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Managing the Bottleneck with PCB - Consequences of a Comprehensive Field Study*

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Abstract

Purpose - Increasing productivity continues to be essential for survival. With the Production Cultural Biorhythm (PCB) we enable the recognition and use of previously hidden potentials of up to 80% additional performance.

Design/methodology/approach - This paper describes the results of a quantitative field study conducted in over 100 manufacturing companies. Critical metrics were recorded at short time intervals over months, then averaged to produce a standard day.

Findings - Specific patterns emerged that make corporate cultural behavior visible. The field study also identified six basic patterns across companies. Working with these basic patterns, in combination with a developed visualization especially at bottlenecks, enables a phase-centered and thus simplified leadership style.

* This is an extended and substantially revised version of the paper < The production cultural biorhythm as a new LEAN learning process > previously published in < D. J. Powell et al. (Eds.): ELEC 2021, IFIP AICT 610, pp. 42–49, 2021. https://doi.org/10.1007/978-3-030-92934-3_5

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Originality/value - We combine the classical bottleneck management according to Goldratt with the new insights of the Production Cultural Biorhythm PCB. The connecting element is a new form of real-time bottleneck visualization on the shop floor resulting in a significant increase in throughput in the value stream.

Keywords: Bottleneck, Corporate culture, Production cultural biorhythm, Leadership, visualization, Performance increase, Value stream, Shop floor

1. INTRODUCTION

In practice, the realization of the significant potential of Lean Management and Six Sigma encounters a variety of obstacles since production processes as socio-technical systems are characterized by complexity at their core. As such, they defy conventional thinking that there are unambiguous cause-and-effect relationships. Rather, they are probabilistic systems with strongly interacting influences and surprising human interactions. If, contrary to reality, they are viewed as a combination of causal chains, the conclusions drawn from them regularly prove to be unsuitable. A solely technocratic-mechanistic implementation of lean management will therefore hardly achieve desirable results already in view of the variance of personality traits and fluctuations of human performance. Such an approach could reasonably be considered a planned failure.

The procedure described in the following study therefore starts with measured reality. The first step is a comprehensive data collection and evaluation in more than 100 industrial production plants. For example, electricity consumption or productivity are measured, in each case at minute intervals. Averaged over months, characteristic patterns emerge. The underlying probability system of previously unstructured interpretable processes becomes apparent in the form of standard days and can thus be specifically influenced. We call these patterns the Production Cultural Biorhythm or PCB.

The simplicity, clarity and previously unavailable conciseness of visualizations of the PCB with regard to the effects at the beginning of a shift, for example, and with a particular focus on bottlenecks, allows the reduction of complexity and thus a significantly improved management of the implementation of lean principles. With the PCB, managers and their employees receive easily interpretable graphics with ACTUAL and progress to TARGET depicted. It is essential that the results, due to the averaging of momentary values, include the probabilistic element of reality and at the same time make it easy to interpret. The focus of action on the PCB performance gaps at bottlenecks proves to be decisive. Leadership action brings about significant improvements in overall production at low cost. Some of the resulting strategies, applications and potentials are also described with reference to Six Sigma. In practical cases, productivity increases above the 50 % mark could be achieved by applying the PCB.

Lean management, with its strategic core of maximizing flexibility, represents an ideal response to the increase in volatility, uncertainty, complexity and speed of change in the world. The first goal of this paper and the research of industrial practices, is therefore to enable an urgent increase in the probability of implementation of lean management principles. The second goal is to reveal and unlock a hitherto undiscovered and significant potential of operational efficiency.

This cannot be a matter of adding a newly conceived method consisting of a sequential stringing together of sub-steps. It will be necessary to adopt a comprehensive perspective that appropriately incorporates the complexity of reality, makes it easy to grasp, and thus at the same time makes it possible to change processes in a targeted manner. In the following, the path will be outlined, starting with an overview of the published state of the science, followed by novel results of field research in real industry, up to the resulting possibilities for increasing flexibility and productivity which have already been realized in practice.

This still does not make the successful implementation of lean management in a concrete company a trivial matter of course. However, we may assume to enable feasibility and sustainable success for a larger number of companies than before.

2. THE CIRCADIAN BIORHYTHM AND STATUS OF SCIENTIFIC FIELDS OF ACTION

There is increasing pressure to rationalize and this pressure is demanding a high rate of change. Due to increasing dynamics and complexity, this demands a growing degree of flexibility from product, process and production systems. This demand applies to the entire life cycle. Hitoshi Takeda described the fundamentals required for this in his book on "synchronous production" with the essential LEAN goal of one-piece production, the one-piece flow, to increase flexibility while reducing lead-time [1].

If we consider at the beginning the fluctuation of inquiries and orders of the customer market, these are translated on the part of the suppliers by leveling and smoothing (heijunka) into a constant performance demand under consideration of the customer cycle, into the production of the plants. This results in cycle times which are based on the principles of division of labor in production. Thus the generated standardized times (normal time) therefore represent the performance in the long run and on average of the shift time, which would be achievable by the workforce at a performance level of 100% [2]. In practice, these activities are planned as if they followed deterministic principles of high predictability and manageable cause-effect networks. The structure for highly variable mass production that is still common today is, among other things, the line balanced flow assembly. [3], describes in this context how the employees adapt their work performance to their personal performance in the absence of mandatory standard times.

The reality of the characteristics of human capital is important to a highly functioning organization. For this reason, the lifelong learning model [4], is the focus of much research and operational programs in industry. For some time, academia has been concerned with whether and how workers should adapt to work systems. The research is also about how and to what extent the work system must adapt to the workers.

The artificially generated, rigid demand and planning are only opposed by fluctuating performance on the part of humans. Following [5], the human performance results not only from the factual but also from the psychological and psychophysical performance potentials. These can be subdivided into the principal, situational and individual performance potential on the one hand and the willingness to perform on the other. Without claiming to be exhaustive, essential characteristics relevant to the field of research are listed below:

- Dispositional characteristics and personality traits such as age, intelligence, motive profile, resilience, self-efficacy expectancy, conflict tolerance, and physiological aspects such as biorhythmics.
- Qualification and competence characteristics, including experience and knowledge, skills and abilities, both in terms of technology and communication
- Adaptation characteristics such as stress, fatigue, and momentary motivation.
- Constitutional characteristics such as heredity, physique, and cultural background.
- Interaction characteristics such as relationship qualities and histories.

2.1 The Natural Variance of Human Performance

As late as 1968, it was stated [6], that human beings are highly versatile with respect to biological, physical, psychological and social aspects and therefore not "normable" in the sense of recognizable patterns. In fact, it is well documented that the range of human performance is subject to considerable variation [5]. In contrast to the beliefs in 1968, modern psychology, which has been comprehensively mathematically based since about 1980, is continuously deciphering reproducible, reliable patterns of behavior. The puzzle of unmanageable versatility is transformed into a model of growing conclusiveness, predictability and influenceability. In this context, the field of general psychology deals with processes within individuals, which we call "intraindividual". Differential psychology explores differences between individuals with "interindividual" variance. Sources dated before 1980 should be carefully examined to determine whether they meet modern criteria of validity or are more likely to be classified as philosophical and thus not to be taken as established knowledge.

The described versatility can be seen, for example, in individual performance at different times of the day and by different demands on performance reserves. Johnson R V [7], describes this variability using the example of processing times in the form of a scatter. Hopp WJ [8], differentiate the natural variability of performance in 2008 into a controllable and a non-controllable component. Depending on the author, the range of variation of the real processing time at a manual workstation is described between 80% and 150% around the planned value [9], and between 96% and 106% for a variant flow assembly [10].

Of particular interest is the physiological fluctuation in performance of the biorhythm, which according to the studies of [11], and in [12], leads to errors in vigilance activities. Tasks of this type demand a constant high level of attention, which is incompatible with the natural fluctuations of attentional performance and human exhaustion phenomena. Biorhythms can be divided into ultradian effects in the seconds range, circadian effects, which are related to the day, and circannual effects, which are seasonal or annual. [13], strengthen with their investigations our assumption of circadian and natural biorhythm related performance fluctuations. In addition to intra- and interindividual effects, we also know cyclical effects that are imposed on companies from their environment. Cyclical variability such as the hog cycle, sales peaks at the end of the month, the seasonality of winter or summer products or fashions and trends are examples in this context.

If people behaved according to the companies' planning approach and thus ideally, they would not show any fluctuations. Productivity would correspond in the performance capability as indicated in the data sheets of the machine manufacturers. The reality of companies as socio-technical systems is far removed from this. We assume that the visible performance fluctuation patterns of machine-based operation as a result of human-machine interaction are based on a combination of the corporate-culture-traditional behavior and the natural biorhythm of humans. Further variation on performance is introduced with personality traits of involved humans as well as their relationship qualities and histories and also the corporate culture. It is always astonishing to experience how management explicitly points out that people are not machines and at the same time designs processes contrary to this own insight.

2.2 Organizational Inclusion of Natural Performance Variations

Although performance fluctuations are highly relevant in manual assembly, they are largely ignored in today's planning processes and personnel management. Possible methods of influencing the fluctuations include flexible personnel deployment and adjustment of target times. Jungbluth and Mommsen, 1968 [6], and [14], describe the goal of "respecting the temporal performance lows within the circadian rhythm in order to be able to use high phases for improved work performance." [15], investigated improvement opportunities for shift groups in manufacturing companies. Here the real processing time is the essential performance factor. They describe as a goal to adjust the processing time available for a work task to the humanly possible, typical performance offer. Fletcher et al, Nihuis et al., [16, 17], and [10], have fundamentally identified the circadian biorhythm from different perspectives and discussed the effects on collective performance variations. Glonegger M [18], in his deductive approach, pursues flexible staffing and the influence on performance fluctuations induced by processing times. This field study was conducted in an automotive engine assembly and its assembly planning for the narrow field of variant flow assembly with a value-added share of assembly of up to 60%, but a share of lead-time of only 25-50% on average. An adjusted order sequence, according to the performance curve, was also described in a research report. In contrast, [19], recommends a general slowing down of the assembly line, especially at the beginning of each shift, in order to take into account the employees' familiarization phase. Without this familiarization phase, there would be an increased error rate at the beginning of the shift. This is also based on the fact that, as described in [20], no employee can begin his or her work at full intensity. Only after 20 to 30 min can full performance be offered and successfully demanded in industrial work. Glonegger M [18], summarizes: "The planning of shift start and end as well as the distribution and length of breaks is state of the art. In addition, the effects of familiarization and fatigue are considered to be researched in terms of work physiology". Statistically validated actions recommended were related primarily to the planned flexibilization of the work speed and note was made that "the planning of the activity mix as a function of human performance fluctuations no longer plays a role in today's variant flow assembly systems". Further interesting possibilities to compensate performance fluctuations are offered by the biodynamic light described in [21], or also an extrinsic influence by wage supplement, which [5], mentioned.

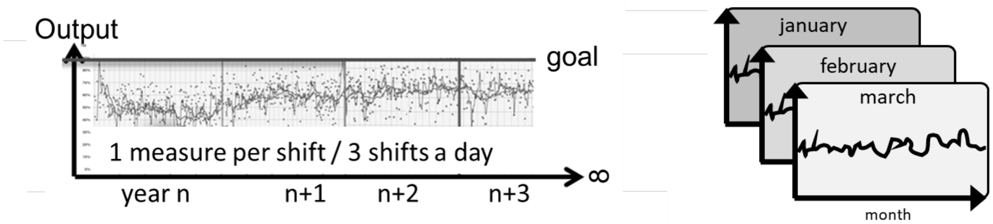

Figure 1: left: Output over time, right: monthly KPI chart (Source: own elaboration)

3. ADVANCED DATA MANAGEMENT ADaM24 AND THE PCB

Review of the literature did not reveal a corporate cultural reference. Only [16],spoke of the effect of an “attitude” on the output in the circadian course. All publications examined deal with manual activities and the variability of processing times in clocked systems.

Operational performance measurements identified show considerable weaknesses. Classically, only a single measured value per shift or day is recorded and plotted in a time series for review by shop floor management. FIGURE 1 on the left shows the time series progression of a production parameter without a time limit. Here a slight downward trend can be seen in the initial year, while in subsequent years there is hardly any relevant improvement. In the case of typical shop floor management in particular, the longer-term trend is not seen by the workforce as typically only monthly diagrams are posted. See FIGURE 1 on the right.

A more refined measurement has recently been introduced. Langer B et al, [22, 23], describe data mining and analysis using ADaM24, Advanced Data Management over 24 hours. Here, one or more performance indicators are measured per day in small time increments, typically five minutes duration. These performance indicators might include the number of pieces or transactions, processing time per piece, Overall Equipment Effectiveness, energy consumption or quality values such as first pass yield. The spectrum of potential metrics is broad, and the selection is made based on the situation on site. The result is the profile of each individual day. The measured daily profiles are averaged over the data collection time period of time to smooth out the influence of time and location specific occurrences. The result is an averaged standard day that characterizes production.

The average daily profile is called the Real Output Profile (ROP) in the ADaM24 diagram (FIGURE 2). In a single graph, the ROP accounts for setup times of varying lengths associated with the product and order mix, as well as batch size fluctuations, varying capacity utilization, breaks, effects from shift startup, handover and runout, disruptions for a wide variety of reasons, maintenance measures, changes in the shift workforce and other systematically occurring influences. The overall study shows that the quality of the results increases considerably with a shortening of the measurement intervals. The critical time interval must be small enough that the patterns of variation emerge. From the study of metrics in industry, the measured ROP proves to be stable from averaging of data over about three months.

If the ROP is determined only once for an analysis object, we speak of static ROP (statROP). This shows the PCB once as a basis for new findings about its own processes and already enables targeted optimization activities. The ROP can also be determined dynamically (dynROP) in order to be able to continuously track the effects of implemented measures by means of an average over an averaging period of, for example, the last three months. It is helpful to average time periods block by block in order to show the effects of interventions in a particularly concise and timely manner. The sustainability of implemented change projects can also be checked by testing the dynROP for stability. In further analyses, it is also possible to analyze the varROP around the averaged ROP line. The aim is to qualify the varROP as a measure of the stability of the process and to reduce it continuously by means of suitable measures.

Langer B [22, 23], describes that "it appears to be a fractal phenomenon that occurs at any size of both the consideration frame and the consideration content." The ROPs presented in this paper can be created not only for the clocked systems previously described in the literature, but also for layout or value stream related objects, namely

- selectively for machines, systems or workstations,
- in lines or between machines in the value stream, and
- in the area for entire areas or plants.

The procedure can also be related to different degrees of automation such as

- manual,
- semi-automatic,
- fully automatic or
- robot-assisted.

In addition, influences of function-related classifications, for example differentiation can be made according to

- production,
- logistics and
- indirect areas such as staff units and administration.

We call the revealed profile, which repeats itself in the daily rhythm and characterizes the production, the ROP. This ROP is the "production-cultural biorhythm (PCB) or the PCB effect of production. We found it in every (!) company studied. Surprisingly, even fully automated machines, fully automated plants and robotic systems exhibit the principle of a circadian rhythm. This should not exist in a classical technocratic view, since the plants are planned for autonomous operation. This can be explained in that the human production cultural biorhythm is "transferred" to the fully automatic machines by the human-machine interaction: Machines are simply not operated, malfunctions are not detected, ignored or not corrected, as described in [22, 23]. The central insight: humans are and remain critical and impactful factors. The PCB shows the cultural behavior of

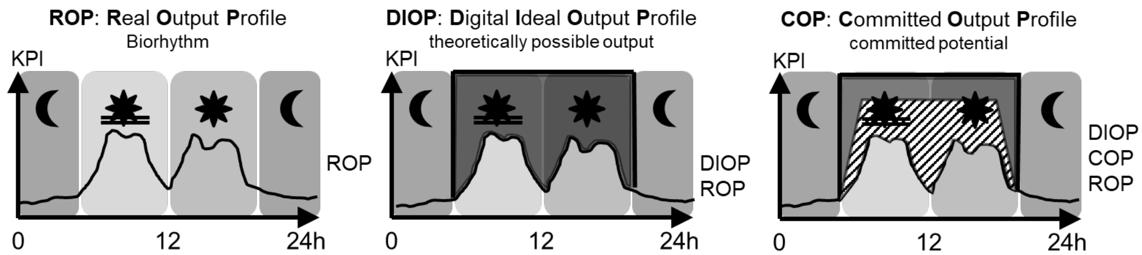

Figure 2: Definition of Measures (Source: own elaboration)

the workforce, regardless of which ERP system is used to plan or control or which sequencing is used, whether lead time planning (scheduling), push or pull [24], or push/pull is the underlying operational model. Framework conditions, processing lead times or activity mix are also included in the ROP. FIGURE 2 on the left shows schematically the standard day, which is represented by the Real Output Profile (ROP).

The graphics generated by ADaM24 with the displayed ROP are generally understandable by production employees and are accepted as fact. The displayed PCB effect typically surprises both managers and employees. If we ask the relevant group of people what the ROP looks like before showing it to them, they usually only shrug their shoulders. Manipulation is ruled out by averaging over a long period of time. Due to the averaging, the ROP is a rather sluggish value, i.e. better work must be done over a longer period of time in order for the ROP to reach a higher level. The same applies to the drop in performance. Of course, time periods can be freely selected block by block for the targeted testing of initiated measures.

The Digital Ideal Output Profile (DIOP), depicted in the center of FIGURE 2, corresponds to the theoretical perfectly operated technical plant. The ideal is that the machines start up without delay at the beginning of the shift, automatic machines do not know any breaks and the facilities are operated seamlessly over shift changes. Only at the end of an operation are they usually switched off with the machine is assumed to be digitally on/off with respect to its operating status. Thus, the DIOP describes the best possible state. In most cases, investments and price calculations are made on this basis. The area between ROP and DIOP represents the untapped potential of a piece of equipment or facility. This ROP-DIOP potential may be quite large in the case of non-bottleneck machines, but in the case of bottleneck machines a value of zero should definitely for the target. In on-site investigations, we have often been able to demonstrate a ROP DIOP potential of well over 80% for automated bottleneck machines.

In many cases, the presentation of the DIOP initially generates a great deal of resistance among the workforce, since obstacles are rarely technical but rather cultural and people-related, such as a traditionally slow shift start-up. For this reason, a third profile is presented. With the Committed Output Profile (COP), management agrees with the relevant workforce on a target profile. See FIGURE 2 on the right. At the meta level, we have often observed that management does not demand the DIOP from the workforce, even in the case of bottleneck machines, but forgoes the considerable potential "for the sake of peace and quiet" at the expense of a wide range of parameters such as throughput time, delivery time, flexibility and thus profitability. As an essential new parameter, we have defined the radicalness of the change R_V = COP/DIOP. The basic aim is to ensure the highest

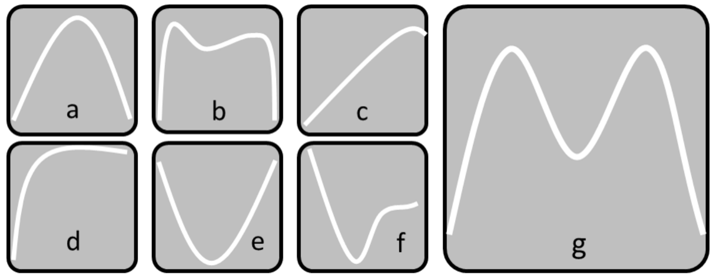

Figure 3: The six MURA patterns (Source: own elaboration)

possible radicality, especially for bottleneck machines. This cannot always be achieved everywhere, but it can be achieved at key locations during short periods of time by means of manageable efforts on the part of personnel management.

4. MURA AND META-MURA-PATTERNS

Lean management provides approaches of designing waste-free processes that have proven themselves in practice. The forms of waste are classified with MURI, MURA and MUDA or also 3M. While MURI describes the overloading of employees and the non-adherence to standards, MURA deals with the wasteful state of imbalance. MUDA describes the resulting seven typical types of waste. A good example is the rush hour in daily life. It arises because many vehicles move at the same time in the same directions and thus create imbalance. As a result, the same traffic jam is produced every day, which leads to the wasteful form of waiting time. As a chain of effects can be deduced: MURI drives MURA drives MUDA.

Against this background, a ROP represents, by definition, the visualization of imbalance and thus the MURA pattern. If the ROP were a horizontal line, the system would be balanced, regardless of its level. This is not found in practice. Meanwhile, we have identified six basic MURA patterns of ROPs and their superposition. FIGURE 3 shows these MURA patterns Peak (a), Valley (b), Long Ramp, (c) Short Ramp Up (d), V (e), Root (f), and with (g) being the aforementioned pattern frequently found in practice.

The MURA patterns correspond to culturally traditional workforce behaviors - and, as expected, lead to the seven types of waste such as waiting times or unwanted inventory.

A practical example of a "long ramp-up" (c) is the shift start effect, which is essentially due to three deficits:

1) The process for beginning of shift activity is not well defined which results in the operator carrying out work preparation based on personal criteria. For example, the operator obtains an overview of the current situation on site, organizes the workplace, organizes materials and supplies. Committed managers may be tempted to counteract this hustle and bustle with progressively more detailed process instructions. This proves to be only moderately successful

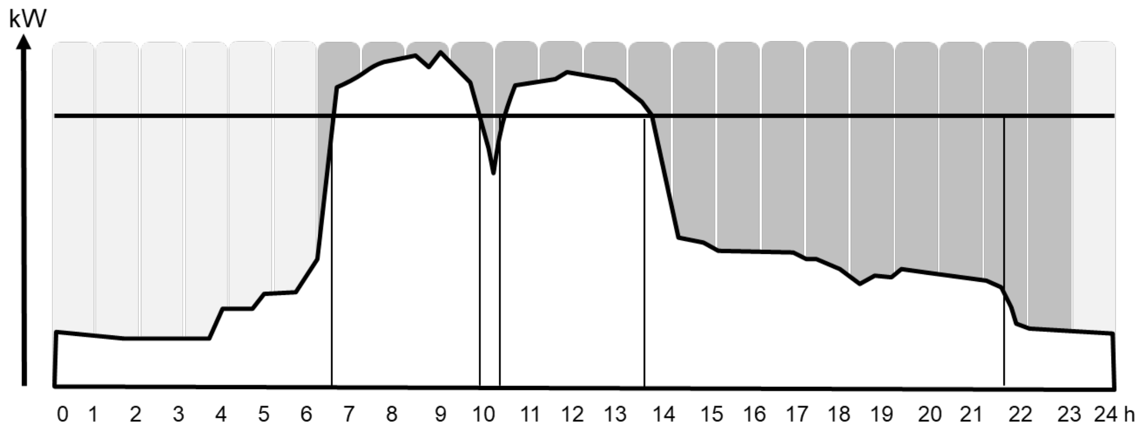

Figure 4: Current/power curve (Source: own elaboration)

for two reasons: Due to varying personality traits, people show different starting state needs in real terms, and precise action instructions activate the autonomy motive in a negative way.

2) The collectively handed-down behavior of not starting productive work immediately at the beginning of a shift has become part of the corporate culture.

3) An accumulation of unsolved technical problems during the previous shift delays an effective start of the shift. Managers have not adequately incorporated resolution of diverse micro- and macro problems.

Glonegger M [18], postulates that "[...] individual influencing factors act on each assembly line, which is why no recommendations for action for other assembly lines, e.g. of other companies, can be made from the analysis of one system." This impression of patternless arbitrariness is understandable if we try to understand systems technocratically-deterministically rather than psychologically-probabilistically. Our current research is concerned with the identification of patterns by means of artificial intelligence. Hereby, we can, according to the hypothesis, develop generic fields of action and options across industries. AI in particular is suited to discover probabilistic patterns in large, supra-individual data sets. Against this backdrop, we expect to use AI to decipher overarching META-MURA patterns. We are already pursuing this area of research under the names MURA^{KI} and MetaMURA^{KI}. It should be added that in a next step, we also fundamentally investigate these correlative patterns for causality and subsequently select them.

Our approach also includes the different phases of production planning and production control. In this context, we again reference [19], who recommends a general slowdown of the assembly line, especially at the beginning of each shift, in order to be able to take into account the MA's habituation phase. From our point of view, this is an artificial PCB in the form of a "long ramp-up", which is not only counterproductive from a bottleneck point of view, but rather resembles a scandal.

Three examples from industry are now presented to highlight the significance of the PCB/ROP principles in practice.

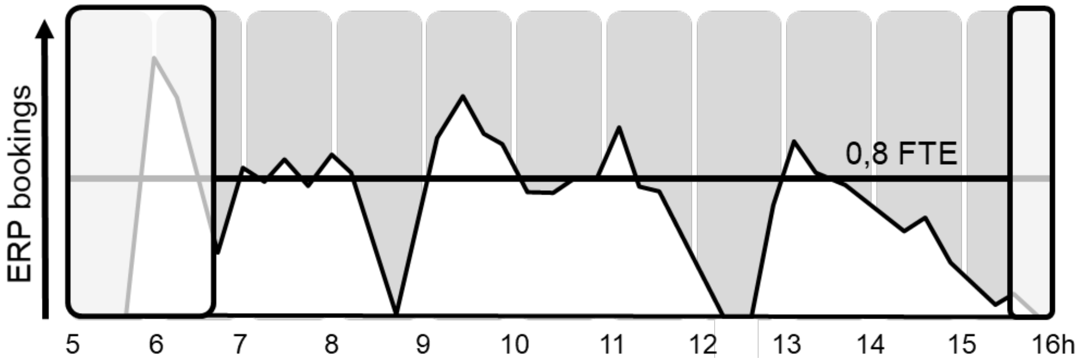

Figure 5: ERP bookings (Source: own elaboration)

FIGURE 4 depicts a power consumption curve (power curve) for an entire plant, This PCB represents the collective cultural performance behavior of an organization which includes delays at the beginning of the shift, handover and run-out behavior as well as the usage profile of the equipment during the shifts. It thus also reflects the level of performance that has been consciously or unconsciously set by managers over longer periods of time and has since become the norm. The transparency of the PCB makes clear to everyone that the activity profile is the same each day. In the example shown, the early shift is scheduled from 6:00 to 14:00. It is clearly seen that the operational start of the shift is delayed by 45 minutes, a low performance phase is recorded before 9:45, followed by an inadmissibly extended break. The second half of the early shift is characterized by a premature drop in performance and is effectively terminated 30 minutes before the end of the shift. The course of the late shift shows an overall low and continuously decreasing level, with productive activity terminated about 30 minutes before the end of the shift. Based on experience, some managers are very reluctant to make meaningful changes to traditional behavior, while others combine their leadership training and the resulting completely different experiences and implement improvements on an ongoing basis.

FIGURE 5 shows ROP shows the rate of manual postings to an ERP system. This is a highly employee-specific progression where personality, experiences and routines manifest themselves in an individual, rhythmic profile. In the example, it becomes visible that the employee achieves a peak performance one hour before the official start of work at 7:00. After that, the individually characteristic daily profile with distinct MURA patterns sets in. If we transform the performance curve mathematically to a constant level, the result is a work demand of a constant 0.8 FTE, which can be performed in a relaxed manner within a single shift. The PCB graphic makes the waste obvious to all involved. Based on this insight, organizational leadership has the opportunity to significantly reduce MURA waste. The PCB provides management with transparent key performance indicators (KPIs) that they can use to guide middle management.

Companies invest in fully automatic machines and, in the course of the investment calculation, largely assume that these machines produce according to the manufacture's specifications. This specification typically represents the DIOP. ADaM24 shows in the schematic FIGURE 6 that the promised output is not achieved in reality, but that there is a significant performance gap. The machine output also shows considerable underperformance during shift start-up, transfer and run-down (short ramp-up/ramp-down). Compared to the DIOP, the early shift also shows significant

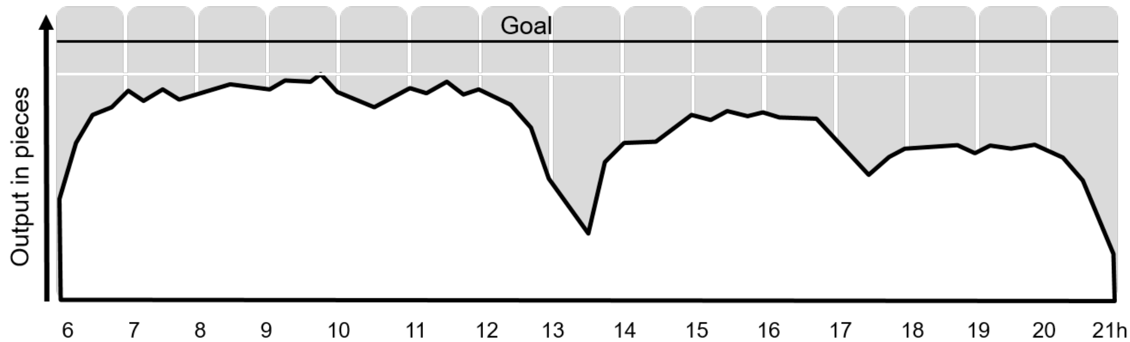

Figure 6: fully automated assembly equipment (Source: own elaboration)

loss effects in the form of a long ramp-up and reaches a short-lived and unique peak output around 10:00. The performance of the late shift basically runs at a lower level and shows a further drop in performance in the second half.

The three schematic examples from industry are representative of PCBs in a large study of industrial practice. The simplicity and conciseness of the diagrams enable immediate understanding by both employees and managers. They can thus be used highly effectively management tools.

5. OPTIMIZING PRODUCTIVITY: THE PROCESS MODEL ACCORDING TO ADaM24

The PCB serves as the basis for a new type of LEAN learning process. Focus of the tool is initially based on identifying high-potential time slots in the course of the day, for example from 6:00 am to 6:30 am. Management efforts and measures with a targeted reference to these phases can pay off particularly well. Ongoing ADaM24 graphs distinctly show before/after effects when averaged by time block and the longer-term graphs shows the sustainability of the effect.

In [23], the ADaM24 procedure model according to Langer and Mussler was presented. In the model both optimization success and a desirable production-cultural change in behavior are achieved in six systematic steps.

Step 1: Determine the ROP and analyze it to reveal previously hidden inefficiencies at identifiable times.

Step 2: Determine the DIOP to define the maximum possible value of the measure under ideal conditions.

Step 3: Negotiate the COP as an agreed target curve to achieve a common internal alignment of employees and managers working towards the achievement of a feasible goal. At the conclusion of this step, the radical RV=COP/DIOP is reported

Step 4: Quantify the potential achievable by means of COP, for example in terms of units, monetary units or quality metrics. This compares the COP potential to DIOP as the maximum possible, in order to provide additional performance incentives that extend into the future.

Step 5: Identify point-of-interests areas narrowing down inefficient time phases in the daily cycle so that concrete time-selective improvement projects can be initiated. This step may also include the decision to design the handling of the PCB as a single project or as a continuous improvement process.

Step 6: Implement change projects on the shop floor in order to eliminate identified inefficiencies causally and thus finally and to sustainably realize identified potentials. The realization of this step requires site-specific management actions.

In addition to steps 1 to 6, project experience shows that it is beneficial for implementation competence to conduct feedback rounds to draw conclusions. In the spirit of a learning organization, successful and unsuccessful forms of action and other future-oriented findings and conclusions should be recorded in writing and made available across the board, anonymously if necessary. Only with this completed step can practical improvements in organizational project or change management competence be expected.

In the following, we relate this procedure to the context of real production environments in which production bottlenecks occur.

6. FOCUSING PCB ACTIVITIES ON THE BOTTLENECKS

Bottlenecks and their absence are revealed when analyzing a value stream: In a perfectly balanced system, no bottleneck exists. This logistically ideal process state is called flow. Within the Lean paradigm, this state is approached by striving for one-piece production, the "One Piece Flow". Real systems, on the other hand, are never perfectly timed and therefore always have one or more bottlenecks. Bottlenecks limit the throughput of the overall system by providing too few parts to downstream processes or providing them at inappropriate times. To make matters worse, their location can be variable; we then speak of dynamic bottlenecks. If, on the other hand, a workstation does not represent a bottleneck and nevertheless produces more parts than the downstream process can handle, this creates a push and thus local overproduction. From this perspective, it is even counterproductive to try to achieve DIOP at a NON-bottleneck. From this, the recommended course of action is to manage and optimize production as a whole in relation to the bottleneck.

Various definitions of the bottleneck can be found in the literature.Krajewski LJ et al. [25], describe a bottleneck as "the process that limits output." Chase RB et al. [26], call it "a resource whose capacity is less than demand" or "the process that limits throughout." Roser C et al. [27], and [28], define bottleneck as "a stage in a system that has the greatest impact on slowing down or stopping the entire system." Kuo CT et al. [29], state that in manufacturing, a bottleneck is "often defined as the machine whose production rate, in isolation, is the lowest of all the machines in the system." They also define the bottleneck "as the process whose sensitivity of the system's performance index to its isolated production rate is the greatest compared to all other processes." Roser C et al. [30], describe bottlenecks as "processes that influence the throughput of the entire system." The greater the influence, the more significant the bottleneck.Lawrence SR et al. [31], provide additional definitions for bottleneck not detailed here. The following statements regarding bottlenecks are relevant to PCB research:

1. In the simplest case, there is a static bottleneck. This is a permanent overload of a specific workstation that is unable to achieve the throughput demanded by the overall process. This can only be resolved by increasing capacity.
2. In a real value stream there are mostly dynamic bottlenecks, individual workstations represent a bottleneck only temporarily. The bottleneck transition is described by means of the "active period" [32]. The dynamic is due to
   - planning and production control effects
   - deficiencies in balancing
   - Lot size effects: Large lots moving through a sequence of processing steps may move the bottleneck from operation to operation as work orders behind it must wait for the large lot to be processed at each machine.
   - unplanned disruptions, such as unplanned maintenance. which can leading to micro- and macrostops at a workstation
   - performance variations that are not adequately recognized and included, such as the PCB presented in this paper is capable of uncovering.
3. The work center with the longest cycle time is referred to as the "hot spot". All other cycles, labeled "Cold Spot", are shorter and wait for the "Hot Spot".
4. Summary capacity load provides another perspective. It involves the multiple use of workstations for different products. The load of a machine is typically generated by the ERP system. The data from ERP system can then be used for Pareto analysis to highlight most heavily loaded workstations. They do not necessarily represent a bottleneck at any time, but they do have high risk potential. We refer to them as "latent bottlenecks".
5. From a supply chain perspective, a distinction is made between internal and external bottlenecks. Internal bottlenecks are generated within the company, external bottlenecks by influences from the supply chains. We refer to the latter as supply chain bottlenecks.

Detecting and dealing with bottlenecks is an essential foundation for improving the output of a production system [33–35]. Our research area of PCB is dedicated to this permanent goal. The overarching goal is to increase throughput in the enterprise through a variety of coordinated levers. The historical basis for this is provided by the Theory of Constraints TOC, which was described in the form of the novel "The Goal" by [36]. To resolve bottlenecks, Goldratt defined a 5-step plan, which is presented here in a modernized form based on the scientific knowledge associated with ADaM24 and PCB:

1) Find the bottleneck: The first challenge is to correctly identify the current bottleneck. Several methods have been developed for this purpose [37–42], complemented by another two by one of the co-authors of the present paper [43], and [30]. Much less research exists on forecasting bottlenecks [44–46], and the impact of improvements in bottleneck performance [47]. In most mid-market companies and in the corporate environment, the question of bottleneck identification tends to be treated as a side issue. There, people think they know exactly THE bottleneck based on the calculated capacity limits of machines and systems or ERP planning runs. For this reason, company representatives often jump to Goldratts step 4 leaving significant potential untapped. More recently, new methods have been developed through AI and Data Science, especially in the area of production control, to identify dynamic bottlenecks and their causes [48]. Our research group uses AI to determine the current bottleneck(s) in real time and to simulate the improvement of throughput times in a system by means of a COP capacity increase in order to identify existing potential and enable targeted measures.

2) Load this bottleneck to the maximum: A successful maximum utilization of the bottleneck would correspond to the DIOP. For this to occur two essential aspects of the process must be addressed. First, constant production must occur through the beginning and end of the shift with no interruptions during shift handovers. Second, a maximum and constant output level defined by the purchased machine capacity in the specifications is maintained. In this context, it is important not to accept any reduced availability, for example due to previously unrecorded maintenance, malfunctions or setup time losses. These incidents are to be regarded as problems to be remedied. Practical studies in connection with ADaM24 and the PCB show that a production control or the management may well have identified a bottleneck, but this does NOT reach the relevant workforce at shop floor level or at the machine as information of significance. Simply put: The employee often does not know that his machine is currently the bottleneck and what this means. Therefore, there is no recognizable reason for him to behave in any manner to alleviate the bottleneck. The result is avoidable macro and micro stops in large numbers. The simple and timely communication of bottleneck information is thus probably the simplest form of useful management action.

3) Subordinate all non-bottleneck activity to bottleneck optimization: System throughput-optimized order sequencing according to a predetermined model, for example an AI-based real-time value stream, must not be overridden by micromanagement on site or spontaneous reprioritization by management representatives. This demand, simple from a technocratic point of view, becomes a formidable challenge in socio-technical system reality. First, managers with high values on the individualized component of the power motive experience it as intoxicating to act out dominance by overriding sensible regulations. Second, shop floor managers lose degrees of freedom, which negatively activates the autonomy motive and can lead to a so-called "turn to the denied alternative" and thus to disruptive interventions. For example, rush orders may be interjected into the production plan but the action would not stand up to scrutiny in the optimization of the bottleneck. In this case, management can set up a "frozen zone" in which interventions are prohibited by disciplinary action. However, here too, the negative activation of the autonomy motive will lead managers to point out to their management that the frozen zone is inappropriate. Ways out of this and other impasses are non-trivial and may be open to solutions based on business psychology.

4) Expand the bottleneck as a last option: Only if the bottleneck proves to be demonstrably and in principle unresolvable, i.e. it would remain a constant bottleneck despite SMED, Heijunka and DIOP output, must the bottleneck be fundamentally resolved by a new investment.

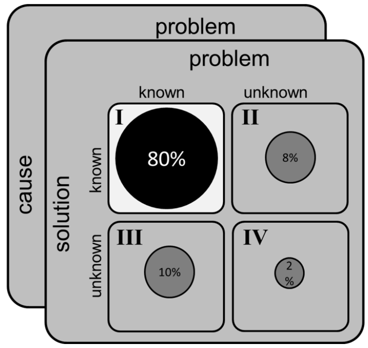

Figure 7: Johari-Window of problem solving (Source: own elaboration)

5) Start again at step 1: The 5-step logic according to Goldratt leads to the fact that after step 4 at the latest, the current bottleneck is no longer a bottleneck. Therefore, the process of continuous improvement starts again at step 1.

A successful, more advanced approach to selecting particularly easily achievable successes in the context of the PCB has been described by [32, 49]. This refers to the classification of problems according to the JOHARI window as shown in FIGURE 7. The focus here is on JOHARI I problems. These are characterized by the fact that both the problem and its solution are known. These problems have a known or unknown cause. Empirical studies show that about 80% of all problems belong to this class. If they occur in practice, a makeshift workaround is chosen instead of the known, sustainable solution. As a result, the problem recurs regularly, wasting considerable resources over time. In line with the nomenclature of lean management, we choose the term MULA for this, the waste category for multiple identical problem solving according to Langer.

The new convergent approach can be summarized as follows:

Step A: Focus on the current bottleneck workstation in each case because this is where the impact on results occurs.

Step B: At the bottleneck, the focus is on the temporal phases of the PCB performance gaps, because this is where the greatest potential for improvement is identified.

Step C: Johari I problems are identified at the starting point, which is now precisely defined in terms of location and time. A sustainable problem solution increases the ROP and at the same time frees up considerable resources.

If employees are actively involved in shaping and reflecting on this process right from the start, organizational optimization competence increases overall.

7. DATA COLLECTION IN THE DIGITAL AGE

Research by [10], indicated that until then there were few described methods for recording and processing real collected processing times in variant flow assembly systems. He described the methodical approach of a time-based data record elimination to exclude unclear data at shift start, breaks and shift end. This represents data cleaning by focusing on “valid time ranges” and provides data on phases of high performance as revealed by the PCB. However, it is precisely the time ranges excluded by Glonegger that are of utmost importance for structured optimization, as the PCB equally demonstrates.

A mandatory prerequisite for the successful execution of an ADaM24 process is high data availability in the sense of both temporally constant data strength and quality. This is necessary to generate raw data through which the PCB effects can be determined. The raw data can be collected from four possible sources.

1. Manual collection: for low cycle rates or few events, manual entry is sufficient in many cases to determine a statROP. This has the advantage that the employee gains an understanding of a bottleneck utilization according to Goldratts second step by recording the raw data. However, this raw data is, consciously or unconsciously, susceptible to manipulation.
2. System data acquisition, for example in ERP or MES: Data acquired in this way can be used directly to determine static and dynamic ROPs. As a rule, these are not subject to manipulation, or only to a limited extent. Likewise, ROPs can be determined retrospectively through historically recorded data sets, which becomes useful when evaluating measures before and after improvement.
3. Machine control: In many cases, data like pieces or times can be read directly from machine controls. This requires interfaces and local expertise as well as IT resources, which are often not available.
4. Dedicated data acquisition system: Data acquisition can be performed locally for the acquisition of raw data at bottlenecks by means of specifically suitable sensor technology, including image and video recording. As part of the research activities, an easily installed MURA box is being developed to not only collect the raw data system-independently. The Mura Box can display the current PCB with real time monitoring as well as generate potential views. Both cloud-based virtual and local-offline operated physical hardware can be integrated. The MURA-Box offers added value for consulting activities, as company data cannot be leaked uncontrolled via the cloud.

8. REAL-TIME BOTTLENECK IDENTIFICATION AND SIMULATION OF PCB EFFECTS ON LEAD TIME

In a simulation, the planning and order data of a medium-sized company with individual resource groups was used as a typical initial situation. A typical product mix with many variants was assumed, with different production stages and 3520 production operations and their individual operation sequences.

In the simulation, a typical ERP backward scheduling results in a resource allocation according to FIGURE 8.1., where each line of the figure is a resource over time. The lead-time for all orders of 284 days and an average lead-time for a single order of 80.2 days.

FIGURE 8.2 shows the result of an AI-based flow-oriented (not utilization-oriented) bottleneck optimization. The optimization objective is to achieve the shortest possible LEAD TIME of all orders (objective 1) with as close to 100% delivery reliability as possible (objective 2) through order sequencing optimization considering account resource capacities. In the flow-oriented "ideal" arrangement of the operations, the resources that are mostly occupied with regard to the flow now become apparent based on the longest continuous queues. These are to be considered as bottlenecks in this simulation. A lot-size splitting according to heijunka is not yet implemented here.

The bottleneck optimization task is prepared by modeling the optimization problem using Axxelia's modeling algorithms, the so-called "Hyper HDG Heuristics".

At the core of the resource allocation optimization and to solve the multidimensional optimization problem, AI-powered optimization algorithms from Google OR Tools are used. Google OR Tools is an open-source software suite for mathematical optimization problems "tuned to solve the world's most challenging problems in vehicle routing, traffic flow, integer and linear programming, and constraint programming."

The bottleneck optimization results in a lead-time for all orders of 166 days and an average lead time for a single order of 36.9 days. This is an improvement of the lead-time of all operations by 42% compared to the initial state.

FIGURE 8.3 shows the summary work content per resource, which is identical before and after each optimization stage. This means that significantly shorter lead times and thus better delivery reliability can be achieved with the same worklist but different sequence planning. In a further simulation, the effects of increasing capacity using the PCB approach were examined. For this purpose, the resources at the top ten bottlenecks from FIGURE 8.3 were doubled, which corresponds to a thoroughly realistic level.

Subsequently, an AI-based flow-oriented bottleneck optimization and thus resource allocation was performed again. The result in FIGURE 8.4 shows a further improvement of the lead-time for all operations of 97 days and an average lead-time for a single order of 27.2 days. This improves by another 42% compared to the first optimization step and thus 66% compared to the initial state.

As lead-time and inventory are directly proportional, a significant reduction in WIP would be expected as a complementary measure.

9. THROUGHPUT OPTIMIZATION WITH visTOC

In accordance with the Theory Of Constraints, where a bottleneck is identified the bottleneck should be loaded to the maximum and all related non-bottleneck activity directed to support the efficiency of the bottleneck. Where a bottleneck is identified, lean techniques such as set up reduction, total productive maintenance and 5S may be used to address many workstation inefficiencies that impact utilization. In addition, a new form of visual controls can be incorporated to influence human behavior to further alleviated bottleneck impacts. In order to achieve action-guiding effectiveness, three components resulting from the research are integrated into a visual control system:

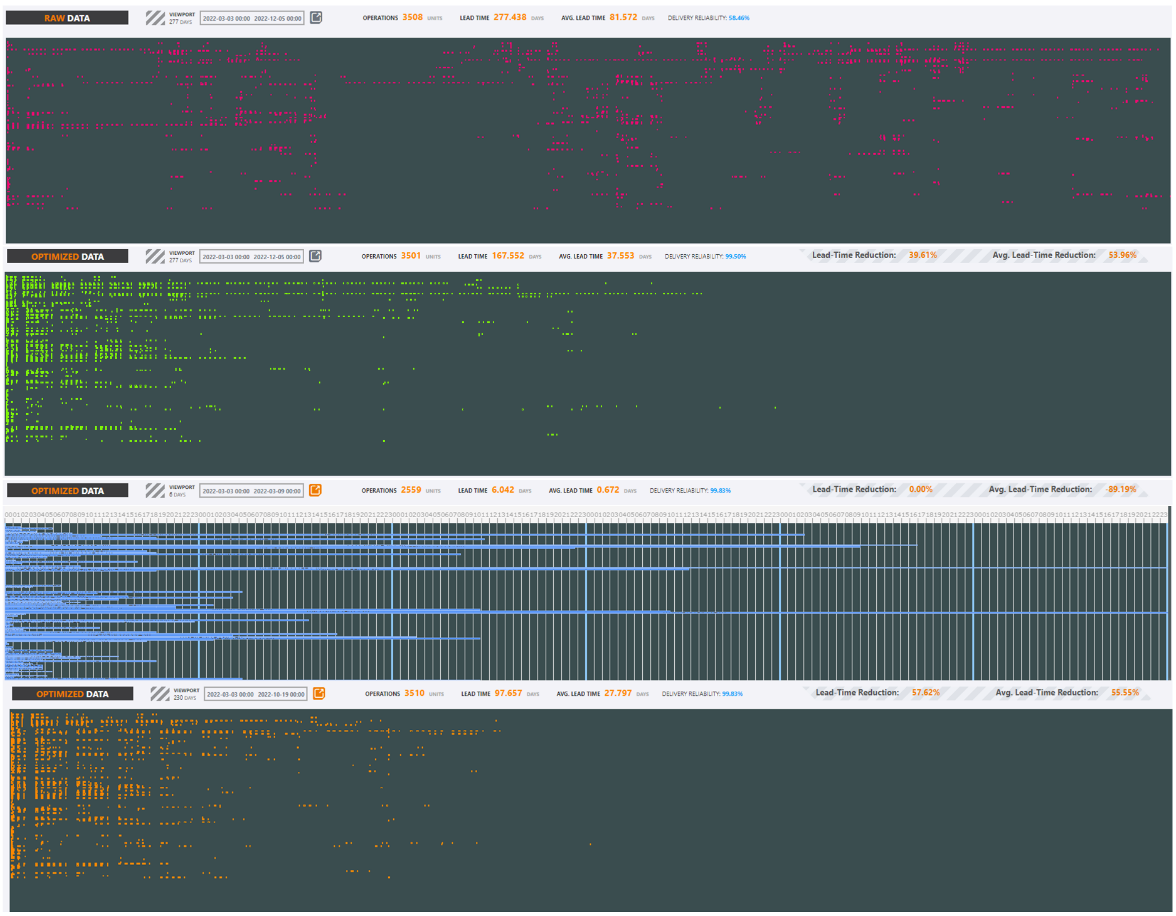

Figure 8: Figure 8.1-8.4 KI and PCB optimization (Source: own elaboration)

1) Bottleneck Marker (9.1): Employees receive real-time information that their workstation will soon become a bottleneck or is already the bottleneck for everyone else. This can be done by concise light signals up to floodlights. This is particularly important where dynamic bottlenecks are prevalent.

2) Utilization Indicator (9.2): Employees are shown the degree of utilization of the workplace generated by them. This provides them with feedback on the extent to which changes in behavior may bring the ROP closer to COP or DIOP. At the same time, the graphical display activates performance and self-esteem motives, and the self-commitment to agreed goals generated by negotiating the COP becomes effective.

3) Intervention Activator (9.3): In the event of process disruptions, this display makes it clear to all employees, including support personnel, to what extent their response and their speed are appropriate or in need of improvement.

We call this visual-automatic feedback system visTOC, as shown in FIGURE 9. The components in the system are further explained in the sections below. In the interaction of these three local

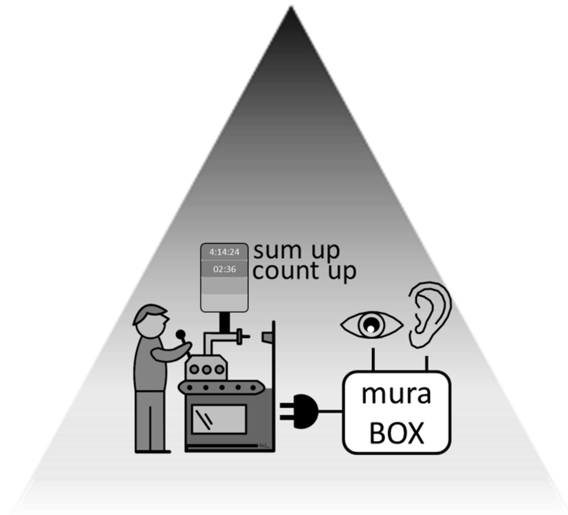

Figure 9: concept of visTOC (Source: own elaboration)

components with competent leadership, real throughput optimization can be achieved. This noticeably reduces the resistance to change frequently experienced on the part of managers. The tool “resistance radar”, which was developed by [50], was used to identify the main change resistances.

9.1 The Bottleneck Marker as an in and Out Spotlight

In organizations with high levels of lean maturity, principles such as the continuous improvement process, called CIP or kaizen, are just as anchored in increasing efficiency as installing meaningful habits, called kata. Surprisingly, even in these companies, employees often do not behave effectively at bottlenecks. We can identify two causes for this:

1) Employees are not aware in real time that and when their workplace is a bottleneck. We regularly find the situation that the local manager is aware of the current bottleneck situation, but this information does not reach the workstations.
2) Employees are simply not given the task of creating maximum utilization at the bottleneck and thus achieving the DIOP (Goldratt #2).

In the sense of eliminating the first cause, the situation at the respective workplace related to bottlenecks must be made clear to the employees continuously, insistently and in real time. Workstation operators, as well as management should be aware of whether a workstation is currently the bottleneck (display: bottleneck NOW), will soon become the bottleneck (bottleneck NEXT) or is currently not a bottleneck (display: RELAX), as shown in FIGURE 10 on the left. The research team proposes a striking form of visualization for this purpose where dynamic bottlenecks are prevalent. Above each possible bottleneck workstation, a luminous surface is installed on the hall ceiling, which in the case of “Bottleneck NOW” illuminates this workstation in a conspicuous manner, as depicted in FIGURE 10 right.

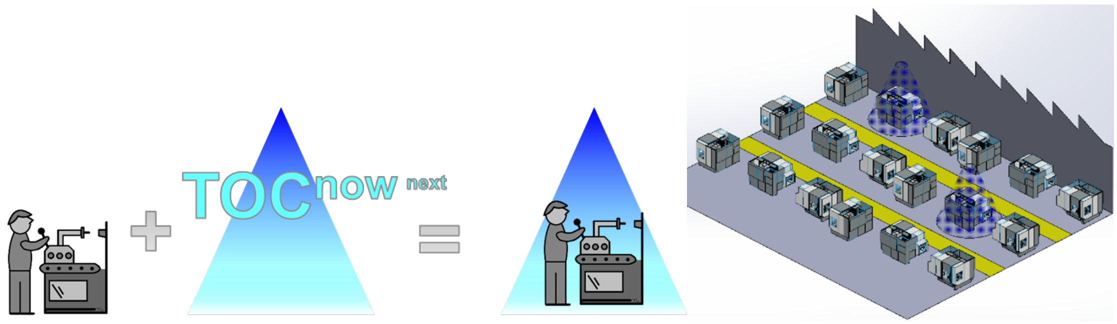

Figure 10: Spotlights for bottlenecks (Source: own elaboration)

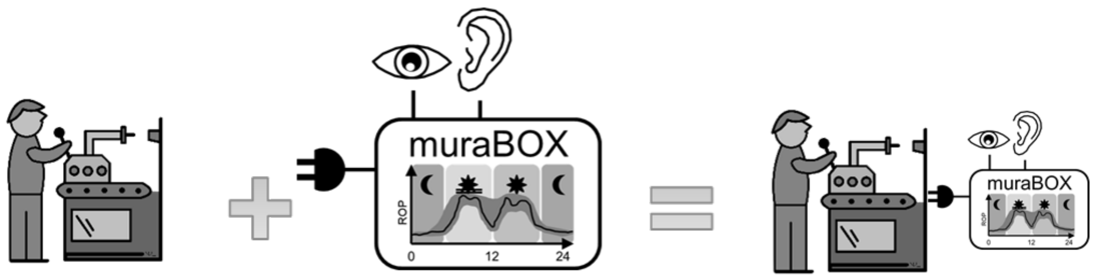

Figure 11: MURA Real Time Monitor (Source: own elaboration)

The spotlight highlighting makes it unmistakably clear to the bottleneck employee the importance of the workstation and that particular attention must be paid to the efficiency of the process which will often require behavior modification by the operator. In a dynamic bottleneck environment if an employee repeatedly finds himself in the company-wide spotlight, this will likely prompt precautionary action in the sense of behavioral prevention to become the center of attention less often. In addition, visibility generates pressure on management and other personnel not to interfere or distract the operator, and to provide immediate external support such as material handling which can help the operator to alleviate the bottleneck situation. The spotlight also alerts support personnel, such as maintenance, that should their services be required, the workstation takes priority.

Using a real-time value stream analysis in a dynamic environment the next bottleneck can be identified. This status of the bottleneck next is also made clear by means of an illumination, but with less urgency and different identification compared to the bottleneck now. Employees working there are thus encouraged to take measures to prevent the status of bottleneck now. The situation can be further highlighted by displaying a countdown to activate the performance motive. If the workstation enters the bottleneck now status, either planned or unplanned, the principles introduced for this purpose take effect. It is essential to regularly reflect on the processes and adjust them in order to achieve sustainable improvements.

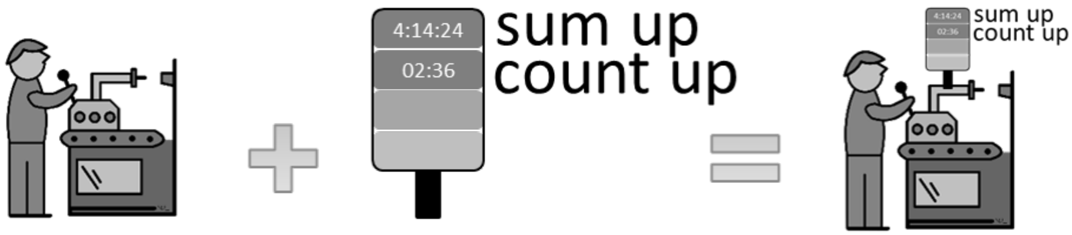

Figure 12: Slack Indicator (Source: own elaboration)

9.2 MURA Real-Time Monitor at the Bottleneck

To be able to act appropriately in real time, employees can benefit from a permanent information display about the instantaneous values of the ROP as a real output profile. This visualization of the dynROP is generated by a ROP monitor directly at the relevant workstation, as depicted in FIGURE 11. An "easy plug'n'play MURA box" also includes a ROP monitor as a central PCB unit. Optionally, the COP is also displayed so that the employee can permanently develop his work performance in line with his goals. For this reason, the display of the degree of ROP stability achieved is also of considerable motivational importance; it positively activates the performance motive.

The previous remarks make it clear that impactful capture periods for determining the ROP are, in particular, those during which the workplace is a bottleneck. Thus, the location and period of maximum effectiveness of interventions are clearly determined; we speak of ROP^{TOC}. Leadership efforts prove to be well invested exactly there and then maximally in terms of productivity as demonstrable leadership success.

9.3 CountUp / SumUp – Slack Indication

Another important piece of information that is suitable for positively activating both the self-esteem and performance motives is that relating to downtimes. For this purpose, a count-up signal lamp was developed which, in addition to the classic traffic light color elements green, yellow and red, contains a digital display for time information. This indicates in seconds how long the machine has already been in the STOP state, cf. FIGURE 12. This downtime could be due to any number issues from lack of material, machine breakdown, long setup times or lack of operator availability. The display can motivate an increase in the quality and speed of employee reaction where control of stoppage can be immediately influenced by employee action. Studies in operational practice show a considerable added value here: the obviousness of the time periods causes the problem to be stopped more quickly. As a further display, a SumUp module is integrated, which visualizes downtimes summarized and related to selectable time periods.

Many companies already have an evaluation of downtimes on real-time fault monitor systems. However, the results are only available in the offices and not on site, directly at the machines, where they could be directly effective. On-site visualization therefore leads to a direct and permanently effective influence on the work actions of the employees and thus on the ROP in the direction of COP or DIOP.

10. PHASE-CENTERED PERSONNEL MANAGEMENT AT THE BOTTLENECK

People are and remain the critical success factor in a company. The usage behavior of bottleneck machines, which is shaped by corporate culture, is transparently represented by the ROP. Crucially, the “new” task of how employees must behave relative to a machine while it is a bottleneck must be clearly and formally delegated by management. The two competing approaches of ‘adapting systems to users’ and ‘adapting users to systems’ can be flexibly adapted within the framework of the PCB approach: “Change your behavior only while you are working at a bottleneck!”. This requires a temporary and short-term change of behavior and leadership. The PCB leadership approach creates a bottleneck-oriented cultural realignment.

11. THE PCB AS A SOURCE OF INSPIRATION IN THE APPLICATION OF SIXSIGMA

Since the concepts of Six Sigma were developed by Motorola in the late 1980s [51], DMAIC, has become a prevalent approach to achieving breakthrough improvements in industry. The PCB has the potential to become an important tool in every phase of the structured approach of DMAIC.

The DMAIC phases were summarized in a generic manner by [52], as follows:

Define: Problem selection and benefit analysis

Measure: Translation of the problem into a measurable form, and measurement of the current situation

Analyze: Identification of influence factors and causes that determine the CTQs’ behavior

Improve: Design and implementation of adjustments to the process to improve the performance of the CTQs

Control: Adjustment of the process management and control system in order that improvements are sustainable

The PCB can help the problem selection process during the Define phase by highlighting inefficient use of critical resources as indicated in the Real Output Profile (ROP). A business case can be made for the improvement, particularly as noted for bottleneck equipment. Project improvement expectations can be established in the form of a Committed Output Profile (COP) for the resource [53, 54].

For the Measure phase, additional detail data as needed may be collected by ADaM24 relative to the output of the process. This data may be in the form of rate of output or quality level/yield, both of which can be depicted in an ROP. A measure, Vx, can be established as a baseline in the form of the ratio of the ROP to the COP.

During the Analysis phase, the detailed assessment of the ROP can indicate the times of the day in which the process needs improvement. A cause-and-effect analysis can then be performed which directly targets the conditions at the times in question.

The time selective project can then be implemented. In the Implementation phase, verification of effectiveness must be performed. By collecting additional data after implementation, a new statROP can be established for comparison to the previous ROP and will provide a visual depiction of an improvement. The new ratio, Vx, can also be compared to the previous and statistical analysis and may be performed to determine the significance of the change.

For the Control phase, periodic assessment of the process with the dynROP will show whether the process remains in an acceptable and stable state. The potential also exists for the development of a statistically based tool to monitor deviations.

The PCB provides a significant and helpful new tool for applications in all phases of DMAIC projects. Appropriate use of the information from the PCB using the varROP will help to reduce process variation and to achieve the breakthrough results in improving processes using the Six Sigma methodologies.

12. DISCUSSION AND CONCLUSION

By means of ADaM24, the Advanced Data Management over 24 hours, and the resulting production-cultural biorhythm PCB, a rich and effective set of tools is available to significantly improve the efficiency and flexibility of production processes. The PCB is used to identify the impact potential of interventions in production as a whole and at selected workplaces and to visualize them using visTOC.

The PCB provides a tool for analysis to target efforts to alleviate a static bottleneck. In a dynamic environment, interventions may only be relevant to results at a momentary bottleneck. Management efforts are concentrated locally at the respective current bottleneck and temporally on the phases of maximum potential identified with the help of the PCB. In conjunction with the bottleneck marker, the visTOC visualizations generate an understanding of the situation real time and promotes acceptance on the part of all employees. In this way, leadership becomes efficient and is now reduced to short, intensive phases. The incorruptible display of the DIOP target and the currently achieved performance values is also suitable for generating motivation as intended and for developing fundamental strategies for optimizing the handling of bottlenecks.

We refer to the entirety of this approach as the PCB topology, which is a further development of management systems.

In the future, a variety of new concepts and techniques will be developed for the factory of the future, towards dissolving assembly line work as a constraint (cf. Arena36, value stream kinematics).

Especially here it will be interesting to prove the expected PCB in the emerging cells and, if possible, to use it preventively for optimizations of the system design.

In this paper, we have highlighted a new area of improvement opportunities. Considering the current state of scientific field research, one factor in particular emerges in companies as being target-oriented for successful implementation of any change: the lived commitment of the management. This management commitment is needed to make the cultural changes needed to effectively address the bottlenecks and enable more efficient processes.

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