Available online at www.sciencedirect.com
ScienceDirect
Procedia Manufacturing 8 (2017) 300 – 307
Procedia MANUFACTURING

14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa

Considering Interdependencies of KPIs – Possible Resource Efficiency and Effectiveness Improvements

N. Stricker[a]*, M. Micali[b], D. Dornfeld[†b], G. Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany*
[b]*University of California, Berkeley, 1115 Etcheverry Hall, Berkeley, CA 94720, USA*
**Corresponding author*

Abstract

When an assembly line experiences downtime, it incurs both financial and productivity costs, in addition to environmental costs resulting from inefficient or ineffective uses of resources. Material is wasted in the form of scrapped work in progress (WIP), and energy is wasted in powering idle machines and facilities while the line is restored to an operational state. This work performs an analysis of 20 key performance indicators (KPIs) to investigate their potential impacts in maximizing the uptime of a simulated assembly line with automation and quality inspection. Previous work has not considered the linkages between baseline KPIs. The interdependencies and effects of baseline KPIs such as preventative maintenance time, corrective maintenance time, time to failure, and others are explored in order to analyze the production system on a more granular level. The results of this work inform production planning efforts and enable more effective and sustainable operation.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing

Keywords: Performance Measurement; KPI Sensitivity

1. Introduction

New product lifecycles, wide varieties of parts to produce, and increasingly dynamic markets [1] result in high production complexity [2]. Despite these challenges, a production system needs to perform well under all circumstances. In order to ensure this, the performance needs to be measured correctly. Understanding the productivity of a generalized production system lays the foundation for characterizing its performance, as well as aspects of its overall sustainability such as material and resource effectiveness. While measuring system productivity directly is possible, determining the root causes and relationships of production variability is complex, involving parameters that are difficult or infeasible to measure.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing
doi:10.1016/j.promfg.2017.02.038

Despite limitations on directly gathering some important information about a production system, the system can still be characterized by analyzing a set of quantities, or "indicators", which are easily measured. These values are typically not the exact quantities desired for analysis, however they are used as a proxy simply due to the fact that they are measureable. The indicators used are called key performance indicators (KPIs), and they can concentrate multiple metrics [3] into one numerical value [4]. A set of well-chosen key performance indicators can be closely related to important system quantities, and as such the KPIs can be treated as analytical variables.

1.1. Goal

Understanding the relationships that a KPI has with system quantities is important, but it is also important to identify and characterize the linkages and interdependencies between two KPIs. The goal of this work is to establish relationships between several of the more fundamental indicators.

Since higher-level KPIs can be calculated from a fundamental set of measured quantities, the addition of these fundamental interdependencies will allow better and more realistic estimations of the impacts that disturbances in the production system will have on overall performance or other indicators.

The interactions regarded in this work are quantitative in nature, and are investigated using a model of a production line with automation and failures in order to get a holistic view. The general framework and conclusion of the paper are also applicable to other production lines, which do not include parallel machines. As stated above, this paper deals with relationships between KPIs. Existing works on KPIs, especially in the relevant field of machine-related KPIs, are presented below.

1.2. Brief Overview of Existing Work

There are a variety of standards and works on KPIs in existence – the most relevant of which are [5], [6], [7], [8], and [9]. Additional relevant literature for the scope of this paper is [10]. The given calculation of each KPI carries information on its link to other KPIs. The calculation formulas, however, are not consistent throughout the literature. The lack of consistency precludes direct assessment of performance based purely on the existing standards.

Other work also presents statements on links between KPIs. Especially in the field of performance measurement, some quantifiable KPI systems have been established. Existing performance measurement systems were particularly focused on financial indicators, such as the R & L system [11] or the ZVEI system [12], [13]. The focus of this work is on non-financial KPIs, as we are more interested in the direct production performance. The Balanced Scorecard [14] widened the focus of the financial systems. It explicitly calls for other perspectives such as internal processes, knowledge, and customer perspective. It also stresses the need for considering the linkages between these perspectives. As no specific KPIs are predetermined for the fields, their relationships are not given but subject to discussion in the process of establishing a balanced scorecard.

The relationships between certain KPIs have been intensively studied in the field of production logistics. Exemplary work on the influence of on-time-delivery have been performed by [15] and [16]. [17] focuses on the relationship between lead time, capacity, costs and schedule variance. [18] also gives a detailed review and analysis of logistical KPIs. He increases the prediction accuracy of the theory of logistic operating curves and also supports the selection of appropriate improvement actions. These mentioned works focus on very specific logistical KPIs. The linkages between these were extensively studied, but a more general analysis on the variety of KPIs beyond logistics is missing. An approach focusing on a wider perspective is provided by [19]. The approach points out quantitative and qualitative connections between different processes and objectives. However, the processes and objectives are general, as opposed to clearly defined KPIs.

The existing work is either focused on the quantitative link between very few specific KPIs or financial measures, or regards broader connections without being linked to quantitative KPI-connections. Quantitative relations between several KPIs are required in order to realize the benefits mentioned earlier (e.g. the estimation of the effects of possible measures for improvement).

1.3. Specification of Scope

This paper focuses on production lines. A production line consists of several sequentially-interlinked machines. Buffers within and between the machines are also regarded as part of the production line. Buffers providing products to the first machine or storing products after processing on the last machine are not included in the scope. The KPIs focused within this scope consider maintenance and machine monitoring. Also the effects of individual machines on the overall performance of the line shall be described quantitatively in the KPIs.

1.4. Structure

The structure of the paper is as follows: Section 2 introduces the framework of machine-related KPIs which connects a higher-level KPI network (section 3) and includes machine health considerations, which are explained in more detail in section 4. Exemplary interactions of KPIs and their effects are shown in the case study of section 5. Section 6 gives the conclusions and a brief summary.

2. Framework

This paper shows relevant KPIs in the field of maintenance and machine monitoring. Many relevant KPIs can be identified in several international standards. Since the different standards use different wordings and have varying definitions, the KPIs have to be transformed into one consistent format. This transformation leads to a higher-level KPI network. The network consists of 21 KPIs, which are calculated from fundamental variables and measured directly in the production line. Standards treat the fundamental variables as independent from one-another, since no quantitative interactions among them are included.

The interaction of the fundamental variables will be discussed further in section 4. The defined interactions will be included in the framework to give a holistic view.

The resulting framework of KPIs can be seen in Fig.1. An arrow between two KPIs shows the existence of a quantitative relationship. The arrow's direction shows a cause-and-effect relationship. The KPI at the starting point of an arrow is the reason for a change in the connected KPI. The + or – on the arrows indicate if the influence is positive or negative, i.e. if an increase in the causing KPI result in an increase in the connected KPI (+) or in a decrease (-). The solid arrows show the interactions based on standards. The dashed arrows will be explained in section 4.

The overall framework in Fig.1 will be used to predict the effect of certain changes in the fundamental variables on the higher-level KPIs. As the effects on higher-level KPIs are often used to support decisions on possible improvement actions, the ability to predict these changes precisely is crucial. The following two sections show the higher-level network and the machine-health consideration for the framework.

3. Higher-Level KPI Network

The mentioned international standards have varying KPIs in the field of maintenance and machine monitoring. The standards have been combined and checked for inconsistencies. Among the different definitions of a KPI, the one most consistent with the other KPIs was chosen, or an adapted one established. This results in a KPI network covering the most relevant KPIs and their interactions.

The network primarily covers machine failures and other sources of machine downtime. Some KPIs can be directly measured on the shop floor, which are referred to as fundamental variables. Other KPIs are calculated from those fundamental variables. The standards assume the fundamental variables independent, and no quantitative relations among them are given.

A series of machines considered together is a production line. The machine-related KPIs therefore influence other KPIs of the whole production line. The KPIs considered in this paper are all machine level, aside from one production line KPI, the actual system technical delay time (ASTDET). Herein, the line is referred to as a system. Taking the ASTDET into account allows analysis of how the effects of changes on machine level propagate through the whole production line.

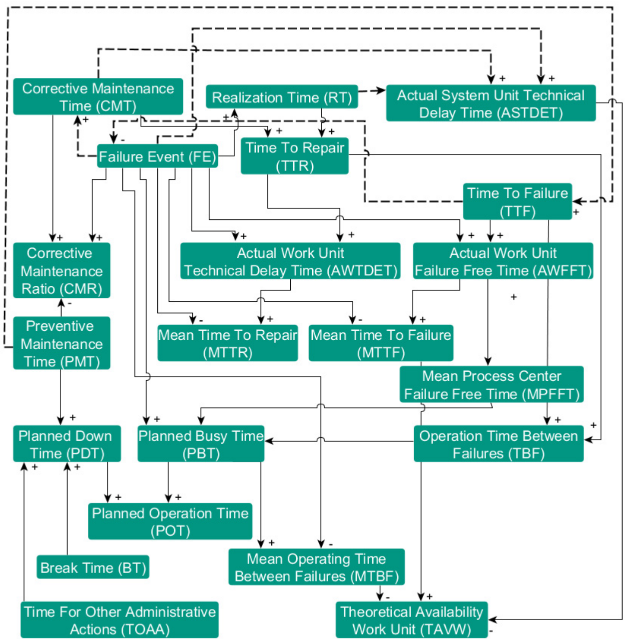

Fig. 1 Framework of higher-lever KPIs and machine-health considerations

The fundamental variables used are: break time (BT), preventive maintenance time (PMT), corrective maintenance time (CMT), realization time (RT), time for other administrative actions (TOAA), time to failure (TTF), actual system technical delay time (ASTDET) and the amount of failure events (FE). These fundamental variables build the basis for many other KPIs which can be seen in Fig.1.

The network and its underlying quantitative interactions between the KPIs allows for an estimation of the effect of changing fundamental variables. If the preventive maintenance time (PMT) were increased, how would the other KPIs change? This knowledge can be used as an evaluation of potential improvement actions. Apart from the KPIs seen in the framework section, other KPIs are also relevant in order to decide on possible improvement actions. The most important one might be the overall equipment effectiveness (OEE). The OEE integrates many fundamental variables. The fundamental variables are aggregated into higher level KPIs, which are further aggregated to other KPIs. These aggregation steps have to be repeated several times before the OEE is built. Thus, the OEE cannot directly be integrated in Fig.1; however, the general influence of the regarded fundamental variable on the OEE can be seen in Fig.2.

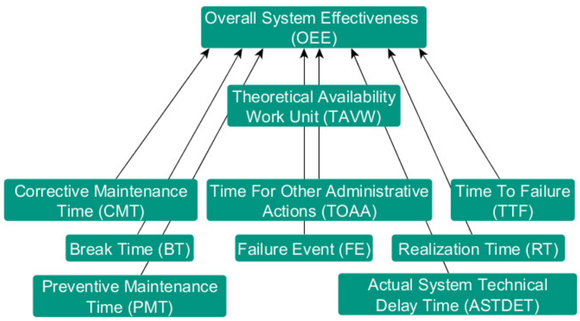

Fig. 2 OEE and links to fundamental variables

4. Machine-Health Considerations

Previous works have considered the fundamental variables in the higher-level KPI network to be independent of one another. This assumption was made due to the missing links in the international standards. The standards are not able to give a generally applicable quantitative interaction, since the effects among the fundamental variables are highly dependent on the individual machines. For example, the corrective maintenance time needed for a certain amount of failure strongly depends on the complexity and accessibility of the machine, as well as the availability of its components.

Thus, further analysis on the interactions of fundamental variables is needed. The machine-health considerations should give an idea on possible quantification of the fundamental variable interactions. The formulas established are not generally applicable, but they give examples. They are applied in a case study to show the impacts of the consideration of interactions between fundamental KPIs on the estimation of effects on higher level KPIs.

This section focuses on the links between the preventive maintenance time (PMT), the corrective maintenance time (CMT), the amount of failure events (FE), the time to failure (TTF) and the actual system technical delay time (ASTDET). The break time (BT) and the time for other administrative actions (TOAA) are planned time intervals, and they are both independent of the actual amount of maintenance time and failures. The same assumption holds for the realization time (RT) which describes the amount of time that is needed to identify a given failure. The RT will hardly be affected by the amount of individual failures.

The established interactions are based on basic knowledge of machine failures. Machines suffer from different kinds of failures: early failures, random failures and wear-out failures [20, 21, 22]. Only the wear-out failures can be addressed by preventive maintenance activities. The early failures could sometimes even be intensified by preventive maintenance activities, such as replacement of components. The random failures cannot be detected and are not affected by preventive maintenance activities. Given this knowledge, the preventive maintenance time and the amount of failure events cannot be independent. An increase in the preventive maintenance time will reduce the amount of wear-out failures, while the other failure types remain mostly unaffected. Accordingly, the corrective maintenance time is also linked to the preventive maintenance time. The more PMT is allocated, the fewer failures will occur. When fewer failures occur, less corrective maintenance time is required. As such, the downtime of the line due to technical failures will be reduced (ASTDET). The link between failure rate and time can be modelled in a so called bathtub curve [23]. It is a particular form of a hazard function. The specific parameters to fit the function to a regarded machine component often need to be determined by the means of experiments; however, even a simple modelling approach can lead to improvements when integrating them into the higher-level KPI network. The KPIs connected by a model, as presented in the next section, are shown as solid arrows in Fig.1. The effects of these interactions on the estimated change in the OEE is discussed in the following section.

5. Interaction Examples

The interactions with higher-level KPIs will be considered to estimate the effects of more detailed knowledge about machine health. The effect on the OEE will be analyzed in particular, due to its popularity and wide use. This example is conducted with analysis on a realistic sample production line.

5.1. Sample Production Line

The sample production line regarded is built of 23 machines, which are sequentially interlinked. The system does not contain any buffers, so a failure at any of the 23 machines will result in downtime of the entire line. This real industrial system is highly automated and allows realization times of 1 minute. For the regarded time period of 7 weeks, 15 failures were observed. The preventive maintenance activities for the whole line summed up to 7 hours (420 minutes). The corrective maintenance time (CMT) for each machine was 52 minutes. The complete interlinked and synchronized line had an actual technical downtime of 32 hours. That time is greater than the sum of CMTs for all machines because the ramp-up of the production line after an individual machine is corrected can take some additional time. Additionally, the conveyor belt has technical problems and that is not considered as part of the CMT for any individual machine.

These fundamental variable values for the actual system were recorded in a real production line. The regarded improvement action is an increase in the preventive maintenance time. The effect of increased PMT on the OEE shall be estimated.

5.2. Results

As an increased PMT can reduce the amount of wear-out failures, the CMT and the ASTDET for the production line are expected to decrease. In the higher-level KPI network, these fundamental variables are independent of one another, so the network does not give information about how much the count of failures changes as PMT is increased. To estimate the OEE using the higher-level KPI network, all fundamental variables need to be estimated because they are needed for the calculation of the OEE. A convenient approach to estimate all fundamental variables is to assume linear behavior. Given this assumption, the PMT and CMT also have linear relationships, since the mean time needed to repair a failure is constant.

With these assumptions, the effect of an increase in PMT on all other fundamental variables can be estimated. These fundamental variables will be the inputs for the higher-level KPI network, allowing estimation of the effect of increasing PMT on the OEE.

Machine health knowledge allows better estimation of the fundamental variables. As only late failures can be addressed by increasing PMT, the connection between PMT and the count of FE can be described in terms of exponential decay (see Fig.3).

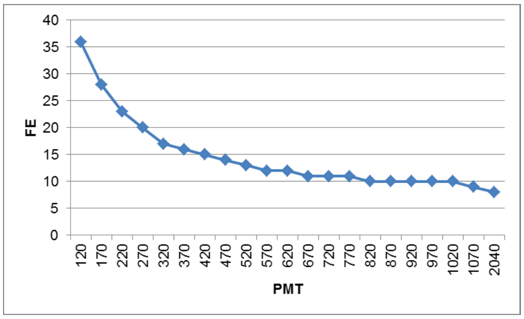

Fig. 3 Connection between PMT and FE

The parameters are pure estimates but still lead to more realistic FE values than the linear assumption does. The other fundamental variables CMT and ASTDET are calculated from the FE under the assumption of constant repair times per failure event.

$$CMT_{new}=CMT_{org}/FE_{org}*FE_{new} \qquad ASTDET_{new}=ASTDET_{org}/FE_{org}*FE_{new}$$

These differences have huge effects on the OEE. For the analysis, the PMT was increased in several steps. To achieve a good comparison between the assumption and the machine health considerations, the PMT was increased extremely. The PMT values considered are 420 minutes, 630 minutes, 840 minutes, and 1050 minutes, so the entire amount of maintenance time is shifted to preventive maintenance.

Table 1. Fundamental variables under linear assumption

PMT	7 hours	14 hours	40 hours	59 hours
FE	15	8	3	2
CMT	52 hours	26 hours	9 hours	5 hours
ASTDET	32 hours	26.6 hours	10.6 hours	6.3 hours

The effects on the OEE can be seen in Table 2. Given the linear assumption, the OEE increases to a value of 83%. The more realistic machine health considerations lead to an OEE of only 73%. The simple linear assumption neglects the fact that some failures cannot be eliminated by preventive maintenance (early failures, random failures). As a result, the linear assumptions leads to only two remaining failures, while the machine health considerations estimate nine remaining failures. More time is required for corrective maintenance, and thus the OEE increase is smaller.

Table 2. Fundamental variables under machine-health considerations

PMT	420 minutes	630 minutes	840 minutes	1050 minutes
FE	15	12	10	9
CMT	52 hours	42 hours	34 hours	31 hours
ASTDET	53.2 hours	46.1 hours	35.5 hours	31.9 hours

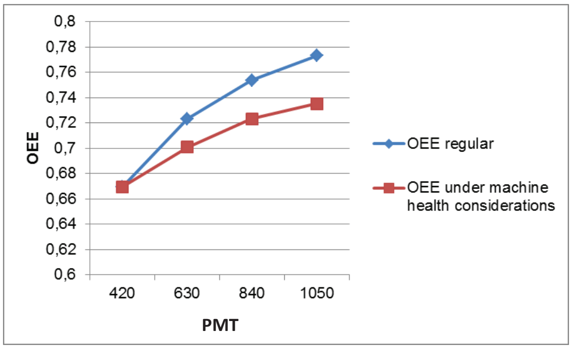

Fig. 4 Connection between PMT and OEE

If an improvement action is chosen based on a linear assumption, it may not pay off, as its effect on the OEE is smaller than expected. Fig. 4 shows calculated OEE values under varying PMT with linear assumptions (upper) and with consideration of machine-health (lower).

The sample calculations show large changes of the PMT; however, even smaller changes to 14 hours of PMT result in an OEE difference of 6%. Given typical small variations in the OEE, an increase of 6% is a remarkable improvement. Also, only the influence of the machine-related KPIs on the OEE was regarded. As the OEE is composed of many fundamental variables (e.g. out of the field of quality), the machine variables are only one influencing factor. The deviations can be seen clearly in the ASTDET in Table 1 and Table 2, which vary extremely even for small changes in the PMT.

6. Summary and Conclusions

This paper focused on maintenance and machine monitoring KPIs in production lines. It showed some of the most relevant KPIs in the field and their connections according to given international standards in the higher-level KPI network. The KPI used can be distinguished through fundamental variables, which can be measured on the shop floor, and other KPIs which are calculated from them. Both kinds of KPIs were adapted to be consistent with each other. The fundamental variables were assumed to be independent, since the standards do not give relations between them.

These relations can be used to estimate the effect of fundamental variable changes on the higher-level KPIs, which are often used to make operational decisions. Therefore, the simultaneous changes in all fundamental KPIs need to be estimated. This was done for a change in the preventive maintenance time (PMT) in a real production line. The simultaneous changes in the amount of failure events (FE), the corrective maintenance time (CMT) and the system technical downtime (ASTDET) were estimated, and the changes in the OEE were be calculated. These results were compared to an estimation, which takes into account further machine-health considerations. These considerations gave a relation between the named fundamental variables. Using this knowledge, the same changes in the PMT lead to different OEE values.

More knowledge built into the KPI framework results in more precise estimations of the effects of improvement actions. The importance of regarding all known KPI relations when estimation improvement effects was demonstrated in this example. Thus decisions can be taken based on more precise estimations. Through smarter operational decisions, manufacturing production lines become inherently more sustainable by maximizing their efficient utilization of assets and resources.

Acknowledgements

Research has been supported by the German Research Foundation (DFG) with the research project LA 2351/35-1. and the Karlsruhe House of Young Scientists (KHYS) at KIT, Germany. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1106400. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

[1] Scholz-Reiter, B., Freitag, M. & Schmieder, A. A Dynamical Approach for Modeling and Control of Production Systems, AIP conference proceedings, American Institute of Physics, Melville, N.Y., 2002, pp. 199–210.
[2] Monostori, L., Valckenaers, P., Dolgui, A., Panetto, H., Brdys, M. & Csáji, B. C. Cooperative control in production and logistics, Annual Reviews in Control, 39 (2015), pp. 12–29.
[3] Reichmann, T. Controlling mit Kennzahlen: Grundlagen einer systemgestützten Controlling-Konzeption, Verlag Vahlen, München, 2001.
[4] Horváth, P. Controlling, Verlag Franz Vahlen, München, 2002.
[5] International Organization for Standardization. Automation systems and integration. Key performance indicators (KPIs) for manufacturing operations management, 22400-2, 2014.
[6] Verein deutscher Ingenieure. Zuverlässigkeitskenngrößen, VDI Verlag, Düsseldorf, 4004-4, 1986.
[7] Verein deutscher Ingenieure. Materialfluss und Fördertechnik, VDI Verlag, Düsseldorf, 3649, 1992.
[8] Verband Deutscher Maschinen- und Anlagenbau. Manufacturing Execution Systems Kennzahlen, Beuth, Berlin, 66412-1, 2009.
[9] Verband Deutscher Maschinen- und Anlagenbau, Manufacturing Execution Systems Kennzahlen-Wirkmodell, Beuth, Berlin, 66412-2, 2010.
[10] Smith, D. J. Reliability, Maintainability and Risk, Elsevier Science, Burlington, 2011.
[11] Reichmann, T.; Lachnit, L. Planung, Steuerung und Kontrolle mit Hilfe von Kennzahlen, ZfbF, 28. Jg, 1976.
[12] Betriebswirtschaftlicher Ausschuß des Zentralverbandes Elektrotechnik und Elektronikindustrie (ZVEI) e.V. ,1989.
[13] Sandt, J. Performance measurement. Controlling und Management, 49(6), 2005, pp.429-447
[14] Kaplan, R. S. & Norton, D. P. The Balarlced Scorecord: Measures That Drive Performance, Harvard Business Review, 1992, pp. 71–79.
[15] Kuyumcu, A. Modellierung der Termintreue in der Produktion, 2013.
[16] Bertsch, S. Modellbasierte Berechnung der Termintreue, Garbsen, 2015.
[17] Kerner, A. Modellbasierte Beurteilung der Logistikleistung von Prozessketten, Garbsen, 2002.
[18] Busse, T. D. Modellbasierte Bewertung der Belastungsstreuung auf das logistische Systemverhalten, Garbsen, 2013.
[19] Knüppel, K. & Nikitin, I. Target-Based Evaluation of Disturbances in Production Systems, Advanced Materials Research, 1018 (2014), pp. 589–596.
[20] E. J. Henley and H. Kumamoto, Reliability Engineering and Risk Assessment, Prentice-Hall, 1981.
[21] Bertsche, B. ; Lechner, G.: Zuverlässigkeit im Fahrzeug- und Maschinenbau, Springer-Verlag, Berlin/Heidelberg, 2004.
[22] Abernethy, R B.: The New Weibull Handbook, Robert B. Abernethy Publishing, North PalmBeach, 2000
[23] Halley, E: An estimate of the degrees of the mortality of mankind, drawn from curious tables of the births and funerals at the city of Breslau; with an attempt to ascertain the price of annuities upon lives, Philosophical Trans. Royal Society of London 17 (1693), pp. 596–610