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Managing Variability in Production

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Abstract. The corresponding author worked for many years with Toyota coaches, supporting Bosch in the development of pilot value streams for the Bosch Production system. The coaches spent considerable time and effort to analyze and decouple production from customer fluctuations and to stabilize the flow of production with adequate inventory buffers and capacity. The project team, on the other hand, was impatient, wanting to redesign lines, install Kanban and perform Kaizen activities. They did not understand that their coach was reducing unevenness and overload, so called Mura and Muri, striving for basic stability, as a precondition for lean activities. Later, they denoted a line possessing this basic stability in Bosch as an “improvable system”. In this paper the authors develop methods to analyze and reduce variability in value streams. The value stream is divided into zones, which are then qualified as stable or unstable. Measures are introduced to turn unstable into stable zones, step by step, enabling sustainable improvement activities in those stabilized zones. An IT system is developed to acquire and process the vast amount of data needed for variability measurements, and to provide structured information to support the management of variability in production.

Keywords: Lean Production, Variability, Value Stream Mapping.

1 Introduction

Implementing lean is still a major challenge for companies around the world. Over the years, companies took many steps from applying lean as a toolbox to a management system, guided by lean thinking and leadership. However, outside of Toyota, expectations in terms of quantifiable results are often not met [1].

The Toyota Production System (TPS) is still the benchmark for lean practices and results [1]. These are achieved by Kaizen activities through involving all employees. Production at Toyota is based on a clear and distinct flow of information and material [2]. The scheduled delivery time of cars allows the leveling of customer demand and decoupling customer order variability from production. Inventory buffers compensate

for the remaining variability within the flow of products. This setup enables the stable execution of standards, as a precondition for Kaizen activities [3].

Production beyond cars is often characterized by variants with a wide range of work content, multiple product paths and equipment options, which are often automated. The demand fluctuation is high, combined with short or no delivery time to the customers [4]. The result is high variability in the flow of products, which cannot be compensated by a feasible amount of inventory. Standards cannot be maintained and shopfloor personnel is busy with continuous rescheduling of production and firefighting, with little time and prospect for sustainable Kaizen activities. Analyzing and reducing variability becomes the major challenge in such value streams. However, variability has many sources, the effects of which can be felt all along a value stream. A systematic approach is needed to identify the sources of variability and to determine the areas and activities with the highest reduction leverage to stabilize production step by step.

In a steady flow system, meaningful results are attained by measuring variability on a single spot over a limited period of time. Managing variability in an unstable system, requires continuous, discrete time measurements at many points in the value stream, as well as information on the product identity. Unlike in steady flow systems, the vast amount of data required demands the automated acquisition, processing and presentation of information to support appropriate conclusions and decision making of management. In the context of Industry 4.0, the availability of production data is growing rapidly, allowing its capture continuously along the flow of products.

In this paper, the fundamentals on the influence of variability in production are identified and discussed in section 2. Section 3 then describes the classification of value streams into ordered and unordered systems. In section 4 a concept is introduced to divide a value stream into ordered and unordered zones and to reduce variability in unordered zones. This concept is then discussed in section 5. A summary and an outlook on the application of the concept in section 6 conclude this paper.

2 Related work

JIT and Jidoka are the pillars of the TPS (Fig. 1). Jidoka is defined as the safe failure of machines, prohibiting the passing of defects from their point of occurrence to following processes [5], and also the prevention of defects through effective quality management.

Dealing with Variability in Quality is a widely covered topic, from SHEWHART's statistical process control in the 1930's [6] through six sigma initiatives [7] and the management of quality assurance [8] to current approaches which are evolving out of data science in the context of I4.0 and is not further evaluated in this paper.

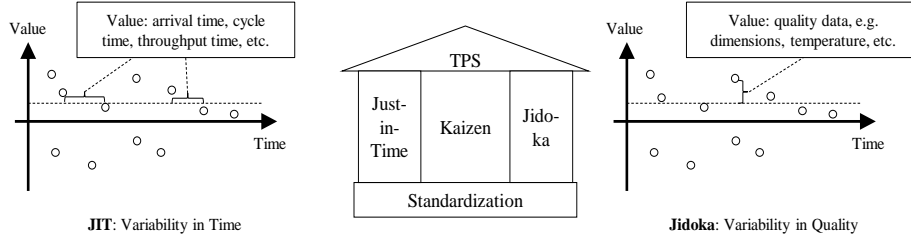


Fig. 1. Just-in-Time: Variability in Time, Jidoka: Variability in Quality

JIT deals with timeliness in a value stream. Material must be available at the point of use, just when it is needed. JIT is implemented by synchronizing the elements of production, which demands low variability in time in the flow of products, up to Toyota's "ideal state" of zero Variability in Time [9–11]. Value Stream Mapping (VSM) [9] is a widely used method to analyze and design material and information flow in production. VSM is based on snapshots or average data and thus unsuitable for mapping variability in time. Functions must be added to VSM to manage variability, which we denote as *dynamic value stream mapping*.

In TPS, wasteful practices are characterized as Muda, Mura and Muri. Muda is described by the seven forms of waste; Mura is translated as "unevenness" and thus comprises losses caused by variability. Muri is translated as "overburden", and often interpreted as losses caused by human fatigue, but also as variability amplification due to capacity constraints [3]. Thus, by interpreting Muri and Mura as forms of waste, variability is a fundamental part of TPS and put into practice with the design of the production flow [1], as described in the introduction. While western companies are familiar with the concept of Muda and the seven forms of waste, Muri and Mura are widely unknown, which indicates the low attention paid to variability in western lean activities.

HOPP AND SPEARMAN [12] conclude that variability always reduces the performance of production. To compensate for variability, they introduce the concept of buffers in time, inventory and capacity. HOPP [1] identifies the lack of attention to variability as a major weakness in the implementation of lean systems outside Toyota. He suggests an adequate mix of buffers in time, capacity and inventory, depending on the type of business and customer relations.

$$E(W_q) \approx \left(\frac{\rho}{1-\rho} \right) * \left(\frac{c_a^2 + c_s^2}{2} \right) * \tau \quad (1)$$

$$Muda \approx Muri * Mura * \tau$$

Already in the 1960's, KINGMAN [13] quantified the effect of variability and capacity utilization on throughput times, as part of queuing theory. The Kingman formula (eq. 1) distinguishes between the average and the variability of process time, and the timely variability of parts arriving at the waiting queue. The formula quantifies the lengthening of throughput time relative to growing variabilities, but also reveals a rapid increase of throughput time in the case of high capacity utilization. It demonstrates that variability, in combination with high capacity utilization, quickly becomes the dominating factor

determining throughput times, underlining the need to focus on variability reduction in such value streams.

BICHENO [14] connects Toyota's concept of Muda, Muri and Mura with the Kingman formula. Muda is represented by waiting time, Mura by arrival and process variability and Muri by the utilization rate (eq. 1). In essence, BICHENO's work allows the quantification of the effects of Muri and Muri on Muda (eq. 1). Therefore, BICHENO emphasizes the importance of removing bottlenecks in areas of high variability and to measure process and arrival variability to identify the most affected areas. He also introduces the concept of "hidden waste" to reduce variability of customer orders.

DEUSE ET AL. [4] pick up SPEARMAN's conclusion regarding variability as major cause of performance losses. They identify many product variants, high spread of work content, multiple production paths and usage of equipment as the cause for high variability in many value streams in today's industry. DEUSE ET AL. suggest alternative methods for production control in such value streams, like the use of conwip instead of Kanban.

SNOWDEN AND BOONE [15] developed a portfolio and criteria to structure business environments in simple, complicated, complex and chaotic systems. Simple and complicated systems are summarized as "ordered systems", characterized by clear or detectable cause-and-effect relationships. The system behavior is predictable and management of the system is fact based. Complex and chaotic systems are summarized as "unordered systems" and characterized by high unpredictability and unknown cause-and-effect relationships, requiring pattern based leadership. While SNOWDEN developed his ideas to describe adequate management practices, commensurate with the turbulence of the respective business environment, we apply SNOWDEN's framework to identify a value stream or parts of a value stream as "steady/ordered" or "unsteady/unordered" and to allocate appropriate measures for improvement.

3 Classifying ordered and unordered systems

TPS is built on flow lines with buffer in time to decouple customer variability and buffer in inventory to reduce and separate variabilities in the flow. Decoupled shifts are exploited as buffer in time or capacity [16]. Low cost automation is installed to provide sufficient capacity in the flow, avoiding the amplification of variabilities by capacity constraints. With sufficient buffers to customers, within production and to suppliers, cause-and-effect relationships for variabilities remain local and transparent. The system is predictable and the management of it is fact based. With this, production at Toyota fits the criteria of an ordered system and broad Kaizen activities are performed with sustainable results with sparing use of experts.

In production beyond cars, it is often challenging to decouple customer demand fluctuation. Also manufacturing is often automated, with the need for high utilization and multiple use of equipment. The flow becomes unsteady and the resulting variability is amplified by the high utilization rate. A critical point is reached as a buffer cannot provide requested material or cannot store delivered material, which is referred to starving or blocking [17]. Waiting times and impromptu build sequence changes are the result.

Operational standards, like standardized work and/or leveling, are disrupted. As a consequence, variabilities overlay and cause-and-effect relationships become difficult to identify. If high variability demands an unfeasible amount of inventory or if the inventory level cannot be maintained due to capacity constraints, the value stream turns from an ordered to an unordered system.

4 Variability reduction in value stream zones

Since parts of a value stream themselves could be ordered or unordered, we decompose a value stream into zones. Each zone represents a connected part of the production flow and a buffer may represent each nexus of a zone. Based on historic data, we analyze the stability of each zone and identify effective improvement measures for critical zones. Critical zones can be de-composed further in sub-zones, allowing a hierarchical approach, for managing complex value streams.

4.1 Autonomy of zones

Events of blocking and starvation of adjacent processes caused by a buffer are captured to calculate the service level of the buffer for a chosen time period (Fig. 2).

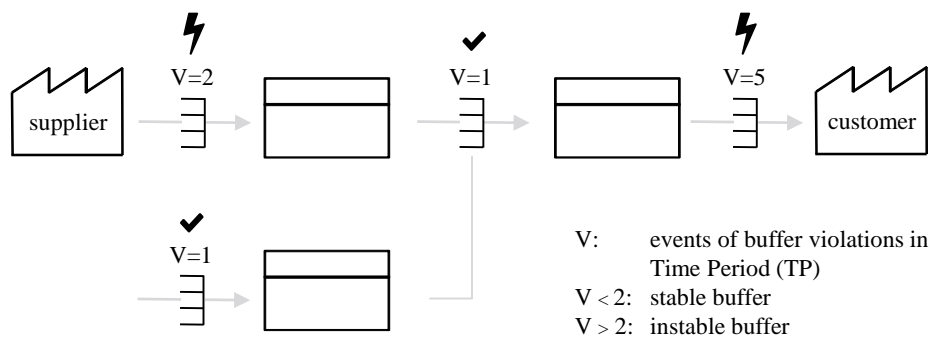


Fig. 2. Service level of buffers

With the definition of a minimum service level for each buffer, occasional events are tolerated, since they still allow the execution of standards and may even trigger improvement activities. If the service level is breached, the status of the buffer turns from stable to critical. Zones with stable buffers on each nexus, have a high degree of autonomy (Fig. 3).

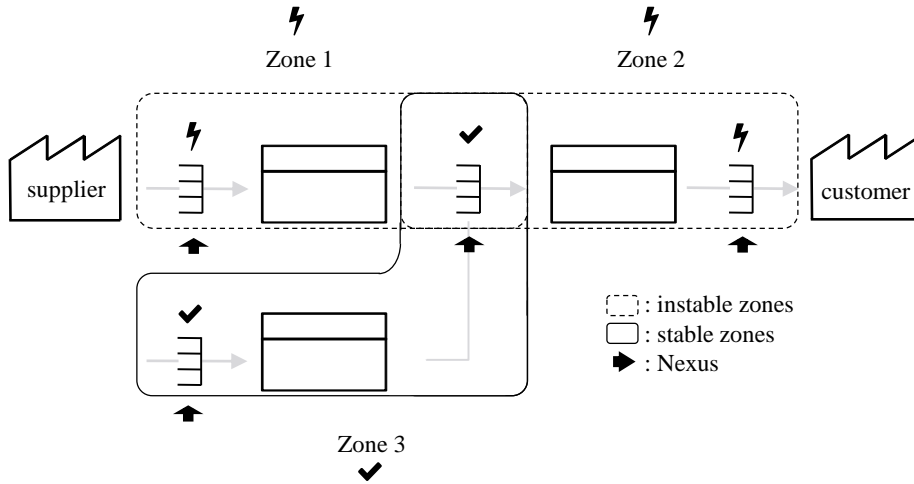


Fig. 3. Stable and unstable zones of a value stream

Only little variability is introduced from the outside and internal variability is compensated with sufficient buffers. Some more decomposition may be needed, but the pre-conditions for an ordered system are met and lean activities can be applied with the benefit of sustainable results. Next, the size of buffers of the critical zones are re-calculated. If feasible, some buffers may be increased or even some surplus inventory may be transferred from stable to critical buffers, to further compensate variability without an increase of total inventory. Based on the acquired data in some field applications, the restructuring of production may be required in the first improvement cycles. This is not further detailed in this paper.

4.2 Capacity constraints

To further reduce the required buffer, we analyze the value stream for capacity constraints, applying the method of ROSER ET AL. [18] for the detection of dynamic bottlenecks. As a result, we receive a ranking of processes, representing bottlenecks in the evaluated time period (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

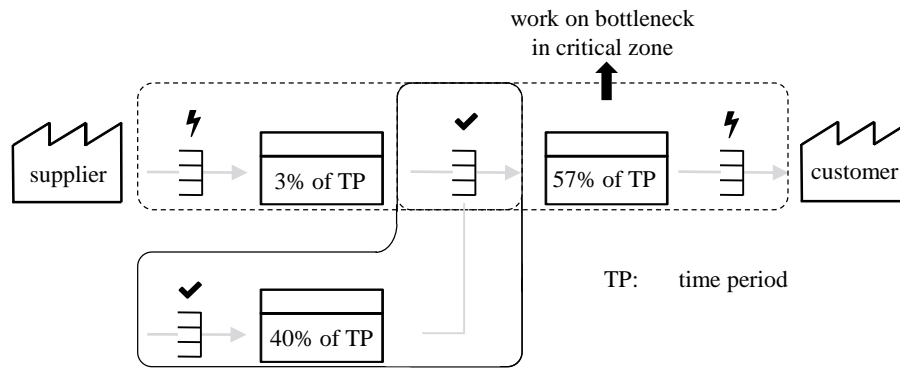


Fig. 4. Identify bottlenecks in critical zones

Since high utilization rates amplify variabilities, bottleneck processes in critical zones must be addressed, even if the output of the zone is sufficient. To free up capacity in those bottleneck processes, OEE losses or cycle times have to be reduced, or some products may be re-routed to other available capacities. As we learned from KINGMAN, a minor reduction of utilization rates may have a significant impact on throughput times and required buffer sizes. However, the gain in capacity should not be consumed with increased production rates.

4.3 Quantifying variabilities

Variability is measured at dedicated points of a value stream. It is quantified as the coefficient of variation of arrival times at this spot and classified corresponding to the limits suggested in [12] into low, moderate and high variability.

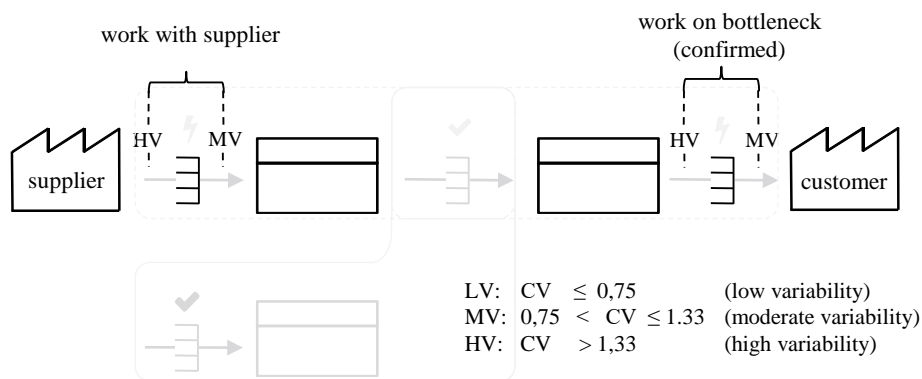


Fig. 5. Set priorities for further improvement activities

However, in cases other than a one by one flow, the measured value is only representative for this spot, not for a zone or sub zone. Measured and visualized, however, on the

nexus of zones, it provides insights into potential sources of variability and priorities for further improvement activities (Fig. 5). In any case, it provides fast feedback of the effectiveness of such activities.

5 Discussion

Without standards, there is no improvement [3]. Lean production requires basic stability to execute standards and to perform sustainable Kaizen activities. Applying lean methods in unordered zones may not provide the expected results. Ordered and unordered zones in a value stream can be identified and separated, using the service level of buffers, as shown in the example in section 4. So far, the presented research is limited to pull systems with buffers in form of supermarkets and FIFO lanes. Zoning allows dealing with value streams of high complexity, but there is more experience in regards of adequate structuring and sizing of the zones required. Measuring service levels, bottlenecks and variability is considered as state of the art. Applying those measurements in unordered zones provide insights and priorities for variability reduction. The systematic approach needs to be further detailed with practical applications. An IT System as a pre-requirement for dealing with variability has been developed for that purpose.

6 Conclusion

Managing variability means reducing variability. In successive management cycles, the actual situation is analyzed, critical zones and bottlenecks are identified, and priorities for reduction activities are derived and executed. The influence of variability in production has been widely researched. In this context, approaches such as statistical process control and Six Sigma methods reveal possibilities for dealing with variability in quality. The literature also shows the influence of variability in time on production performance. BICHENO shows that both types have a direct impact on waste in operations. With the enlargement of stable zones presented in the concept of this paper, broad kaizen activities can be applied for further reduction of waste in form of inventory as well as capacity and productivity improvements.

To cope with variability, an IT-system for dynamic value stream analysis has been developed and has shown encouraging results in first field studies in electronic production. Data is transferred from Manufacturing Execution Systems (MES) or directly acquired via sensors in production. Buffer levels, cycle times and throughput times are continuously measured and displayed in the form of box-plots. Capacity constraints are calculated as bottlenecks. Based on the resulting variability-oriented actual state, the buffers in the form of inventory, capacity and time can be designed in a targeted manner to avoid the described effects of the prevailing variability influences. Under development is the application of different mathematical and statistical approaches to enable near-real-time anomaly detection for the early identification of upcoming transitions in a zone from an ordered to an unordered state. Artificial intelligence methods offer the possibility of forecasting future system states, which enables the prescriptive management of value streams.

In summary, the zone concept developed in this paper, in combination with appropriate digitization technology, offers a new approach to manage systems based on variability.

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