in Equations 12 and 13.

\[ \text{QC}(t) = \text{INTEG} (\text{QCSR}(t) - \text{QCQR}(t), 0) \]  
\[ \text{QCQR}(t) = \text{DELAY FIXED} (\text{QCSR}(t), \text{IT}, \text{QCSR}(t)) \]  

The sampling plan in the depicted system is designed to be after the third manufacturing stage (production) where a given number of samples are sent for quality testing as shown in Equation 14.

\[ \text{QCSR}(t) = \text{PR}_3(t) \ast \text{(sample size)} \]  

Meanwhile, semi-finished products are kept as incomplete release. When quality control is completed, finishing (packaging, labeling, etc.) is carried out and products are sent to finished goods inventory for delivery. The approval of the inspection results are controlled by the quality signal. If the no. of defects (see Equation 15) is less than the acceptable quality level (AQL), the finishing rate is not delayed because the quality control process is done parallel to the production rate. However, if the no. of defects is greater than AQL, the finishing rate is delayed by “Delay time” as observed in Equations 15, 16, and 17.

\[ \text{FR}(t) = \text{IF THEN ELSE} (\text{QS}=1, 1/\text{CT}_d(t), 1/((\text{CT}_d(t)+\text{DT}) \ast \text{MA}/100) \]  
\[ \text{QS} = \text{IF THEN ELSE} (\text{D} \leq \text{AQL}, 1, 0) \]  
\[ \text{D}(t) = \text{(no. of defects)} \ast \text{QC}(t) \]
4.4. Leanness score system

The leanness score system consists of three metrics (as shown in Equation 18) which (in the authors’ point of view) reflect the main important aspects of lean manufacturing systems. The three metrics are: the Overall Equipment Efficiency (OEE), Overall Work-in-process Efficiency (OWE), and Overall service level (OSL).

\[ \text{MLS} = \text{OEE} + \text{OWE} + \text{OSL} \]  

4.4.1. Overall Equipment Efficiency (OEE)

Overall Equipment Effectiveness, or OEE, is one of those metrics that is easily applied to any process, department, or the entire organization. It is recognized as the standard measure for lean manufacturing environments, and it should be viewed as a ‘Continuous Improvement Engine’ that provides a robust framework for the lean journey. OEE is comprised of three factors: machine availability, performance efficiency, and quality rate. OEE can be calculated as shown in equations 19 to 27.

\[ \text{OEE} = \text{MA} \times \text{PE} \times \text{QR} \]  
\[ \text{MA} = \frac{\text{NOT}}{\text{NAT}} \times 100 \]  
\[ \text{NOT} = \text{NAT} - \text{UPDT}(t) \]  
\[ \text{NAT} = \text{SPT} - \text{PDT} \]  
\[ \text{UPDT} = \text{RANDOM NORMAL} \text{(Min, Max, Mean, STD, Seed)} \times \text{SPT} \]  
\[ \text{PE} = \frac{\text{IOT}}{\text{NOT}} \times 100 \]  
\[ \text{IOT} = \text{FOR}(t) \times \text{SPT} \times \text{TCT} \]  
\[ \text{QR} = \frac{\text{IOT} - \text{LOT}}{\text{IOT}} \times 100 \]  
\[ \text{LOT} = \text{TCT} \times \frac{D}{\text{production unit}} \times \text{SPT} \]

Note that, Scheduled production time is equal to the planned production time, planned downtime is equal to the scheduled downtime events, unplanned downtime is the unscheduled downtime events, ideal operating time is the time to produce all parts at rate, and lost operating time is the time lost due to production of scrap or non-saleable product.

4.4.2. Overall WIP efficiency

Work-in-process (WIP) is a double-edged sword. It improves the efficiency of the process because firms know that it has this number of goods in process and it will get them ready by a certain time. It can be harmful because excess WIP have negative effect on the operational measurements evaluated and is always viewed as a typical waste in the lean context. It ties up customer funding that could be used to produce more critical needed items. Customers do not pay for their product until delivery. It also means that you have lesser finished items on hand and more in process may signal that may the company is not efficient as it is taking so much time to make the finished goods. WIP is critical to maintaining a competitive sales rate that firms charge its customers. A manufacturing entity must balance WIP to ensure balanced productivity for known and future requirements. From this analysis, firms should establish its target WIP and compare actual WIP with this target as explained in equations 28 to 30.

\[ \text{OWE} = \frac{\text{TWIP}}{\text{Target WIP}} \times 100 \]  
\[ \text{TWIP} = \int_0^T (\text{WIP}(t) + \text{FGI}(t)) \]  
\[ \text{Target WIP} = \text{DR}(t) \times \text{TCT} \times \text{SPT} \]

4.4.3. Overall service level

The backlog level is used as an indicator for the responsiveness level of the manufacturing system. Most manufacturing firms cannot deliver immediately and maintain a backlog of unfilled orders that accumulates the difference between orders and shipments. Backlogs arise whenever there is a delay between the receipt and delivery of an order. Such delays can be caused by administrative activities such as credit approval and order processing, by the need to customize or configure the product to the needs of particular customers, and by delays in shipping to the customer site, among others [21]. The overall service level is the ratio between backlog and target throughput (see Equations 31 and 32), in other words the percentage of delayed orders to target orders.

\[ \text{OSL} = \frac{\text{(Target TH-B)}}{\text{Target TH}} \times 100 \]  
\[ \text{Target TH} = \text{DR} \times \text{SPT} \]
5. Dynamics of Increasing System’s Responsiveness

In this section, the analysis of the developed multi-stage, multi-product manufacturing system is provided. This analysis examines the dynamics associated with increasing the responsiveness level of firms (through decreasing target delivery delay) and its impact on its leanness score. Shorting the TDD will help in closing the gap between optimized and reflected time events. The model is simulated for 200 Hours in order to get the monthly leanness score.

5.1. The Impact of Target Delivery (TDD) on the Overall Service Level (OSL)

Overall service level is the level at which the customer orders is filled on time. Figure 2 displays the effect of decreasing TDD, as a management policy for increasing the responsiveness, on the service level.

The analysis of Figure 2 shows that increasing the responsiveness level via decreasing the target delivery delay will increase the overall service level of firms. By reducing the target delivery delay firms will provide customers with their orders faster. Also, this reduction will decrease the backlog level in the system. However, it is not always the case. Reducing the TDD from 20 to 10 (10) hours will improve the OSL from 90 to 95 % (5). But, the continuous reduction of TDD from 5 to 1 doesn’t lead to further significance improvement in OSL.

5.2. The Impact of Target Delivery Delay (TDD) on the Overall Equipment Effectiveness (OEE)

OEE measurement is commonly used as a key performance indicator (KPI) in conjunction with lean manufacturing efforts to provide an indicator of success. Figure 3 displays the effect of shortening TDD on the OEE.

It is shown from the figure that decreasing the TDD from 20 to 10 hours doesn’t affect the OEE. While continuing to reduce TDD from 10 to 5 hours will lead to a sharp rise of the improvement (10%) in OEE. After this value, the effort made for ongoing improvement in responsiveness level doesn’t payoff in terms of OEE.
5.3. The Impact of Target Delivery Delay (TDD) on the Overall WIP Efficiency (OWE)

In lean context, the inventory and WIP are the mirrors of the imperfection of manufacturing systems. Figure 4 indicates the effect of shrinking TDD in the overall WIP efficiency.

![Figure 4: The impact of TDD on OWE](image)

The analysis of Figure 4 implies that there is a gradual rise in the efficiency of WIP. Reducing the TDD from 20 to 5 hours lead to slight improvement in WIP efficiency compared to the effort made to decrees the TDD with this value. After that, there is no enhancement occur if OWE.

5.4. The Impact of Target Delivery Delay (TDD) on the Monthly Leanness Score (MLS)

Shrinking the delay time push the system to react under uncertain conditions. In lean context, reduction of delivery delays can be achieved by different tools. One of them is the elimination of waste that does not add value to process or service. Another tool is the value stream that can provide the possibility of improving system design that resulted impact on lead time. Also, JIT mechanisms support delay time compression to deliver the orders on time. Figure 5 illustrates the impact of decreasing TDD on Leanness score.

![Figure 5: The impact of TDD on MLS](image)

The figure combines the results of WIP efficiency, overall equipment effectiveness, and the overall service level. By the drop of TDD from 20 to 5 hours, a gradual improvement in leanness score occurs until it reaches 60%. And again, after that there is no remarkable improvement in the leanness score.
6. Conclusion and Recommendations
The need for lean systems assessment under uncertainty conditions is becoming explicit. This paper presented a new system dynamic model to measure the leanness of manufacturing firms. The model captured the dynamics associated with the uncertain manufacturing environment and their impact on the leanness score. The analysis addresses a multi-stage, multi-product manufacturing system. This analysis examined the effect of shrinking the target delivery delay (TDD), as a management policy to increase the level of responsiveness, on the leanness score of firms. Various dynamic matters were demonstrated through different scenarios and summarized as follows:

- Decreasing the target delivery delay improve generally the overall WIP efficiency, overall equipment effectiveness, overall service level which result in the enhancement of the overall leanness score of manufacturing firms.
- Results showed that there is a threshold point after which management investment in increasing the responsiveness level doesn’t lead to further improvement in the system. It is important to explore such threshold points in the system before taking different decisions concerning improvements investments.
- Dynamics associated with manufacturing systems have a significant effect on its leanness. Ignoring this dynamics will mislead the decision makers. Taking the decision of increasing responsiveness, via extending working hours, increasing equipment efficiency, hiring labor, training workforce, and many other initiatives, is very costly and sometimes doesn’t payback.
- More effort is required to better manage and control the uncertainty within the manufacturing environment. Further work is still required to explore more dynamic issues in manufacturing systems. For example, the impacts of uncertain demand rate on the leanness score. Also, the impacts of stochastic changeover time and inspection time on the lean system performance. In addition, the effect of the quality level may be investigated. Moreover, sensitivity analysis for the different parameters involved in the model will help in better understanding the role of these parameters in lean system performance. Furthermore, the impacts of lean tools, techniques, and initiatives on the leanness score under uncertainty can give better insights on how to best implement lean principles. In conclusion, the dynamics associated with the implementation of lean principles need to attract attention of decision makers to avoid wrong decisions and can help in identifying optimal lean transformation plans.

References