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Assessing Lean Systems Using Variability Mapping

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Abstract

A new approach to assess lean manufacturing based on system's variability is proposed. The assessment utilizes a new tool called variability source mapping (VSMII) which focuses on capturing and reducing variability across the production system. The new tool offers a new metric called variability index to measure the overall variability level of the system. Based on the mapping and the new metric, VSMII suggests a variability reduction plan guided by a recommendation list of both lean techniques as well as production control policies. An industrial application is used to demonstrate the new tool. Results show that VSMII managed to reduce the overall variability level of the system as well as non-value added activities. Finally, the new variability index was successfully applied as a leanness assessment metric.

Keywords: Variability; Lean Manufacturing; Assessment

1. Introduction

Lean Manufacturing is a manufacturing paradigm based on elimination of wastes. The lean approach to eliminate wastes is to capture non-value added activities and work to reduce or totally eliminate them. Toyota's Taiichi Ohno, the lean manufacturing pioneer, describes this saying: "All we are doing is looking at the time line from the moment a customer gives us an order, to the point when we collect the cash. And we are reducing the timeline by reducing the non-value added wastes [1]". The typical tool used to capture value added and non-value added activities and applies what Ohno said is the value stream mapping (VSM). VSM is a mapping tool that is used to map the production process. It maps not only material flows but also information flows that signal and control production.

Although focusing on value (with its relative interpretation) and waste elimination is a fundamental way to improve manufacturing systems' performance, however, this can lead to the overlooking of another fundamental approach that fulfills the same goal. This second approach is variability elimination. One can argue that variation is another source of waste that will be captured by the current lean manufacturing tools and techniques. However, the current practice of lean implementation shows that most of the lean tools focus on reducing time and material through techniques that rarely capture variability and try to eliminate its different sources. For this purpose, this paper presents a new lean manufacturing tool that complements the current VSM and tries to capture variability sources across the time line of the production process. The new tool is called variability source mapping (VSMII) and having the Greek number two to differentiate between the new tool and the current VSM tool.

Variability is the enemy of manufacturing and the source for many of its problems. Lower throughput, congestion, high WIP levels and longer lead times are some examples of variability impact on production systems performance [2]. Variability at a manufacturing station can be due to processing time variability, machine availability, rework activities (bad quality) and setup times. A distinctive characteristic of variability in manufacturing systems is that it propagates along the system [3]. Thus the variability sources do not only cause variation of process times at the production station, but also variability propagates to next stations

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downstream and usually in an amplified manner leading to what is known as flow variability. Under such variability and with the uncertainty associated with these conditions, one can figure out the complex task of production planning and control and how to improve it. In addition, delivery reliability and customer service become a core issue with variability problem.

Typically lean campaigns would approach controllable variability sources (rather than random or natural variability) in the systems and try to reduce or eliminate them in order to achieve sustainable improvement. However, all current available lean tools focus on the first order measures of variability (like throughput and WIP means) and do not consider the second order measures of variability (like throughput and WIP variances). This usually lead to partial improvement in terms of variability reduction since the main behaviour of variability is not well captured. Thus there is a need to complement the current lean improvement tools with a tool that can capture variability sources, measures variability and offers solution to manage such problem. This tool will also act as a beneficial metric that will help in the lack of available leanness measurement metrics problem. The VSMII tool is proposed to fulfill these two needs

2. Literature Review

Among the early attempts to capture the productivity variability was the work of Miltenburg [4] to model variation in the produced parts of a transfer line with buffers. He presented a numerical technique to evaluate this variability. In [5] and [6] an analytical technique for throughput variability in a serial production line with unreliable machines was developed together with its numerical implementation.

Gershwin [7] presented a new formulation for the same productivity variability problem in serial line. The formulation was based on the exact calculation of the production variance for a single machine with the Markovian reliability characteristics and a decomposition technique for longer lines. These ideas have been extended in [8] using simulation of both no buffer and finite buffer cases. An attempt to quantify throughput variability through theoretical characterization of analytical bounds for same formulation was developed in [9]. They showed that longer lines reduce production variability.

An approximation method to estimate variance of output from cyclic exponential queuing systems was presented in [10]. The work was extended in [11] to study the variability of the output from a line controlled by constant WIP to determine the production quota, which is an important decision to operate a production line effectively. He et al. in [12] presented an approximate approach to determine production variability, which includes the variance of the number of parts produced in a given time period and the variance of the time to produce a given number of products. They proposed basic relationships between system parameters and production variability.

Tan [13] provided an efficient algorithm for the production variance evaluation in a two-machine lines with any capacity of the intermediate storage.

Variation in the quality level of the manufacturing system was modeled in [14] using statistical relationships between product's quality measurement parameters. These parameters are used to rank the impact of each stage on the product's variation and thus guide management to optimal investment locations. The variation propagation in multi-stage production with multiple products was modeled and analyzed in [15] with the objective decreasing system's complexity.

The reviewed approaches demonstrated successful methodologies to capture part of the variability problem in manufacturing systems, mainly throughput variability followed by quality variability. However, the main problem with these approaches is that they are numerically intensive, which precludes the analysis of systems with many machines and large buffers. Also, and within the same practical line, lean practitioners would favour much less computational metrics to measure and assess variability. In addition, most of the reviewed approaches depicted variation in the overall throughput or productivity only and did not offer a stage by stage mapping of variability which is critical for different lean operational improvement tools. The VSMII tool will offer a practical approach to capture both overall variability of production system as well as a stage by stage variability level across production line

3. Variability Source Mapping

The new VSMII tool is designed to be simple and informative as the original VSM and also to align with the applicability merit of all lean tools. VSMII is based on the following six steps and explained in further detailers in this section:

1- Select product family
2- Map the process as well as the information flow
3- Capture (measure) variation in terms time and flow
4- Identify variability level and high variability locations
5- Set new target system's variability level and improvement plan
6- Implement variability reduction plan (VRP)

3.1. Step 1: Select product family

Deciding on the focus and scope is an important initial step to any improvement approach. Do not try to understand and map everything that is happening in the factory. Instead, map the variability sources for one product family at a time. A product family is a group of

products that pass over the same or similar process steps and equipment.

3.2. Step 2: Map the process and the information flow

. As in typical value stream mapping, this step will map all the processes, transportation and waiting times/locations for the selected part family. In addition, the information flow (customer orders, production authorization…etc) between upstream and downstream is also mapped. The mapping process in VSMII will follow the same icons and notations of the classical VSM. The objective of this step is to visualize and understand the process/information flow at the operational level

3.3. Step 3: Capture variation in terms of time and flow

Starting this step, VSMII will differ from the classical VSM. The later capture information concerning the cycle time, uptime, number of workers, and most important value added and non-value added times for each process or stage along the production stream. However, since VSMII is to complement classical VSM, the data captured in the data box at each station or stage is different. In VSMII it is required to calculate the following:

- The mean cycle time of each stage or station. This will require multiple readings (samples) in order to calculate the average time taken by the job over this stage or station. The mean estimation is done using the unbiased estimator shown in equation 1 where CTi is the reading of the cycle time of the stage or station at reading i and n is the number of readings observed.

$$\mu_{ct} = \frac{\sum_{i=1}^{n} CT_i}{n} \qquad (1)$$

- The standard deviation of the cycle time of each stage. Typically the standard deviation designates the distribution or spread about the average of any process. Thus it is used in VSMII to estimate variability in cycle time using the estimator shown in equation (2).

$$\sigma_{ct} = \sqrt{\frac{\sum_{i=0}^{n} (CT_i - \mu_{ct})^2}{n}} \qquad (2)$$

- The coefficient of variance for cycle time of each stage or station. The standard deviation reflects absolute variability. However, with systems involving different stages and stations, relative variability becomes more important in both capturing the overall system's variability as well as comparing different variability sources for reduction plans. Coefficient of variance (CV) is a reasonable relative variability estimator and shown in equation (3) where the subscript ct denotes that this is the CV for cycle time at this stage or station.

$$CV_{ct} = \frac{\sigma_{ct}}{\mu_{ct}} \qquad (3)$$

The mean time of arrivals between stations or stages. The variability at one station or stage can affect the behaviour of the other station in a line by what is known as flow variability [2]. If an upstream station or stage has high variable cycle time, the flows it feeds to downstream stations or stages will also be highly variable. VSMII captures this flow variability through measuring the variability in the mean time between arrivals. The flow variability can also be measured by arrival rates (jobs per unit time) at a station or a stage and then calculating the reciprocal of that rate to have the mean time between arrivals. To calculate the mean time between arrivals at each buffer location, multiple readings are observed and then averaged using the same mean estimator in equation (1).

- The standard deviation of time between arrivals. This is calculated in the same manner as the cycle time variation and using the same estimator in equation (2).
- The coefficient of variance of the inter-arrival time. The relative flow variability of each station or stage is also measured using coefficient of variance. Equation (4) shows how to calculate CV for flow variability with subscript f to denote that this measure refers to flow variability.

$$CV_f = \frac{\sigma_f}{\mu_f} \qquad (4)$$

It is important to note that this step is crucial in the development of the new VSMII tool. The accuracy of the required measurements will affect the efficiency of the tool as well as the generation of a practical variability reduction plan. As in a typical production environment, this accuracy will be faced with the challenge of balancing between having enough data (multiple readings) and being fast and practical compared to the original VSM tool. Lean practitioners need to realize that since variability is the number one enemy to manufacturing, it is worth the extra time and effort required to capture it. In addition, this time and effort will be paid off by the amount of wasted time and bad quality eliminated or reduced as a result of better managing variability of the system.

3.4. Step 4: Identify variability level and high variability locations

The data gathered as well as the calculated measures from the previous step will be used in this step for two main objectives. The first objective is to develop an overall variability metric for the system. The second objective is to direct the lean planner to set priorities in terms of variability reduction plan for stations or stages

with high CV values.

VSMII offers a new and simple metric for overall variability based on averaging both cycle time variability and flow variability across the production system. The new metric is called variability index (VI) and is shown in equation (5). The dimensionless property of the coefficient of variance allows us to add up the various CVct across the s stages or stations and various CVf across the m buffers in the system and also having a weighted sum for both types of variability.

$$VI = \alpha\left(\frac{\sum_{i=1}^{s} CV_{ct_i}}{s}\right) + (1-\alpha)\left(\frac{\sum_{i=1}^{m} CV_{f_i}}{m}\right) \quad 0 \leq \alpha \leq 1 \qquad (5)$$

Where: s is no. of stations or stages and m is the no. of buffers. It is important to note that setting the value for α depends on the lean practitioner intent to focus more on either type of variability or have an equal focus on both of them by setting $\alpha = 0.5$. In addition, VI is considered an important contribution associated with the proposed lean tool not only by offering a simple and practical tool to capture an approximate value for the variability level of the system, but also to act as a leanness metric. As will be discussed in step five, VI will be used to track improvements in variability level before and after implementing lean tools.

The final activity in this step is to highlight and put a list of the high variability locations across the system (based on the recorded CVct and CVf). This list is important in the analysis required to generate the variability reduction plan since both the magnitude and the location of the variability source impact the overall level of the production system variability

3.5. Step 5: Set new target system's variability level and improvement plan

The output from the previous step will lead lean practitioner to set a new target for a lower VI and to start focusing on major sources of variability through a variability reduction plan (VRP). It is important to note that the mechanisms used to achieve the new VI target are mainly lean tools and principles. However, VSMII will divide the required actions to achieve the new VI target into lean tools actions and production control actions.

Lean tools to reduce variability include:

- Improving the up time (availability) of the production stage or station using total productive maintenance.
- Reducing the setup times within the production station or stage using (SMED) techniques.
- Reducing rework activities by improving quality using mistake proofing approaches.

Production control actions to reduce variability include:

- Adjust utilization level at high variability sources.
- Investigate batching policies implemented.
- Change location of high variability sources.
- Use buffers if needed.
- Share information from downstream to upstream.
- Reduce variable routing

3.6. Step 6: Implement VRP

As in the classical VSM, VSMII will display the different VRP actions and improved VI value through a future VSMII plan. The implementation will follow the actions displayed in the future VSMII plan within a time line set by the VRP team. The proposed variability index will be used to track the impact of the implemented action. It is expected that many of the actions in the VSMII future plan will be identical to those of the future VSM plan when it comes to adopting lean tools. However, many of the control based actions will be added to VSM actions and can even sometimes compete with those actions

4. Case Study

To demonstrate the proposed VSMII tool, a real production process was analyzed and a variability reduction plan was developed and implemented. This application was carried out within a slug bracket stamping and assembly manufacturer. Production process for this product family involves stamping a metal part followed by welding and subsequent assembly. The components are then staged and driven to final assembly on a daily basis

4.1. Current variability sources map

After deciding on the bracket product family (titanium fastening bracket subassembly with two types), the current variability source map, or current VSMII, was developed. The development included mapping the production process and gathering the following data:

The mean cycle time for every stage based on sampling plan, the average up time (UT) for every stage, the change over time (CO) for every stage, the inter-arrival time between stages (multiple visits were conducted) and finally buffer capacity and batch sizes between stages. The current VSMII is shown in figure 1

4.2. Variability measurement:

The first variability measurement was to calculate the standard deviation for both the cycle times at each station and the inter-arrival time between stations using equation 2. This was followed by calculating the coefficient of variance of cycle time for every stage (CVct) and coefficient of variance of flow between stages (CVf) using equations 3 and 4 respectively.

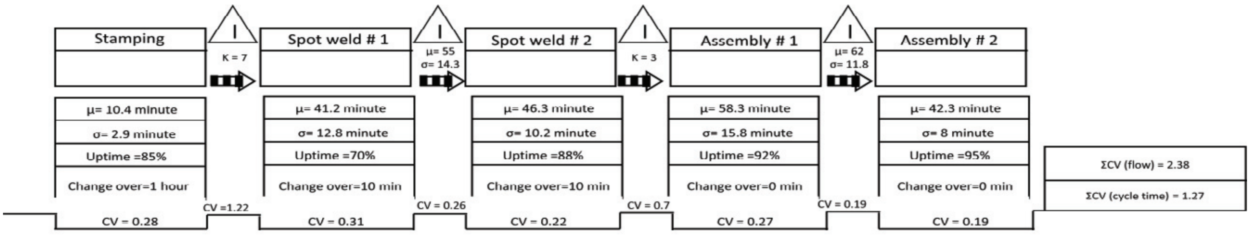

Fig. 1: Current VSMII

However, since the current production policy employs batching between stages and the system has serial unidirectional flow, CV_f at these buffers can be calculated using equation (6).

$$CV_f = \frac{\sqrt{(k-1)}}{2} \qquad \text{where k is the batch size (6)}$$

It is important to note that respective CV_{ct} values are recorded on the current VSMII at the lower part of the variability time line that moves across the process while the respective CV_f are recorded at the upper part of that line as shown in figure 1. Based on the values of both CV_{ct} and CV_f and manipulating equation 5, the variability index (VI) for the current system (with α = 0.5) was found to be:

$$VI = 0.5\left(\frac{1.27}{5}\right) + 0.5\left(\frac{2.38}{4}\right) = 0.43$$

The current VSMII shows that highest variability occurs at the buffer between the stamping stage and the first spot welding station. This is followed by the variability at the buffer between the second spot welding station and the first sub-assembly station. Finally the highest variability in terms of cycle times was witnessed at the first spot welding station followed by the first sub-assembly station. These observations captured form the current VSMII will constitute the priority list for the variability reduction plan

4.3. Developing Variability reduction plan

The lean practitioners at the company decided to reduce the variability of the current system, and set a target to achieve a VI of 0.3 (i.e. 30% reduction in current variability). A variability reduction plan was set as follows

1- The two assembly stations have a high uptime and can be combined together. A Kaizen group was formed to work on two things, first improving the up time for the first station to match the second one. Second studying how a continuous flow can be achieved between the two stations to eliminate the small buffering between them.

2- The buffer between the stamping stage and welding stations was to be replaced by a super market with a smaller buffer. Controlled supermarkets (with designed kanban cards) will have CV_f =0. Thus the flow variability with this setup will be function in the new smaller buffer size that was set to hold only three trays.

3- Investigating the processes carried out in both spot welding stations showed that the two stations can be switched. Since station 1 experience more variability than spot welding station 2, pushing it further downstream will enhance the overall variability reduction.

4- Since, spot welding station 1 experience high variability level, the team decided to lower the utilization of that station a little bit from 95% to 90%. This will increase the cycle time of the station; however, it will be still lower than spot welding station 2 and thus will not affect the effort for production levelling to takt time. Reducing the variability of this station will allow decreasing the buffer size between spot welding and sub-assembly stages (from 3 to 2 trays).

5- The up time for spot welding station 1 was planned to be improved via a kaizen group implementing some of the lean TPM techniques. Although this will increase the utilization of that station which contradicts the previous action; however, this will decrease variability in cycle time due to machine failure rates.

6- The changeover time for the stamping station was targeted to be reduced utilizing SMED technique

4.4. Implementation of the VRP and the new VSMII

The VRP plan was implemented over a period of 6 months and the VSMII of the improved system is shown in figure 2. The overall VI after VRP implementation was 0.32 (26% reduction in the original variability level) which is close to the target set by the improvement team.

It is important to note that the improvement in variability level (26%) could sound much smaller than that achieved if we focus on reduction of non-value added activities through VSM (usually between 70-80%). However, as mentioned earlier, VSMII complements VSM and also most of the VRP activities reduce a lot of non-value added activities within the system.

In this specific case study, the VSM of the original system showed that the ratio of the non value added time to the value added time was 18.2 days/199 min. The VSM upon the implementation of the developed VRP only showed that ratio became 6.3 days/152.2 min. This can be rewritten as follows; 26% reduction in variability lead to 65% reduction in non value added time and 24% reduction in lead time. These improvements are to be added to other improvements gained by variability reduction like lower WIP level and shorter cycle times.

5. Conclusion

Increasing variability always degrades the production system performance. Thus variability reduction is central to improving production systems and should be among the core activities of lean practitioners. This paper presented a new tool (to be added to lean improvement tools) dedicated for variability capturing and reduction.

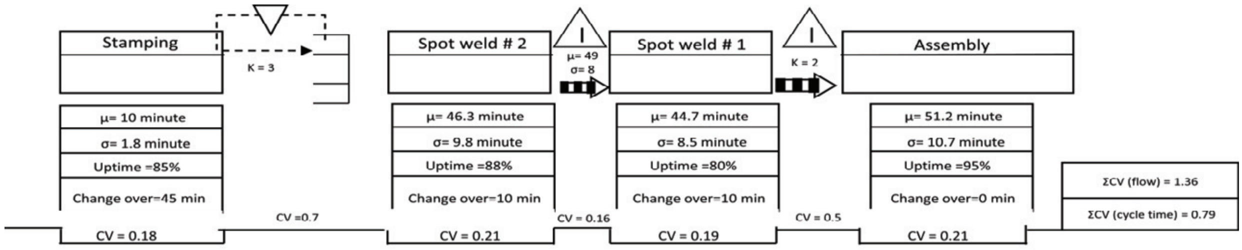

Fig. 2: VSMII of improved system

The variability source mapping VSMII complements the existing value stream mapping VSM tool through focusing on measuring variability sources and offering different techniques to reduce variability. This is done through a practical and structured approach and via a variability reduction plan (VRP). In addition, the new approach is less computational exhaustive than the existing mathematical based variation measurement models. This serves the core advantage of lean systems tools' practicality.

VSMII offered a system variability metric called variability index (VI) based on a weighted average of the overall cycle time and flow variability. VI is used to track improvements achieved due to the implementation of VRP. However, it can also be used as leanness metric to measure the overall leanness of the production system from a variability perspective.

The application of the proposed VSMII to an industrial case study revealed that:

1- The new tool succeeded in capturing various variability sources in the production system and helped to reduce the variability level from 0.43 to 0.32 (26% reduction) on the VI scale. This was achieved through implementing various improvements techniques as outlined by the VSMII variability reduction plan.

2- In addition to the normal gains of variability reduction to the system like less WIP level and better utilization, the VRP actions also lead to reducing non-value added time (by 65% in the considered case) and lead time (by 24% in the considered case).

3- Sometimes a trade off decision is required by lean practitioners when attempting to reduce variability. In the considered case study, it was shown that at the stage where variability could not be highly reduced, lowering the utilization level was adopted to mitigate that variability. Such action will adversely affect the overall lead time; however, the gains from variability reduction will pay-off this drawback as long as the increase in the lead time is not significant (less than the takt time).

As in the case for many new tools, VSMII is facing many improvement challenges including:

- Reducing the time required to capture variability data and calculating the coefficient of variance for both cycle times and flow.
- What other analytical/practical approaches can be used to measure variability other than the second moment of variation (μ and σ)?
- What are the ideal values for the developed VI?
- How can lean practitioners decide on the value of α?
- What is the impact of including variability due demand fluctuations into VSMII measurement step?

Tackling these challenges and answering the above questions is the subject of future work. In conclusion, it is time for the lean manufacturing paradigm to take the next step by not only recognizing the power of variability reduction but also offering more comprehensive tools to capture and manage that problem. VSMII is an attempt in this direction

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