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Manufacturing system lean improvement design using discrete event simulation

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Abstract

Lean manufacturing (LM) has been used widely in the past for the continuous improvement of existing production systems. A Lean Assessment Tool (LAT) is used for assessing the overall performance of lean practices within a system, while a Discrete Event Simulation (DES) can be used for the optimization of such systems operations. Lean improvements are typically suggested after a LAT has been deployed, but validation of such improvements is rarely carried out. In the present article a methodology is presented that uses DES to model lean practices within a manufacturing system. Lean improvement scenarios are then be simulated and investigated prior to implementation, thereby enabling a systematic design of lean improvements.

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1. Introduction

Lean manufacturing (LM) practices are embedded in five core principles: i) determining the value of each specific product in the eyes of the end client; ii) identifying the value flow of each product; iii) making the value flow continuously; iv) letting the customer pull value from the manufacturer and v) seeking perfection [1]. Ensuring Continuous flow of the product within the manufacturing system supports the principles lean. A collection of lean practices such as just in time (JIT) supplier management, quality management (QM), Total Productive Maintenance (TPM), Lot Sizing, Leadership Commitment, Employee Involvement, Setup Reduction, Teamwork, Customer Engagement and many others make up a LM system.

Assessing the overall performance of lean through lean practices is typically done using a lean assessment tool (LAT). Various models have been applied as the basic structure of many LATs [2], such as Value Stream Mapping (VSM), Lean Enterprise Self-Assessment Tool (LESAT), Benchmarking, Lean Index and the Strategos LAT. Others have been used as the basis for a lean assessment audit [2]- European Foundation

for Quality Management and the Shingo Model. The uses of most lean audits and LATs have focused on two primary areas: a) assessing and benchmarking lean performance and b) identifying practices that should be the focus of improvement efforts [2]. Rarely are the lean audits used for investigating what the likely effect would be if the lean improvements were implemented [3]. So while the LATs would have identified which lean practices to improve and possibly how to improve them, little is known about how the proposed lean improvements will behave in reality. For example a lean assessment may identify JIT Supplies as one of the weak performing lean practices because raw material supplies are often delayed. The logical recommendation would be to reduce the supply lead-time, preferably to the “leanest” level possible, say zero minutes. While this is an improvement in the right direction, knowledge is still required as regards the effect this improvement will have on other lean indices and on the whole system. This knowledge is sought for two reasons. Firstly lean practices interact with one another and so there would likely be trade-offs in their improvements. Secondly an optimum level often exists beyond which further lean improvements do not have significant effect on the system- a waste in lean parlance.

For example, [4] found an optimum Kanban capacity in a manufacturing case, and increasing the capacity beyond the optimum level did not correspond to a significant increase in throughput. So in our above example with the supplier lead-time, it may be that the optimum raw material-delay is 30 minutes and going below this may not improve overall lean performance; meanwhile there may be additional cost implications going further. Majority of LATs used in the literature do not validate lean transformations before implementation [3].

The current study is motivated by the need to provide an objective approach to identify the extent of lean improvements after a lean assessment. Meanwhile [5] attempt to investigate this but their methodology was cost/budget-based. It is proposed in this article to advance an objective and quantitative based approach for predicting the likely impact of improvements in lean practices, and one way to achieve this is through discrete event simulation (DES) modeling. For the purpose of describing the approach, ensuring continuous flow within manufacturing system is the focus of the analysis.

2. DES modeling and lean assessment

DES is useful for gaining an in-depth understanding of a system to improve its performance. The DES software models distinct sequence of state changes that occur in time. In order words any system that involves a process flow where events change in time sequences can be simulated, for example a work item that flows through a manufacturing system. In a manufacturing system, the model takes into account the work items, resources and activities used in processing work items, their interactions and the constraints. Model objects (work items, resources, activities etc.) are configured (using input parameters such as work item inter-arrival times, work item routings, and activity processing times) in the DES to mimic the real system. Running the DES model establishes important details that may be otherwise concealed in the real system. In addition, experiments can be performed with the model, rather than with the actual system, and eliminate the need for costly real life experiments for example. These and other advantages of DES modeling have encouraged its use in lean related improvements.

There are previous works where DES modeling has been used to support lean system analysis [3,4,6,7]. Industrial cases have also been reported [see www.lanner.com; www.arenasimulation.com; www.simul8.com]. These and other DES/lean assessment studies have tended to focus on assessment by key performance indicators (KPIs) such as lead-time, Overall Equipment Effectiveness and works in progress (WIP). Yet, modeling lean practices is possible within the various building blocks of most DES software, such that the simulation can be used to provide information about the effects of altering and improving lean practices, while considering the trade-offs that exists between them. There is in fact more to DES/lean assessment relationship than just lean KPI analyses.

3. Problem definition and proposed methodology

Typically after a lean assessment is done, the next logical step is to improve lean, as the assessment would have indicated the directions of lean improvement through the weak performing areas. However, according to [3]

“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”

The above statement is true for majority of lean assessments that have been reported in the literature. The LESAT and other questionnaire-based (such as the Shingo Model and EFQM) lean assessment audits are typical examples. For example the LESAT is an audit questionnaire for self-assessing the performance of the current lean state of an organization vis-à-vis a desired lean state. Both current and desired levels are scored on a scale of 1 to 5 for a list of 54 lean practices, where 1 represents very limited awareness and use of lean practices and 5 represents recognized best lean practices [8]. Lean performance for the system is based on the gap between the current and desired levels of performance. The LESAT assessment indicates areas with substantial opportunities for growth (i.e. those with wide gaps) as well as areas for low perceived potential for growth (i.e. those with minimal gaps) [8]. The LESAT and other audit-based LATs share one deficiency: they do not validate the desired lean state. Analytical-based LATs have not been used to overcome this deficiency either, as majority of previous research works have not validated the future lean state.

[3] have proposed the five step simulation-enhanced approach to implementing LM (Fig. 1). The typical LAT such as VSM would cover steps 1 to 3. The focus of the current article is to look more closely at Steps 3 and 4 i.e. the future state design and validation. The proposed approach in the current article is summarized in Fig. 2.



Fig. 1 Simulation-enhanced approach to lean manufacturing [10]

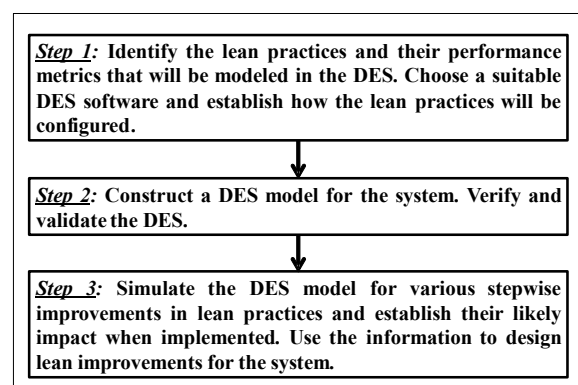


Fig. 2 Methodology steps describing the proposed approach for future state design and validation

In the proposed approach (Fig. 2) the future state design is achieved through a stepwise improvement in the lean practices. Continuous flow is one of the tenets of LM [1]. The 5-step methodology depicted in Fig. 2 is based on how lean practices affect the continuous flow of the product. Improving lean practices will improve continuous flow, which will inevitably enhance lean performance.

The methodology is intended to apply DES to lean assessment in a novel way by configuring various lean practices within the building blocks of the simulation model. By so doing, improving the performance of a lean practice can be simulated prior to its actual implementation. For example, JIT Supplier Management can be measured using the delay in raw material supplies. The delay in raw material supplies can be configured as a distinct activity within the DES model. The activity processing time is then used to represent supplier lead-times. By altering the process time for the activity, the effects of different supplier lead-times on the system can be simulated. The result can be used as the basis for setting the requirements for supplier selection and management.

For better description of the proposed approach depicted in Fig. 2, it is demonstrated in a processing unit of a print packaging manufacturing case. The plant has been implementing lean production practices for about two years. It has seven processing units- slitting, printing, gluing, lamination, cutting, pouching and packing. The printing process is the only process where as all work items must be routed through. Moreover an “enterprise” for assessment may be a unit [LESAT Facilitators Guide]. For these reasons and for the purpose of demonstrating the proposed approach, the printing process is sufficient alone to be used as the case example.

The printing department is fed by and feeds other processes. Sometimes there are material delays from downstream processes, while the printing process delays other upstream processes. There is process scrap, which is inevitable and is a function of setups, changeovers and machine breakdowns. Machine breakdown is a function of the frequency of routine maintenance on the machines. There are five printing machines, and one operator per machine. The other details of the process are described for the relevant aspects concerning the simulation and study objectives, and these are expatiated in the relevant sections following.

4. Description of the approach

4.1. Step 1: Choose suitable DES

After a series of lean audits undertaken prior to this study, the organization identified eleven aspects of LM that were to be the focus of improvement efforts. These practices relate to Setup Reduction, QM, TPM, Waste Reduction, JIT Supplies, Multifunctional Workforce, JIT Production, Workforce Commitment, JIT Customer Delivery, Leadership Commitment and Space Utilization. Leadership and Workforce Commitment like other important aspects of LM such as Information Systems, Quality Circles, Visual Controls and Improvement Suggestions may be difficult to simulate in a DES. The use of surrogate quantitative performance measures

is common within lean assessment [9] and these lean practices can be represented in the DES using surrogate metrics: in the current study, Leadership and Workforce Commitment have been modeled using surrogate measures.

Simul8 DES (www.simul8.com) was chosen for this study because it has been applied in many lean-related manufacturing cases (see case studies in www.simul8.com). In addition, the building blocks and architecture of Simul8 enable the aim of the current article to be realized in a simplistic straightforward manner.

To build the DES model, a flow chart of the process to be modeled is first presented (Fig. 3). There are multiple product types and customer orders are of various quantities and specifications.

Each job order is routed through the simulation as a distinct work item, but configured to replicate the different job order quantities.

The lean practices are configured in the DES in such a way as to use them as the basis or outcomes for scenario analysis. The following provides a better description of how the lean practices for the case study were prepared for modeling within the DES. The first eight are independent variables while the last three are dependent variables (they depend on the parameters of the independent variables). The scenarios of the dependent variables are determined by how the independent variables are modeled. For example, to model an improvement for lead-time (JIT Customer Delivery) various improvements need to be implemented on the independent variables such as shortening the setup or changeover time.

- **Setup performance.** For the manufacturing case, setup is a distinct offline manual operation that includes re-tooling. An activity named “Setup” is placed prior to the machine processing activity so that setup improvement can be modeled. The activity time is set to correspond with the different setup times.
- **Quality Management.** Process scrap arises when there is changeover or machine breakdown.
- **Total Productive Maintenance.** Mean Time to Routine Maintenance (MTRM) and Mean Time Between Failure (MTBF) are configured for machine processing activity. The intention of modeling both within the activity is to simulate scenarios to investigate their individual and combined impact on the system.

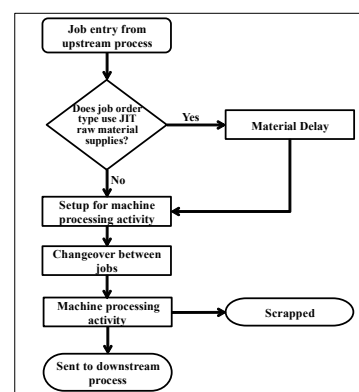


Fig. 3. Flow chart of building blocks for the DES model

- **Waste reduction (Motion waste).** One operator is assigned to both setup and machine processing activities. There is a travel time between both activities. A scenario can be simulated whereby the travel time is reduced for example the operator spends less time to look for tools for setup.
- **JIT Supplies.** The downstream processes are taken as the input supplier of raw materials to the printing process. Delays in downstream processes are modeled as one activity named “Delayed Materials”. The activity time is configured to mimic the various delay times.
- **Multifunctional Workforce.** The ability of resources (plant workers) to be available at multiple work centers (activities) is a measure of performance for a multifunctional workforce. In the current system, resources in the DES are assigned to specific work centers only. The more activities a resource can work at, the higher the lean performance measure for Multifunctional Workforce, as resources can be moved to activities that are starved of resources.
- **JIT Production.** Changeover is used as the measure for this. Changeover activities are associated with on-the-machine product change such as ink and reel change. Changeover times are dependent on sequence of product type entering the activity. Similar product types require no change-over time. A distinct activity named “Changeover” is placed between the Setup and Machine Processing Activity.
- **Workforce Commitment.** One worker operates one printing machine. An efficient worker processes work items at a faster rate than less efficient workers. The activity processing time is therefore used to model efficiency and commitment of workers.
- **JIT Customer Delivery.** Lead-time and percentage of deliveries that are late.
- **Leadership Commitment.** The degree to which managers in the organization are able to utilize the production equipment can be taken as the surrogate performance measure for this lean practice. Machine utilization is used to represent it in the DES model.
- **Space utilization.** WIP in queues are placed on the shop floor on pallets, thereby occupying production space. The less time WIP spends in queues, the better the space usage. The percentage of WIP that spend more than 30 minutes in queues is taken as the measure for space utilization.

4.2. Construct DES model

4.2.1. Model parameters

The inputs and outputs of the model are shown in Fig. 4. Discrete probability profile distributions were defined and used to describe the stochastic nature of most of the system parameters. Historical data spanning three months was used to generate the probability distributions and verified using two weeks of production data. Fig. 5 shows an example probability distribution for inter-arrivals for Product Type 1: there is an 80% probability that inter-arrival time will approximate 54 minutes and 20% probability that it will be 120 minutes. The probability profiles enabled a better description of events and

timing for the case than standard distributions such as the normal, uniform, triangular or exponential distributions.

4.2.2. Assumptions for the DES model

The model assumptions were as follows:

- Scheduling rule is always first-in-first-out. In the real plant under study, this rule applies to majority of work items in queues.
- The system is modeled for peak demand levels. It is assumed that a manufacturing system that performs well in peak demand will also perform well in low demand.
- The correlations between MTRM and MTBF are known. The plant decided to use this as a motivation for carrying out routine maintenance on a regular basis. In reality routine maintenance will elongate the times between breakdowns but the exact duration is probabilistic.

4.2.3. Verification and validation of the DES model

A warm-up period corresponding to four weeks of work was used to populate the model with work items and minimize the effects of initialization bias [10]. Model run time was set at three months to generate enough data to improve the data confidence. The model behavior was verified using different input parameters. 100 replications [10] using different random number generators were used to validate the model. Fig. 6 is a snapshot of key aspects of the model build.

4.3. Simulate the DES for various scenarios of lean improvements

Identifying lean improvement scenarios was based on a stepwise approach. The parameter specifications for a desired future lean state (S_D) were initially set by the organization as being achievable within six months. The specifications are as follows:

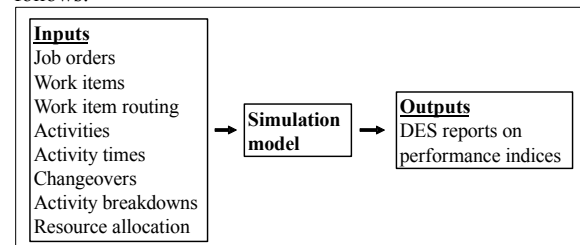


Fig. 4. Main inputs and outputs of the DES model

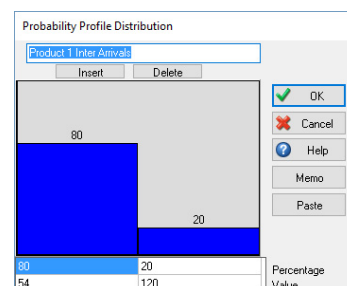


Fig. 5. Discrete probability profile for inter-arrival times for products into the system

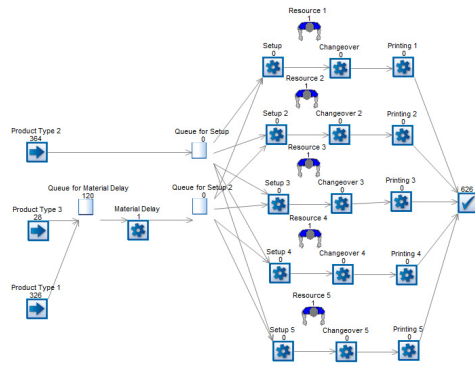


Fig. 6. Snapshot of the main window showing the model components

4.4. Simulate the DES for various scenarios of lean improvements

Identifying lean improvement scenarios was based on a stepwise approach. The parameter specifications for a desired future lean state (S_D) were initially set by the organization as being achievable within six months. The specifications are as follows:

- **Setup time:** This is reduced by 100%.
- **Process scrap rate:** No changeovers between different product types.
- **MTRM and MTBF:** Increase routine maintenance from its current level of random occurrences to daily, while MTBF is set to an average value of 10,000 minutes. The assumption is that if maintenance checks are done routinely every day, then average time between breakdowns will be 10,000 minutes.
- **Motion waste:** The distance between the machine and offline setup is eliminated, by placing them close to each other. The travel time for this is approximately minute for a to and fro journey
- **Supplier lead-time:** This is reduced to zero minutes so that there is no delay in raw materials. This is achievable if downstream processes are improved.
- **Resource use:** Resources are configured to be available at all locations to mimic a multifunctional worker. By so doing, activities need not wait for a specific resource that is normally associated with it.
- **Changeover time:** This is reduced by 100%.
- **Activity processing time:** A machine operator can at best process at the theoretical fastest speed of the machine, which is 40% faster than the current processing times.

A cursory observation of the system and the model indicated that each of the above lean improvements could not be done in isolation. For example, if the downstream material delay is not improved, products are not fed “continuously” into the setup activities. So improving setup alone for example will not improve the other lean parameters such as average lead-time and utilization of the printing machine. Yet another trade-off envisioned is when activity process time is increased. There will be a build-up of queues if the resources (workers) are not multifunctional and available at multiple activities, at the right time. Experimenting with the model confirmed these and other

trade-offs. It will be a “waste” to attempt to improve only one lean practice in isolation. Based on this knowledge, an experimental scenario was initiated where all the lean practices are improved simultaneously, to the desired levels. Table 1 is a comparative analysis of the current situation (S_C) and the experimental scenario (S_D). Fig. 7 is the model showing the re-routing of similar work items so that changeovers are minimized, and process scrap arising from changeovers is reduced.

Table 1. Comparison between current lean state and future desired lean state

	Current Situation	Desired lean parameters (S_D)
Independent Parameters		
Setup	Current plant values	Reduce by 100%
Changeover	Current plant values	Reduce by 100%
Routine Checks	Random infrequent	Routine once monthly
Breakdown	Uniform between 2,000 and 2,500 minutes	Average 10,000 minutes
Operator Travel	7 minutes	1 minute
Material Delay	Current plant values	Zero
Worker Allocation	One printing unit	All printing units
Dependent Parameters		
Process scrap	15.30%	5.50%
Motion Waste	4%	0%
Average lead-time in days	$\mu=4, \sigma=4.5$	$\mu=0.2, \sigma=0.12$
% Orders that are late	41%	0%
% WIP that overstayed in queues*	57.80%	3.60%
Average machine utilization	49.00%	36%

*All queues including material delays and those for setup.

The single scenario analysis provides only one extreme solution based on the desired lean target, but there are various improvements that can be achieved between the current state and the desired lean state. The DES was simulated for various stepwise improvements in lean practices. Fig. 8 depicts improvements in lean practices for two additional scenarios (S_1 and S_2) where $S_C < S_1 < S_2 < S_D$ in terms of improvements in lean practices. The parameters of the independent variables for S_1 and S_2 were set at 50% and 70% improvements respectively over S_C . In reality, the variables would improve at different rates and can be simulated using the model.

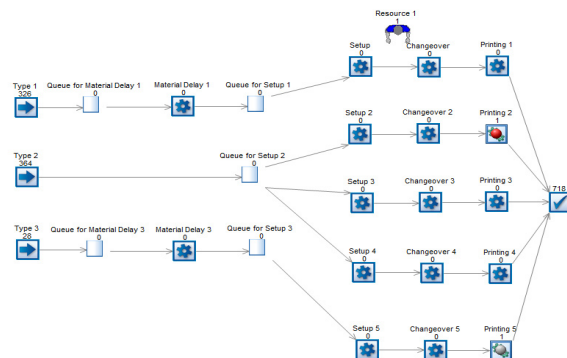


Fig. 7. Snapshot of the main window showing model for desired future lean state

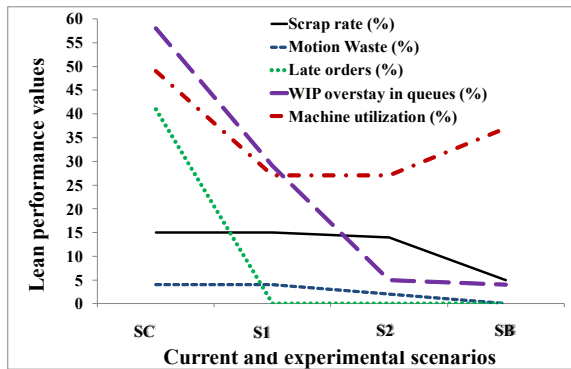


Fig. 8. DES results for current and experimental scenarios

5. Discussions and conclusion

The simulation results (Fig. 8) of the DES model provided useful information for validating improvements in lean practices prior to their actual implementation. A few examples are discussed herewith.

Until changeovers between different work types are completely eliminated, there is no significant reduction in process scrap rate. Re-routing of work types helps to eliminate work type changeovers and this did not affect other lean indices such as lead-time and WIP build up.

Beyond S_1 , lead-time and on-time deliveries do not show any significant improvement. Experimenting with the model indicated that material delay was the main contributor for long lead-times and late deliveries. Material delay was improved by 50% from S_C to S_1 ; so improving material delay further than 50% of the current levels will be unnecessary. If there was to be a single-objective optimization problem, say for lead-time, then the parameters corresponding with S_1 are the optimal set of improvements that need to be undertaken. However for an overall-lean performance (the type assessed using a lean assessment tool), there are multiple objectives in conflict that may need optimization. A multi-objective optimization solution is beyond the scope of the current article, but is achievable with the current model, using OptQuest in Simul8.

In S_D , routine maintenance was initially set to occur on a daily basis for 30 minutes. This affected the customer delivery lead-time as machines were stopped too frequently for maintenance checks. Routine maintenance was then set at once every month for a longer duration of 90minutes, and lead-time was improved. This information helped the company to implement less frequent but long-duration comprehensive maintenance.

Machine utilization remains unchanged for S_1 and S_2 and drops for S_D . Experimenting the DES at the desired lean state (S_D), showed that the system coped well with four printing machines.

Other simulation experiments were conducted using the above scenarios and optimal levels as reference points. The optimal level is that point where a significant improvement has no commensurate positive effect on other lean indices. The information obtained enabled the following design in lean improvements in order of priority and sequence:

- Improve JIT Supplies and Workforce Commitment (operator efficiency) by 50%, which also improves performance of JIT Customer Delivery for all product types from 4 days to approximately 2 hours. This is plausible because only two out of the three product types experience material delays from downstream processes, and account for only about 15% of total production. Space utilization is also improved
- Performance of Quality is improved through a 178% reduction in process scrap rate. This is achieved by: a) re-routing work items to eliminate changeovers and b) improving the performance of TPM through monthly maintenance of machines.
- Setup and JIT Production (changeovers) performances are improved by 50%
- Eliminate motion waste by moving off-line setup activity closer to the machines
- Improve Workforce multi-functionality by enabling machine operators to be available at all work activities (setup, changeover and machine processing)
- Leadership commitment to lean is improved by running the plant with one-less printing machine. This will improve machine utilization by approximately 20%

The methodology described in the current article as well as the results of the case study demonstrate that lean practices and their performances can be simulated for improvement purposes. This is a value add-on to LATs so that they can generate more information than they currently do.

No stand-alone methodology provides a panacea to solving a problem. In effect the results generated from the method advanced in this article should not be used exclusively. In addition, the reliability of a single-case study cannot be used to generalize a solution. Based on these, more case studies modeling a wider set of lean practices within a larger system (such as the entire organization) are needed.

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