

A Dynamic Simulation of a Lean and Agile Manufacturing System

M. Mutingi^{1,2}, C. Mbohwa², S. Mhlanga^{2,3}

¹Faculty of Engineering and Technology, University of Botswana, Botswana

²Quality and Operations Management Department, University of Johannesburg, South Africa

³Industrial and Manufacturing Engineering Department, National University of Science and Technology, Zimbabwe

Abstract

The integration of just-in-time and lean principles in agile manufacturing plays an important role in enhancing the operational performance of manufacturing systems. In this paper, we address this issue by (i) building a set of performance criteria for a typical manufacturing system, (ii) developing a system dynamics model for the system, and (iii) performing experimental “what-if” simulation analyses. Using a system dynamics simulation methodology, the impact of the application of lean and just-in-time policies on a traditional inventory-focused manufacturing system is investigated. System dynamics modelling is used to capture the dynamic causal linkages between different components of the manufacturing system. Different scenarios are generated in order to investigate the dynamics of the system under assumed demand scenarios. The results of the simulation study reveal that manufacturing systems can benefit from the introduction of lean and just-in-time principles, depending on the extent to which the necessary structural changes are implemented. The paper concludes by providing useful managerial insights for effective implementation of lean and agile manufacturing concepts.

Keywords

Agile Manufacturing, Lean Thinking, Manufacturing Systems, System Dynamics

1 INTRODUCTION

Competitive pressures in industry constantly force manufacturers to continuously improve their manufacturing systems for efficient provision of products and associated services to the customers. Most manufacturers have embraced lean practices such as Just-In-Time (JIT), Total Quality Management (TQM), and Total Productive Maintenance (TPM) so as to reduce costs and improve on quality [1] [2]. However, as more and more competitors continue to adopt these practices, some competitive advantages will eventually be lost. As such, some manufacturers have moved a step further by adopting practices that can increase their capabilities towards responsiveness to changes in the manufacturing sector. To this end, a number of manufacturing firms are increasingly becoming more agile than ever [3].

As the lean and agile manufacturing paradigms have been well developed, there has been a tendency to view them in isolation. In the real-world, however, the two manufacturing philosophies should be viewed at in an integrated manner. A few researchers have suggested the integration of lean and agile manufacturing paradigms in manufacturing supply chains; a paradigm now known as “leagile” manufacturing [4]. In this research, we go a step further and propose a systems view on a typical manufacturing system that is implementing leagile manufacturing principles.

2 RELATED LITERATURE

To clarify the lean and agile manufacturing, it is important to first present the key concepts behind the paradigms.

Leanness basically means developing a value stream to eliminate all waste (muda), including time, and to ensure a level schedule [4]. There are four bundles of lean production, namely, Just-In-time (JIT), Total Quality Management (TQM), Total Productive Maintenance (TPM) and Human Resource Management (HRM) [1]. Shah and Ward [5] proposed and tested ten dimensions that can be used to measure the four bundles of lean production. Interestingly, six of the ten dimensions are elements of JIT production. JIT-production focuses on the identification and elimination of all forms of waste, including excess inventories, material movements, production steps, scrap losses, rejects and rework, within the production function. This is consistent with the definition of lean production [5] [6].

Agility, on the other hand, means the use of market knowledge and a virtual corporation in exploiting profitable opportunities in a relatively volatile market place [4] [7].

Elements cited as necessary for agile performance include: the ability to produce large or small batches with minimum setups (and setup time) and a cross-trained flexible workforce [8]; reduced process lead times and costs [9]; relationships with suppliers and

JIT-production [10]. In this view, agility's market winners are speed, flexibility and responsiveness to changes, i.e., service level [11]. Agile manufacturing can be the next logical step or a natural development from the concept of lean manufacturing.

2.1 Lean and agile manufacturing

Leanness and agility can be integrated together to make up a leagile manufacturing system. Agile manufacturing assimilates the full range of flexible production technologies, along with the lessons learned from JIT and lean production paradigms [12]. In other words, agility and lean practices can be integrated, with success. Though earlier concerns pointed out that the two paradigms cannot co-exist [13], a number of researchers and practitioners now predominantly view lean manufacturing as a performance or practice state that is antecedent to agile manufacturing [14]. It is important to note that there is a stream of thought that advocates the simultaneous use of lean manufacturing and agile manufacturing. Leagility proponents believe that manufacturing systems can consist of both lean and agile paradigms, acting together to "exploit market opportunities in a cost-effective manner" [15]. More precisely, a leagile manufacturing system embraces the elements of JIT production such as zero waste, zero inventory or work-in-progress, responsiveness, and flexibility. In light of the above concepts, it is important to model leagility concepts from a system dynamics perspective.

2.2 System dynamics

System dynamics (SD), originated by Forrester [16], is a viable tool in representing the dynamics of complex systems. SD is an effective simulation tool that has been applied to numerous problems such as supply chain management, manufacturing systems, corporate planning and policy design, public management and policy evaluation, economic behaviour, and healthcare modelling [17] [18]. In this regard, we propose a systems dynamics approach for simulation and analysis of a manufacturing system espousing lean and agility principles with the aim of improving its operational performance. The specific objectives of the study are to:

- (i) identify a set of performance criteria for a typical manufacturing system,
- (ii) develop a system dynamics model for the system, and;
- (iii) perform experimental "what-if" simulation analyses.

The proposed SD model can answer what-if questions for a leagile manufacturing systems.

The next section provides the proposed SD model for simulating a manufacturing system that is going lean and agile.

3 PROPOSED SYSTEM DYNAMICS MODEL

The SD model developed in this study seeks to capture the dynamics of various interacting components of a manufacturing system in terms of work in progress (WIP), finished product inventory, shipment, back orders, and demand (orders). Elements of flexibility, speed and operational performance are captured from a systems view point.

3.1 Model description

Figure 1 shows a system dynamics model of a typical manufacturing system. In a make-to-order system, demand influences the *order* rate from the market, leading to accumulation of *backlog*. The manufacturing system strives to make necessary structural and policy adjustments in response to the market changes; factors pertinent to *workflow*, *production* and *shipment* rates have to be adjusted accordingly. According to JIT production concepts, *WIP* and *Inventory* levels need to be kept under control through *cycle time (CT)*, *shipment time (ST)*, and *inventory adjustment time (IAT)*. However, the feasibility of these changes depends on the agility of the manufacturing system. For instance, adjustments to *CT* often require structural and/or policy changes which largely depend on the characteristics and flexibility of the manufacturing system at hand.

The model provides a higher level of abstraction of the dynamics of a manufacturing system in a causal loop form. Important elements of the system are represented as stocks and flows of material and/or information. In this connection, the following notation defines the stock and flow variables:

Stock variables:

<i>D</i>	Demand at time <i>t</i>
<i>B</i>	Backlog level at time <i>t</i>
<i>I</i>	Inventory level at time <i>t</i>
<i>WIP</i>	Work in progress at time <i>t</i>

Flow variables:

<i>w</i>	Work inflow rate at time <i>t</i>
<i>p</i>	Production rate at time <i>t</i>
<i>s</i>	Shipment rate at time <i>t</i>
<i>f</i>	Order fulfilment rate at time <i>t</i>
<i>r</i>	Order rate at time <i>t</i>

In evaluating a pool of alternatives, it is essential to first define a suitable set of performance indicators. In this simulation study, we propose the following evaluation criteria: (i) work in progress, *WIP*, (ii) Inventory level, *I* and (iii) responsiveness, that is, the speed of adaptation to market demand. These are incorporated in the SD model logic.

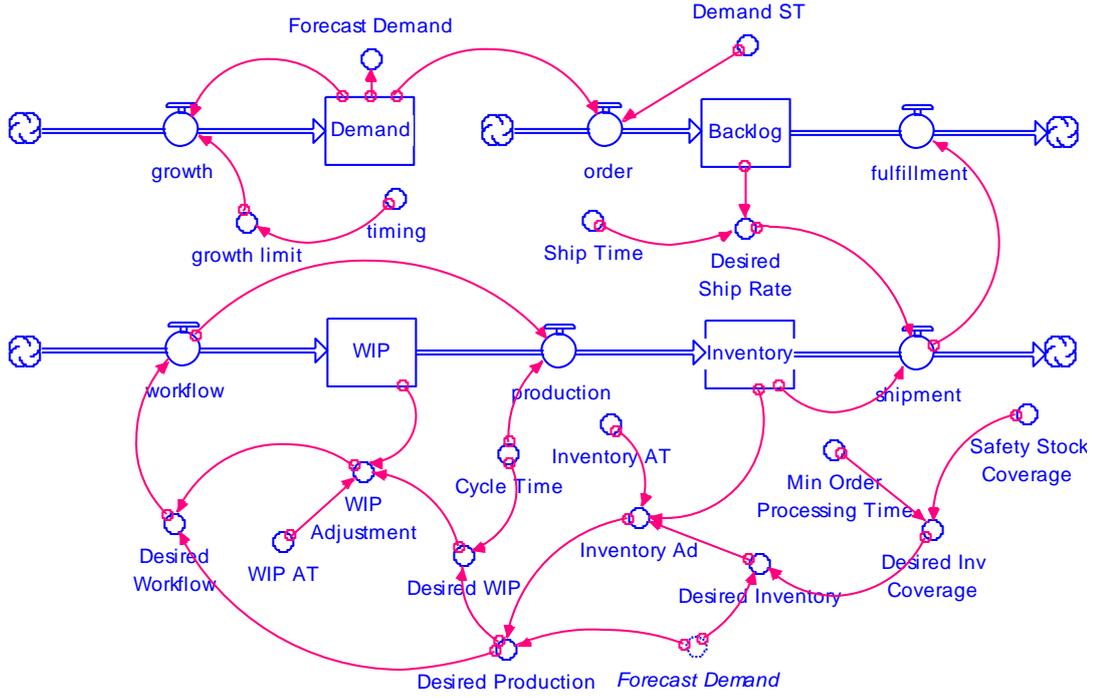


Figure 1 - SD model for a typical conventional manufacturing system.

3.2 SD Model Logic

In this section, the system dynamics equations governing the behaviour of the manufacturing system are outlined. The model assumes an s-shaped demand pattern which depicts a growing market demand common in markets where new products are being introduced.

The mechanics of inventory control is influenced by the inventory gap between desired and current inventory [17] [18]. Thus, the inventory adjustment IA can be represented as follows;

$$IA = (DI - I) / IAT \quad (1)$$

where, DI is the desired inventory level; I is the current inventory level; IAT is the inventory adjustment time.

The value of DI is determined according to the following expression;

$$DI = ForecastDemand * DIC \quad (3)$$

The desired inventory coverage time DIC is influenced by two time factors, that is, the minimum order processing time P_{min} and the safety stock coverage time SC to ensure acceptable market responsiveness;

$$DIC = P_{min} + SC \quad (4)$$

The inventory level I at time t is governed by production rate p and shipment rate s according to the following expression;

$$I = p - s \quad (5)$$

As for production control, the WIP level is influenced by the gap between workflow rate w and the actual production rate p . In addition, the desired WIP level

depends on the desired production rate Dp and CT . The WIP adjustment is controlled by the WIP gap between desired work in progress $DWIP$ and current WIP level. This can be modelled by the following expressions;

$$WIP = w - p \quad (6)$$

$$DWIP = Dp * CT \quad (7)$$

The WIP adjustment $AWIP$ is influenced by the WIP adjustment time WAT , $DWIP$, as well as WIP ;

$$AWIP = (DWIP - WIP) / WAT \quad (8)$$

The workflow rate w is set equal to the desired workflow rate which, in turn, is equivalent to the sum of WIP adjustment and the desired production. The desired production Dp is set to be equal to the sum of demand forecast and the adjusted inventory IA .

$$Dp = \max(0, ForecastDemand + IA) \quad (9)$$

Pertaining to the customer orders, the order fulfilment rate is equivalent to shipment rate, which is set equal to the desired shipment rate Ds . Thus, the desired shipment rate is a function of backlog B and shipment time ST ;

$$s = Ds = B / ST \quad (10)$$

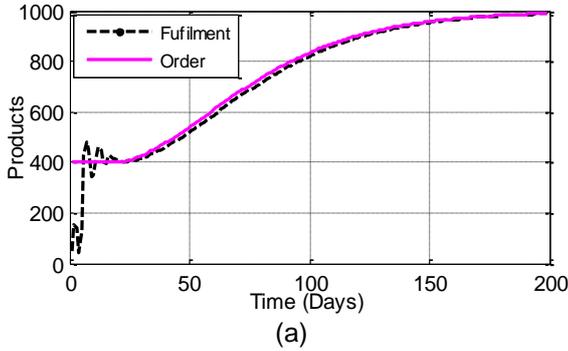
where, B is the difference between the order rate r and the order fulfilment rate f ;

$$B = r - f \quad (11)$$

The next section provides the simulation experiments, results and discussions.

4 SIMULATION RESULTS AND DISCUSSION

The base experimental set up was as follows: The simulation run time was set to 200 days. The shipment time (ST) and the cycle time (CT) were set at 3 days. The minimum order processing time and the safety stock coverage time were both set to 1 day. The simulation time step (DT) was set at 0.25. Figure 2 (a) presents the input demand (orders) used in the simulation experiments.



4.1 Base simulation results

Under the base scenario, the order *fulfilment* rate follows the *order* rate closely over the planning period. Figure 2(b) illustrates the dynamics of inventory and *WIP*. Inventory generally rises with increasing s-shaped demand and begins to stabilise after 100 days. Fluctuations at the beginning of the period are due to initial start-up or transient period of the system simulation.

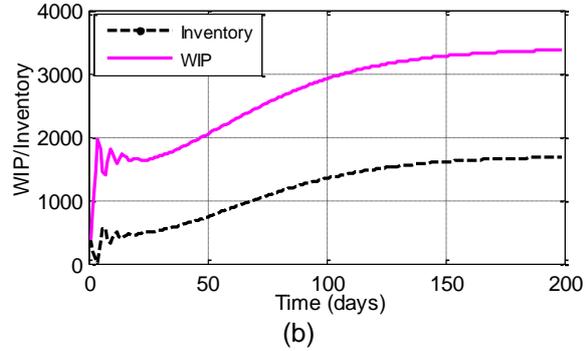


Figure 2 - Base simulation results.

4.2 Further what-if analysis

To analyse the impact of CT , IAT , and ST , a series of what-if experiments were carried out by varying each decision variable from 1 to 5, keeping other variables constant, while observing the behaviour of the system in terms of WIP and Inventory I .

Figure 3 shows the behaviour of the manufacturing system in terms of WIP and I . Part (a) and (b) show the results of the what-if analysis as CT takes values 1, 3 and 5. Unwanted fluctuations in both WIP and I are obtained when $CT > 3$. For $CT \leq 3$, the system behaviour is stable. Further experimentations showed that the best performance is always obtained when the system is synchronised, for instance, with $CT = ST = IAT = 3$. This agrees with the principles of JIT or lean production.

Figure 3 (c) and (d) demonstrate the sensitivity of the system for $ST = 1, 3$, and 5. For $ST < 3$, the system experiences a slight increase in WIP and slight decrease in inventory. For $ST > 3$, WIP decrease while *Inventory* increases. Therefore, a careful trade-off is needed to cautiously balance the impact of ST on WIP , *Inventory* as well as customer responsiveness.

Part (e) and (f) relate to sensitivity analysis based on varying IAT values. Changes to values of IAT to $IAT < 3$ induced extreme unwanted fluctuations in the manufacturing system, in terms of WIP and

Inventory. Moreover, it can be seen that the amplitude of fluctuations increase with demand growth. The most stable system response is obtained with $IAT = 3$. With $IAT > 3$, the system yielded lower *Inventory* when compared to the response obtained with $IAT \leq 3$.

We infer from the above results that a careful trade-off, from a systems point of view, is needed between agility and leanness, if the full benefits of leagility are to be obtained effectively. While agility may be obtained via structural system changes to the manufacturing system to gain flexibility, speed, and responsiveness, system stability may be affected resulting in unwanted inventories as shown by rising WIP and I values. This is especially so with a growing or fluctuating demand patterns, such as the s-shaped market demand. Furthermore, we infer from this simulation study that leagility, being a systems-based manufacturing paradigm, should be addressed from a systems view point, especially given that it embraces two paradigms: lean and agile systems. The most effective way will be to treat the two paradigms based on a systems thinking rather than silo approach. The proposed system dynamics approach is a useful tool to assist decision makers when transforming a manufacturing system from lean to leagile systems. It provides a deeper understanding for management so as to make informed decisions.

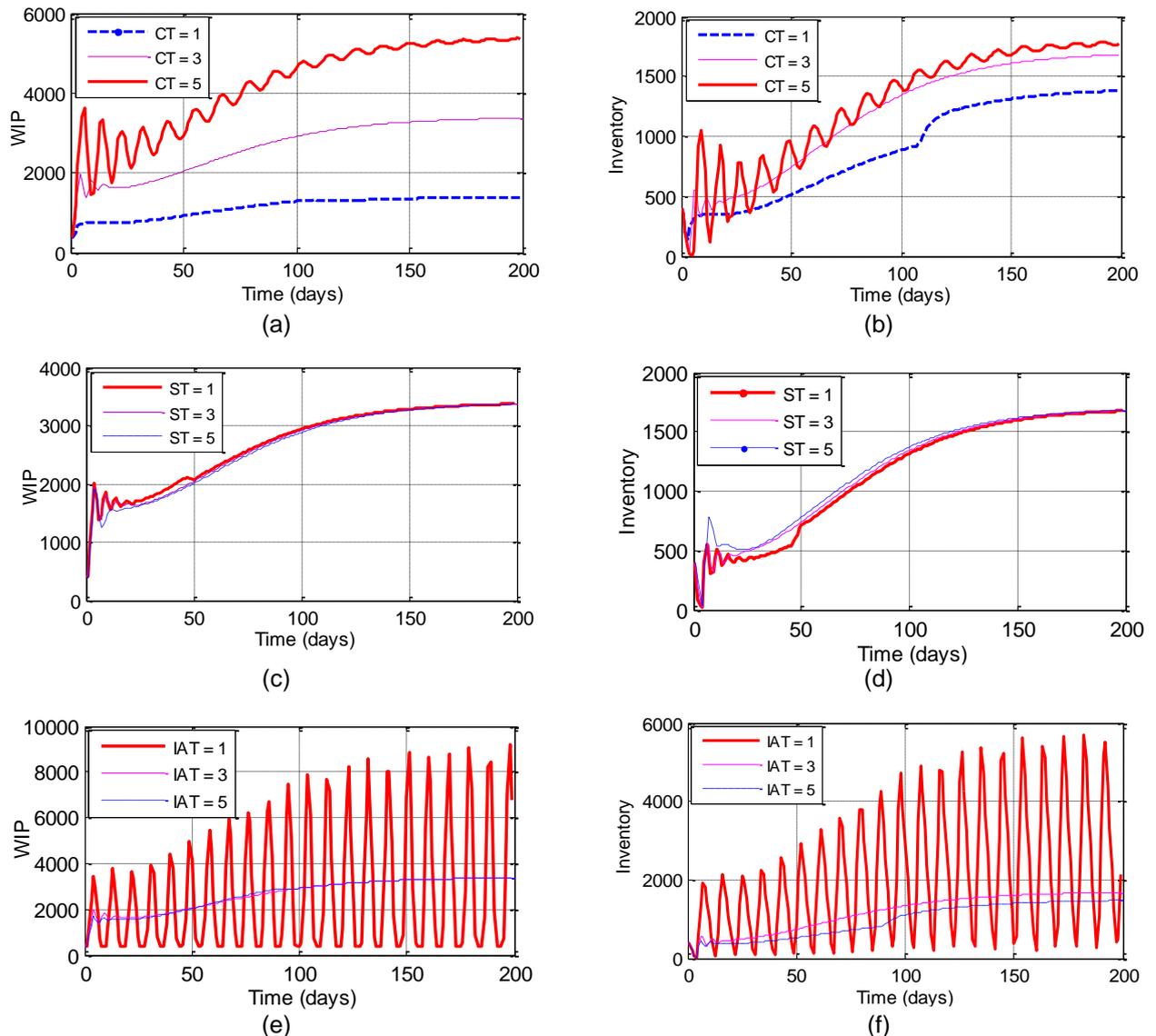


Figure 3 - Variation of *WIP* and *Inventory* with *CT*, *IAT* and *ST*.

5 SUMMARY AND CONCLUSIONS

Motivated by the need for in-depth understanding of the dynamics of lean and agile manufacturing systems, and the transition from a conventional to a leagile manufacturing system, this study examined the dynamics of a typical leagile system from a system thinking perspective. The concepts of lean and agility are implemented on the production and inventory control of a conventional system. Basic simulation analysis and what-if experiments are conducted in this study using assumed demand scenarios: stable demand and growing demand.

The following managerial insights were realised from this study:

- The application of lean and agile (leagile) concepts in manufacturing systems is beneficial. However, a cautious trade-off is required between lean and agile systems.

- A careful trade-off is needed between responsiveness to market demand and stability of the manufacturing system. High instability could introduce costly unwanted fluctuations in the system.
- In general, agility is most beneficial when demand is unstable, in a turbulent manufacturing environment. Conversely, lean is more beneficial with stable demand patterns.
- Conventional manufacturing systems should be transformed to leagile systems by making the necessary system structural changes first, followed by gradual application of lean principles, if full benefits of leagile systems are to be obtained.

Possible further research directions include simulation optimization of the model decision parameters

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7 BIOGRAPHY



Michael Mutingi obtained a Master of Industrial Engineering from the National University of Science & Technology, Zimbabwe. He is a lecturer at the University of Botswana. His research interest is in supply chain management and manufacturing systems



Charles Mbohwa has a Doctor of Engineering from Tokyo Metropolitan Institute of Technology. His research interests are in manufacturing systems and sustainability assessment. He is an Associate Professor at the University of Johannesburg.



Samson Mhlanga obtained a Master of Science in Advanced Manufacturing Systems from Brunel University, UK. He is currently a Lecturer at the National University of Science & Technology, Zimbabwe. His research interest is in rail crew management and manufacturing systems.