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A Hierarchical structure of key performance indicators for operation management and continuous improvement in production systems

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Key performance indicators (KPIs) are critical for manufacturing operation management and continuous improvement (CI). In modern manufacturing systems, KPIs are defined as a set of metrics to reflect operation performance, such as efficiency, throughput, availability, from productivity, quality and maintenance perspectives. Through continuous monitoring and measurement of KPIs, meaningful quantification and identification of different aspects of operation activities can be obtained, which enable and direct CI efforts. A set of 34 KPIs has been introduced in ISO 22400. However, the KPIs in a manufacturing system are not independent, and they may have intrinsic mutual relationships. The goal of this paper is to introduce a multi-level structure for identification and analysis of KPIs and their intrinsic relationships in production systems. Specifically, through such a hierarchical structure, we define and layer KPIs into levels of basic KPIs, comprehensive KPIs and their supporting metrics, and use it to investigate the relationships and dependencies between KPIs. Such a study can provide a useful tool for manufacturing engineers and managers to measure and utilize KPIs for CI.

Keywords: key performance indicator (KPI); manufacturing operation management (MOM); continuous improvement (CI); production systems; dependency; relationship; ISO 22400

1. Introduction

Modern manufacturing industry is becoming increasingly competitive. In order to fulfill the rapidly changing and diverse demands from customers, the manufacturing enterprises have to achieve and maintain high productivity and quality, with fast response, sufficient flexibility, and short lead times. Therefore, manufacturing industry has incorporated various measurement systems to evaluate the performance of manufacturing operation activities, defined as performance measurement systems (PMS). A PMS consists of a set of metrics that are able to quantify the efficiency and effectiveness of manufacturing operations (Neely 1995). Within a PMS, the strategic goals are first determined according to the enterprise's needs to success. Then each goal is supported by a set of detailed indicators contributing to fulfill the strategic goals. Such indicators are referred to as key performance indicators (KPIs).

In other words, KPIs are defined as a set of quantifiable and strategic measurements in a PMS that reflect the critical success factors of an enterprise. The appropriate selection and better understanding of the KPIs can help a firm achieve the desired business success. According to the reports of International Standard ISO 22400–1 (2014) and International Standard ISO 22400–2 (2014), KPIs play a crucial role in understanding and improving manufacturing system performance. The rapid development of information technology has provided unprecedented opportunities for sensing and control at the manufacturing operations management (MOM) level of an enterprise. Radio-frequency identifications, wireless sensors and network, program logic controllers, as well as laptops, tablets, and smart phones, have been extensively equipped on the factory floor in recent years. This has enabled data collection so that the KPIs can be easily obtained. A total of 34 KPIs have been presented in the reports of International Standard ISO 22400–1 (2014) and International Standard ISO 22400–2 (2014), along with their contexts and contents.

In manufacturing systems, once a KPI set is defined in a PMS, every parameter reflects one facet of the system performance. Since different aspects of performance are not independent and cannot be separated from each other, the KPIs also have mutual relationships. Some KPIs may be positively or negatively correlated. Some could be derived and replaced by others. To effectively utilize the KPIs for continuous improvement (CI) or production control, understanding these relationships is of importance. Thus, investigation of the relationships between KPIs can lead to a better understanding and effective use of

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them. Moreover, a much more profitable contribution of identifying the KPI relationships is that the management could rely on the existing known relationship to project and develop potential new KPIs and find the corresponding relationships.

Up to present, the investigation of KPI relationships mainly relies on data-based statistical approaches. Such a method does identify the positive or negative correlations between KPIs. However, it might fail to find the intrinsic connections and managerial insights. In addition, the data collected from different firms may lead to substantially distinct results. Therefore, a new approach to discover the KPI relationships via intrinsic implications needs to be developed.

To achieve this, the KPIs need to be appropriately layered in different levels, i.e. a hierarchical structure should be developed. Therefore, in this paper, we propose a research framework to recognize the intrinsic relationships of KPIs from their original definitions. Using and redefining the KPIs provided in the reports of International Standard ISO 22400–1 (2014) and International Standard ISO 22400–2 (2014) and introducing a few new KPIs, we present a hierarchical structure for KPI categorization. In each hierarchical level, multiple categories are introduced. Based on these, we further explore their detailed relationship and dependencies. These comprise the main contribution of this paper. The results can provide managerial insights for manufacturing enterprises and are applicable for most production systems.

The remainder of this paper is structured as follows. Section 2 reviews the related literature. Section 3 defines some KPIs and provides a categorization for KPIs. Section 4 investigates the relationships between KPIs. The dependencies between KPIs and their supporting measurements are discussed in Section 5. A case study of using KPI to improve production line performance at an automotive manufacturing plant is introduced in Section 6. Finally, conclusions are given in Section 7.

2. Literature review

Manufacturing systems research has attracted substantial attention, where performance analysis has been a major issue of it. Typically, throughput, inventory, lead time, and customer demand satisfactions are the main emphases (see monographs by Viswanadham and Narahari (1992), Buzacott and Shantikumar (1993), Papadopoulos, Browne, and Heavey (1993), Tempelmeier and Kuhn (1993), Gershwin (1994), Zhou and Venkatesh (1999), Li and Meerkov (2009) and reviews by Dallery and Gershwin (1992), Papadopoulos and Heavey (1996), Li et al. (2009)).

PMS for MOM have been studied extensively in recent decades. Financial measures are the main focuses (Ghalayini 1997). However, it has been argued that such a tradition has defects in measuring and integrating the whole metrics critical to the success of a business enterprise (Kaplan 1983; Kaplan 1984; Hayes, Wheelwright, and Clark 1988; Eccles 1991; Fisher 1992; Maskell 1992). To overcome this, many new PMS are developed, such as activity based costing system (Cooper 1988; Cooper 1988; Cooper 1988; Cooper 1989), balanced scorecard (Kaplan and Norton 1996), SMART system (Cross and Lynch (1988)), performance measurement questionnaire (Dixon, Nanni, and Vollman 1990), and integrated dynamic performance measurement system (Ghalayini 1997). Neely (1995) study the performance measurements and their relationship with environment after a review of massive papers and propose a guideline for the design of PMS. Gomes (2004) review the literature on issues related to the different facets of manufacturing organizational performance and identifies some issues relevant to the practice and theory of manufacturing PMS.

Closely related to PMS, the KPIs in production systems have received much interest from researchers in recent years. Rakar et al. (2004) establish a set of KPIs which is able to capture the state of a production system. Ahmad and Dhafr (2002) also build KPIs to quantitatively assess the manufacturing performance of a company. Arinez et al. (2010a) employ discrete event simulation modeling to combine the traditional production KPIs with process energy KPIs and give benchmarks to production system, process energy, and facility energy performance.

The relationships of KPIs are also discussed by many researchers, most of which use data-based methods and apply statistical approaches. Rodriguez (2009) quantitatively investigate the cause-effect relationships of KPIs defined in a performance measurement system. A principal components analysis method is employed to obtain the correlations of indicators. Suwignjo (2000) develop quantitative models for performance measurement systems to identify factors affecting performance and their relationships numerically, where the methodology of cognitive maps is used. Sarkis (1997) investigates the relationship of productivity performance measures of flexible manufacturing systems as they become more complex. Standard data envelopment analysis and cross-efficiency techniques are utilized.

In another direction, by using mathematical models of production lines, bottleneck indicators have been developed to identify and mitigate bottleneck in manufacturing systems for productivity improvement (see Jacobs and Meerkov 1995; Kuo et al. 1996; Chiang, Kuo, and Meerkov 1998, 2000, 2001; Li and Meerkov 2000; Li 2004b; Biller 2010; Meerkov and Zhang 2010, 2011) and quality improvement (e.g. Wang et al. 2010; Wang, Li, and Huang 2012; Wang et al. 2013; Ju et al. 2013, 2014).

In spite of these efforts stated above, the intrinsic relationships of KPIs in production systems are still largely not understood. This paper is intended to contribute to this end by developing a hierarchical structure and using it for KPI relationship investigation.

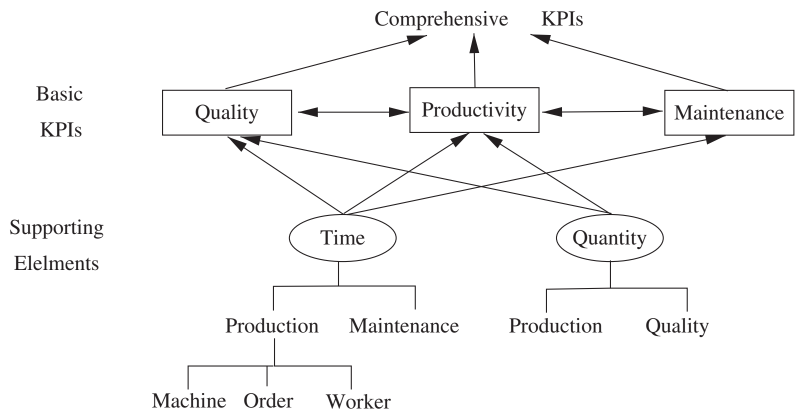

Figure 1. KPI categorization.

3. Definitions, hierarchicalization and categorization of KPIS and their supporting elements

Although reports of International Standard ISO 22400–1 (2014) and International Standard ISO 22400–2 (2014) describe 34 KPIs, more rigorous definitions are needed to clearly distinguish them. Some KPIs need to be redefined and additional KPIs should be included. Moreover, these KPIs should be categorized logically so that it will be convenient to discover the intrinsic relationships among them. Therefore, it is necessary to group the KPIs into multiple categories in various levels, which have explicit cross links.

In production systems, many raw measurement elements are monitored and collected, such as, machine's busy time and production volume. Based on these elements, KPIs of interests to engineers and managers can be derived and evaluated, for instance, efficiency or quality. Thus, the directly monitored elements become the supporting metrics for KPIs. These KPIs mostly reveal a single aspect of system performance only, thus are categorized as basic KPIs. To represent the overall performance, more comprehensive KPIs, supported by several basic KPIs, can be obtained. For example, the overall equipment effectiveness (OEE) index, which is based on individual equipment's (or a group of equipments' overall) working and failure time allocation, provides information related to production efficiency and production loss. The throughput of a production line is dependent on all the machines, the buffers, their positions and interactions. Therefore, based on these attributes, the supporting role, single function, and comprehensive feature of these elements or indicators, we introduce a hierarchical structure to categorize KPIs and the supporting elements.

Specifically, such a structure consists of three categorized levels: direct measurement or supporting elements, basic KPIs, and comprehensive KPIs, as shown in Figure 1. In addition, we group the parameters based on their functions or attributes in each level. In the supporting elements level, the measurements can be divided into time and quantity groups. Within time group, there will be time measurements related to production and maintenance, from the point of view of machines, production orders, and operating workers. In quantity group, measurements are related to quantities on both production and quality. For basic KPIs, the attributes are related to production, quality, and maintenance. These KPIs are calculated by the direct measurements. They all contribute to the comprehensive KPIs. Note that, the relationships not only exist between different levels of KPIs and supporting elements, but also can link KPIs within the same level, which are shown as double arrows between quality, productivity, and maintenance.

Such a hierarchical framework explicitly indicates the causal relationships between different levels of KPIs and supporting elements. Clearly, such a categorization is not unique. Other types of grouping structure can be developed based on the specific goals. Below, the KPIs and supporting metrics illustrated in Figure 1 are described. Since supporting elements are needed to derive the basic and comprehensive KPIs, these elements are presented first.

3.1 *Supporting elements*

The supporting elements are the data directly monitored and collected during production. Using these elements, the basic KPIs can be derived. In the proposed framework, the supporting elements can be divided into two categories: time and quantity.

3.1.1 *Time elements*

The time elements are the data related to the time durations in production systems operations. They are time measurements describing activities related to production and maintenance. In a production process, such times can be measured from the points of view of a machine, a production order, or an operator. Starting with the elements provided in International Standard ISO 22400–2 (2014), we modify and redefine them and introduce new ones to make them rigorously presented.

First, consider a machine or work center, the following time periods can be planned:

- *Planned operation time* (POT): The scheduled time during which a machine can be utilized.
- *Planned busy time* (PBT): The planned time during which a machine is busy.

Such two time periods are not the same due to scheduled non-working time. Thus, to address the relationship between them, the following element is introduced:

- *Planned down time* (PDOT): The planned time during which a machine is unable to produce, which may include scheduled breaks, meetings, maintenance, etc.

Then we obtain

$$\mathrm{POT} = \mathrm{PBT} + \mathrm{PDOT}. \tag{1}$$

Next, from a work piece or production order point of view, we have

- *Planned run time per item* (PRI): The planned time to produce one piece or part.
- *Planned unit setup time* (PUST): The planned time for a machine to setup for an order.
- *Planned order execution time* (POET): The scheduled time for executing an order.

Considering that a production order has processed part quantity PQ, then we obtain

$$\mathrm{POET} = \mathrm{PRI} \cdot \mathrm{PQ} + \mathrm{PUST}. \tag{2}$$

However, the planned time may not be exactly observed in production, due to breakdowns, unbalancing, etc. Thus, the actual time periods are introduced below based on a production order on a single machine or work unit.

- *Actual unit processing time* (AUPT): The time necessary for production and setup on a machine for an order.
- *Actual production time* (APT): The actual time in which the machine is producing for an order, which only includes the value-adding functions.
- *Actual unit setup time* (AUST): The time used for the preparation, i.e. setup, of an order on a machine.

Thus, the following relationship is observed:

$$\mathrm{AUPT} = \mathrm{APT} + \mathrm{AUST}. \tag{3}$$

In addition, to characterize the actual down time, we define

- *Actual unit down time* (ADOT): The actual time in which the production process is delayed due to malfunction-caused interruptions, minor stoppages, and other unplanned events.
- *Actual unit idle time* (AUIT): The actual time when the machine is not executing order production even if it is available. This can also be referred to as *actual unit delay time* (ADET).

Then the actual busy time can be introduced as

- *Actual unit busy time* (AUBT): The actual time that a machine is used for the execution of a production order.

We obtain

$$\mathrm{AUBT} = \mathrm{AUPT} + \mathrm{ADOT}, \tag{4}$$
$$\mathrm{PBT} = \mathrm{AUBT} + \mathrm{ADET}. \tag{5}$$

During completion of a production order, a machine may need to load or unload the part, and the part may need to wait in a buffer or on a machine due to machine interactions with other working units. Such times are defined as follows:

- *Actual order execution time* (AOET): The time from the start of an order to its completion on a machine.

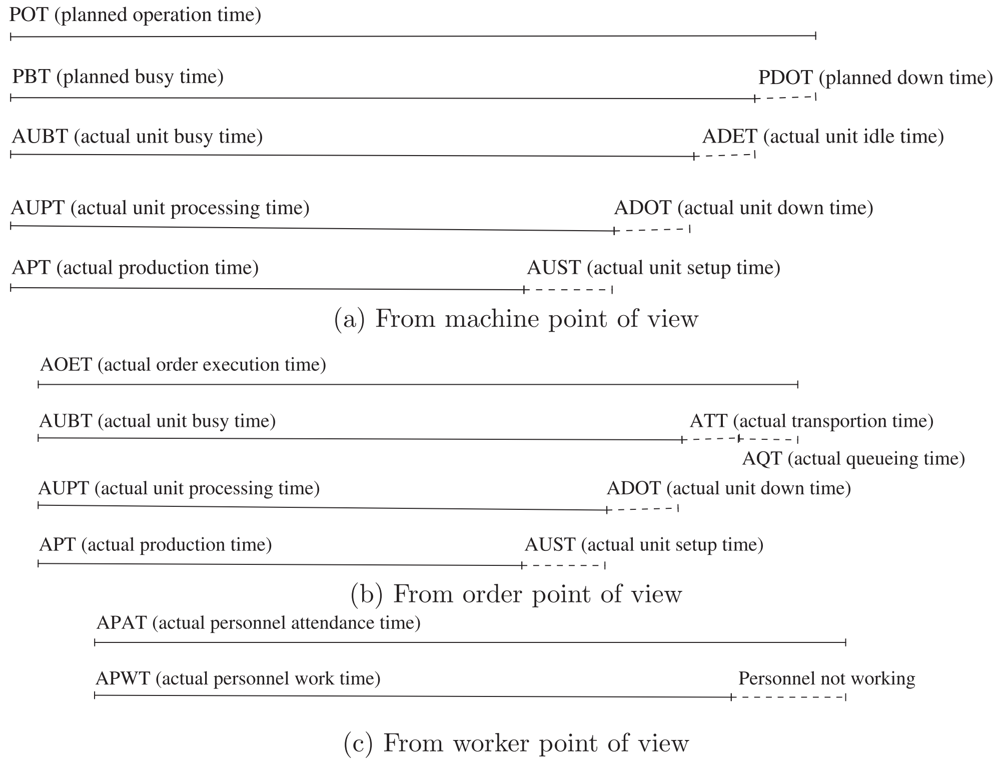

Figure 2. Time elements.

- *Actual transportation time* (ATT): The actual time for transporting parts on or between machines, such as loading and unloading time.
- *Actual queueing time* (AQT): The actual time during which the material is waiting to go through a manufacturing process, i.e. queueing time in a buffer. Sometimes, such queueing time is also referred to as *residence time in buffer*.

The relationship is presented as:

$$\mathrm{AOET} = \mathrm{AUBT} + \mathrm{ATT} + \mathrm{AQT} + \mathrm{ADET}. \tag{6}$$

Moreover, from a worker or an operator point of view, we have

- *Actual personnel attendance time* (APAT): The actual time that a worker is available to work on production orders.
- *Actual personnel work time* (APWT): The time that a worker needs to execute a production order.

Clearly, the difference between them is the time the worker is not working.

The above mentioned relationships are illustrated in Figure 2.

3.1.2 *Quantity elements*

In addition to time elements, the quantity elements (most of them are referred to as logistical elements in International Standard ISO 22400–2 (2014)) provide information on issues related to product quality and quantity. Some major quantity elements are defined as follows.

- *Good quantity* (GQ): The produced quantity that meets quality requirements in the first time of an operation process.
- *Scrap quantity* (SQ): The produced quantity that does not meet quality requirements and has to be scrapped or recycled.
- *Planned scrap quantity* (PSQ): The amount of process-related scrap that is expected when manufacturing the product.
- *Rework quantity* (RQ): The quantity that fails to meet the quality requirements, but these requirements can be met by reprocessing.

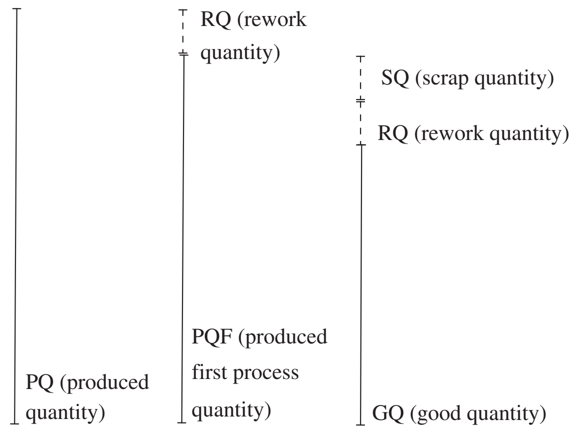

Figure 3. Quantity elements.

- *Processed quantity* (PQ): The quantity that a work unit has processed (which may include the reworked ones and scraped ones).
- *Produced quantity in the first operation process* (PQF): The quantity that a machine has produced in the first time of an operation process.

Assume all reworked parts are in good quality, then the relationship between these quantities can be described as

$$\mathrm{PQF} = \mathrm{GQ} + \mathrm{SQ} + \mathrm{RQ}, \tag{7}$$
$$\mathrm{PQ} = \mathrm{PQF} + \mathrm{RQ}. \tag{8}$$

An illustration of such quantities is shown in Figure 3. Moreover, in practice, PSQ is the planned scrapped quantity, which can be different with the actual SQ. The PQF is the first time quantity, which is used to define first time quality in many practices.

When the reworked parts need multiple times of reprocessing, then the PQ relationship with PQF will add more RQs each time. In other words, if the parts are reworked N times, then

$$PQ = GQ + SQ + (N + 1) \cdot RQ.$$

The formula can be more complicated if each rework results in different number of good quality parts. Reference for studying systems with rework loops can be found in Li (2004a), Li (2004b), Li et al. (2008), and Biller (2010).

3.1.3 *Maintenance elements*

The maintenance elements record information related to maintenance and repair issues of machines. Based on elements introduced in International Standard ISO 22400–2 (2014), some important maintenance elements are defined or modified below.

- *Time to failure* (TTF): The actual time during which a machine is able to produce, starting from the completion of the repair and ending at a new failure. Such element is also referred to as *Time between failure* (TBF).
- *Operating time between failures* (OTBF): The actual unit production time between two consecutive failures of a machine.

The difference between TBF and OTBF on an order will be the idle time and setup time. Then the relationship between them can be described as

$$\mathrm{TTF} = \mathrm{TBF} = \mathrm{OTBF} + \mathrm{ADET} + \mathrm{AUST}. \tag{9}$$

- *Time to repair* (TTR): The actual time during which a machine is unavailable due to a failure, i.e. under repair.
- *Failure event* (FE): The count over a specified time interval of the terminations of the ability for a machine to perform a required operation.

- *Corrective maintenance time* (CMT): The part of maintenance time during which corrective maintenance is performed on a machine.
- *Preventive maintenance time* (PMT): The part of maintenance time during which preventive maintenance is performed on a machine.

In addition to the above elements, energy related elements could illustrate the information related with energy costs. Since such elements are largely unexplored, they are skipped in this paper, but certainly will be an important part in future research.

3.2 *Basic KPIs*

Each basic KPI reveals an aspect of performance for a work unit or system, derived from monitored data of supporting elements. The basic KPIs can be grouped by those representing a group of aspects with similar attributes. In the proposed structure, different from International Standard ISO 22400–2 (2014), we categorize the basic KPIs into three groups: aspects from production, quality, and maintenance. Again such grouping is not unique. Below these groups are described in details.

3.2.1 *Production KPIs*

Some important KPIs addressing production issues are grouped and defined below. First, consider the KPIs at a work unit or machine level.

- *Availability* (A): The percentage of actual time a machine is available, i.e. the APT among the PBT for a machine. It represents the portion of time used for processing compared to the total time that includes AUST, delay time and down time.

$$A = \frac{\text{APT}}{\text{PBT}} \cdot 100\%. \tag{10}$$

The availability is similar to the so called efficiency. Based on various purposes, different efficiency aspects can be defined.

- *Allocation efficiency* (AE): The actual usage and availability of the planned capacity of a machine, which is measured by the ratio of AUBT to planned unit busy time (PBT). The complementary part is the percentage of actual unit downtime.

$$\text{AE} = \frac{\text{AUBT}}{\text{PBT}} \cdot 100\%. \tag{11}$$

- *Technical efficiency* (TE): The efficiency of production vs. malfunction-caused interruptions. It represents the relationship between APT and the sum of APT and ADOT that includes times of malfunction-caused interruptions.

$$\text{TE} = \frac{\text{APT}}{\text{APT} + \text{ADOT}} \cdot 100\%. \tag{12}$$

- *Worker efficiency* (WE): The efficiency of a worker's attendance in production, measured by the relationship between the actual personnel's work time (APWT) related to production orders and the actual personnel's attendance time (APAT).

$$\text{WE} = \frac{\text{APWT}}{\text{APAT}} \cdot 100\%. \tag{13}$$

- *Utilization efficiency* (UE): The productivity of a machine, measured by the ratio between the APT and the AUBT. If the actual unit delay time and setup time are high, the UE will be low.

$$\text{UE} = \frac{\text{APT}}{\text{AUBT}} \cdot 100\%. \tag{14}$$

The following additional KPIs also characterize the efficiency.

- *Effectiveness* (E): How effective a machine can be during the production time, measured by the ratio of planned target cycle time (represented as planned runtime per item (PRI)) to actual cycle time (expressed as APT divided by produced quantity (PQ)).

$$\text{E} = \frac{\text{PRI}}{\frac{\text{APT}}{\text{PQ}}} \cdot 100\% = \frac{\text{PRI} \cdot \text{PQ}}{\text{APT}} \cdot 100\%. \tag{15}$$

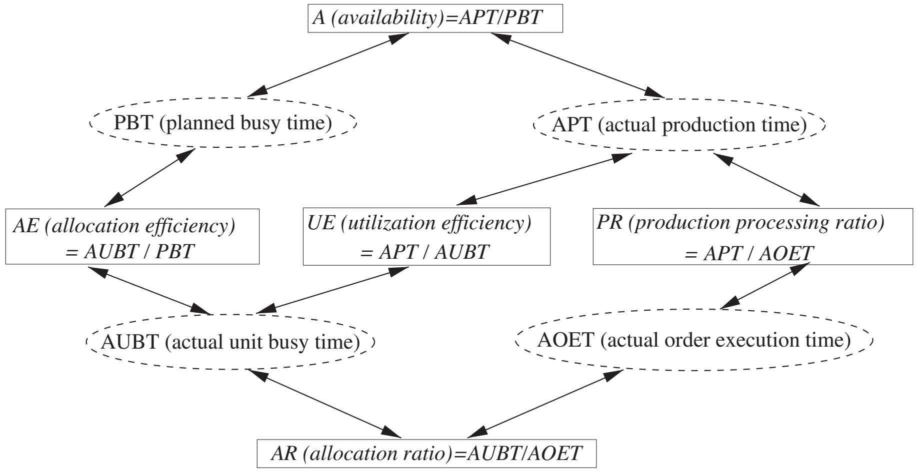

Figure 4. Graphic demonstration of KPI definitions.

- *Setup ratio* (SeR): The relative loss of value adding opportunity for a machine due to setup, measured by the ratio of AUST to AUPT. The complementary proportion is the APT.

$$\mathrm{SeR} = \frac{\mathrm{AUST}}{\mathrm{AUPT}} \cdot 100\%. \tag{16}$$

Second, by considering the whole production line or all machines in a production system, the following KPIs are defined.

- *Allocation ratio* (AR): The percentage of actual busy time of all machines ($AUBT$) among the AOET of a production order. The complementary proportion describes the ratio of actual queuing and transportation time.

$$\mathrm{AR} = \frac{\mathrm{AUBT}}{\mathrm{AOET}} \cdot 100\%. \tag{17}$$

- *Production process ratio* (PR): The efficiency of production when considering the actual unit setup time, delay time, transportation time, and queuing time. It is the ratio between the APT over all work units and work centers involved in a production order and the whole throughput time of a production order which is the AOET.

$$\mathrm{PR} = \frac{\mathrm{APT}}{\mathrm{AOET}} \cdot 100\%. \tag{18}$$

- *Throughput rate* (TR): The process performance indicator in terms of produced good part quantity of an order (GQ + RQ assuming that the reworked parts are in good quality) and the actual execution time (AOET), measured by the ratio of PQ and AOET. Since PQ is a quantity related metric, throughput rate also belongs to the quantity category as well.

$$\mathrm{TR} = \frac{\mathrm{GQ} + \mathrm{RQ}}{\mathrm{AOET}} \cdot 100\%. \tag{19}$$

Using the above definitions, we are able to graphically demonstrate the definitions of KPIs. An example is shown in Figure 4, where the KPIs are presented in solid boxes with italic fonts, and the supporting elements are in dash ovals in regular fonts.

However, the above KPIs only provide basic information of machine or a facility (from an aggregated point of view) performance. They do not depict interactions between machines and material handling systems. Some fundamental measurements that are critical to operation effectiveness are still missing. Therefore, the following new basic KPIs are introduced below:

- *Blockage ratio* (BL): The idle time portion of an equipment due to events that the parts cannot go downstream, which indicates the influence of production interruption from the downstream.
- *Starvation ratio* (ST): The idle time portion of an equipment due to events that the parts cannot arrive from upstream, which indicates the influence of production interruption from the upstream.

- *Work in process* (WIP): The average of total number of work in the system at one time. Sometimes it also refers to buffer occupancy when machines do not hold parts.

To calculate these new KPIs, the supporting elements also need to be expanded. Specifically, the blockage time and starvation time need to be monitored.

- *Blocking time* (BLT): The idle time of an equipment during events that parts cannot go downstream.
- *Starving time* (STT): The idle time of an equipment during events that parts cannot arrive from upstream.
- *Buffer capacity* (B): The capacity of the buffer, i.e. the maximal number of parts a buffer can accommodate.

Then the blockage and starvation ratios can be calculated using these elements.

$$\mathrm{ADET} = \mathrm{BLT} + \mathrm{STT}, \tag{20}$$

$$\mathrm{BL} = \frac{\mathrm{BLT}}{\mathrm{PBT}} \cdot 100\%, \tag{21}$$

$$\mathrm{ST} = \frac{\mathrm{STT}}{\mathrm{PBT}} \cdot 100\%. \tag{22}$$

3.2.2 *Quality KPIs*

Some important KPIs related to quality are defined as follows.

- *Actual to planned scrap ratio* (SQR): The relationship of the actual SQ and the PSQ, indicating how much scrap is produced compared with the expected value.

$$\mathrm{SQR} = \frac{\mathrm{SQ}}{\mathrm{PSQ}} \cdot 100\%. \tag{23}$$

  Clearly a lower value of SQR is preferred since it implies less scrap than expected. However, a constant low SQR value may indicate that the PSQ is too high, which may result in inefficient resource allocation.
- *Scrap ratio* (SR): The relationship between the SQ and PQ.

$$\mathrm{SR} = \frac{\mathrm{SQ}}{\mathrm{PQ}} \cdot 100\%. \tag{24}$$

- *Rework ratio* (RR): The percentage of RQ among PQ.

$$\mathrm{RR} = \frac{\mathrm{RQ}}{\mathrm{PQ}} \cdot 100\%. \tag{25}$$

- *Fall off ratio* (FR): The fall off quantity for a specific production operation in relation to the produced quantity in the first operation, measured by the ratio between the fall off quantity (calculated as produced quantity on the first production order sequence minus the GQ on the current production order sequence) and the produced quantity in the first operation.

$$\mathrm{FR} = 1 - \frac{\mathrm{PQF}}{\mathrm{PQ}} \cdot 100\%. \tag{26}$$

In addition, in practice, the first time quality and the quality buy rate are typically used to characterize the quality performance of a manufacturing process (see Li et al. 2008). Thus, these two KPIs are introduced below:

- *First time quality* (FTQ): The percentage of good quality parts going through the manufacturing process in the first time.

$$\mathrm{FTQ} = \frac{\mathrm{GQ}}{\mathrm{PQF}} \cdot 100\%. \tag{27}$$

- *Quality buy rate* (QBR): The overall percentage of good quality parts after reworks.

$$\mathrm{QBR} = \frac{\mathrm{GQ} + \mathrm{RQ}}{\mathrm{PQ}} \cdot 100\%. \tag{28}$$

Note that the reworked parts are included in the numerator since they become good quality parts after rework. Such a ratio is also referred to as quality rate (QR). However, the QR defined in International Standard ISO 22400–2 (2014) does not include the reworked parts.

These KPIs can be cross linked through the following relationships.

$$\mathrm{FR} = = 1 - \mathrm{QBR} - \mathrm{SR} = 1 - \frac{\mathrm{PQF}}{\mathrm{PQ}}, \tag{29}$$

$$\mathrm{FTQ} = \frac{\mathrm{GQ}}{\mathrm{PQF}} = \frac{\mathrm{GQ}}{\mathrm{PQ} \cdot (1 - \mathrm{FR})}. \tag{30}$$

3.2.3 *Maintenance KPIs*

By averaging all the repair times and operation times in supporting elements, we obtain the following important mean time KPIs:

- *Mean time to failure* (MTTF) or *Mean time between failure* (MTBF): The average TTF or TBF over a long time period.
- *Mean time to repair* (MTTR): The average TTR over a long time period.
- *Mean operating time between failures* (MOTBF): The average OTBF over a long time period.
- *Mean delay time* (MDET): The average ADET over a long time period.
- *Mean setup time* (MSET): The average AUST over a long time period.

Then the average performance will also follow the similar relationships:

$$\mathrm{TTR} = \mathrm{FE} \cdot \mathrm{MTTR}, \tag{31}$$

$$\mathrm{TBF} = \mathrm{FE} \cdot \mathrm{MTBF}, \tag{32}$$

$$\mathrm{MTBF} = \mathrm{MOTBF} + \mathrm{MDET} + \mathrm{MSET}. \tag{33}$$

Moreover, the maintenance ratio is defined as:

- *Corrective maintenance ratio* (CMR): The magnitude of corrective tasks with all maintenance activities performed in a work unit, calculated as the ratio of total corrective maintenance time (CMT) to the sum of CMT and preventive maintenance time (PMT).

$$\mathrm{CMR} = \frac{\mathrm{CMT}}{\mathrm{PMT}} \cdot 100\%. \tag{34}$$

3.3 *Comprehensive KPIs*

Using the basic KPIs, the comprehensive KPIs are defined.

- OEE: The product of a machine's availability, effectiveness, and quality ratio (i.e. QBR). It is an indicator for the efficiency of machines, work centers, and areas with multiple machines or an entire work center.

$$\mathrm{OEE} = \mathrm{A} \cdot \mathrm{E} \cdot \mathrm{QBR}. \tag{35}$$

- *Net equipment effectiveness* (NEE): Similar to OEE but it includes the setup time by changing the availability KPI to the ratio of AUPT and PBT.

$$\mathrm{NEE} = \frac{\mathrm{AUPT}}{\mathrm{PBT}} \cdot \mathrm{E} \cdot \mathrm{QBR}. \tag{36}$$

- *Line throughput rate* (LTR): The throughput rate of the whole production line, which is dependent on all the operations, buffers, their positions and interactions. In the case of finite buffer capacities, the calculation of LTR is a complex procedure (see Li and Meerkov 2009 for more details).

4. Relationships between KPIs

KPIs are derived from measurement elements. Since one element can be used in the definitions of several KPIs, it is impossible that KPIs are independent with each other. There are two types of relationships. One is the identity relation of KPIs based on their definitions. The other is relevance with shared supporting elements that can be obtained by pairwise comparison. Clearly, KPIs in different categories have many relationships and investigation of them is an important task, which involves substantial continuing efforts. In this paper, for illustration purpose, we present several examples of such relationships. More work needs to be carried out in future research.

4.1 *Inherent relationships*

4.1.1 *Examples of relationships between production KPIs*

Since the AE indicates how strongly the planned capacity of the work unit including the setup and delay time is already in use, and utilization efficiency stands for the productivity of work units considering the setup and delay time, then the product of them will be the availability, showing the usage of capacity of a work unit for the production. In other words,

$$\mathrm{A} = \frac{\mathrm{APT}}{\mathrm{PBT}} \cdot 100\% = \frac{\mathrm{AUBT}}{\mathrm{PBT}} \cdot \frac{\mathrm{APT}}{\mathrm{AUBT}} = \mathrm{AE} \cdot \mathrm{UE}. \tag{37}$$

Such an equation can also be revealed in Figure 4.

According to Little's Law (Little and Graves 2008), we have the relationship of buffer occupancy with throughput rate and the time a part staying in the buffer, i.e.

$$\mathrm{WIP} = \mathrm{TR} \cdot \mathrm{AQT}. \tag{38}$$

Consider the OEE and the NEE indices. Since they are comparable with the only difference on the setup time, the ratio of OEE and NEE will be equal to the ratio of APT and AUPT, which is also the complementary proportion of the SeR.

$$\frac{\mathrm{OEE}}{\mathrm{NEE}} = \frac{\mathrm{APT}}{\mathrm{AUPT}} = 1 - \mathrm{SeR}. \tag{39}$$

4.1.2 *Example of relationships between quality KPIs*

For the manufacturing flow, once a product is manufactured, it is either qualified or incompetent. If the part is defective, it should be scrapped or reworked. Thus the conservation relationship holds:

$$\mathrm{SR} + \mathrm{RR} \cdot \mathrm{N} + \mathrm{QBR} = \frac{\mathrm{SQ} + \mathrm{RQ}(\mathrm{N}+1) + \mathrm{GQ}}{\mathrm{PQ}} = 1. \tag{40}$$

4.1.3 *Example of relationships between maintenance KPIs*

The maintenance category captures the failure and operation average time durations. According to Li and Meerkov (2009) and renewal process theory (Ross 2014), the maintenance KPIs, such as MTTF, MTTR, and their ratio $\frac{\mathrm{MTTF}}{\mathrm{MTTF}+\mathrm{MTTR}}$ indicate the availability or efficiency of a manufacturing facility, which can be also defined by the ratio of AUBT and PBT. Therefore, we obtain

$$\mathrm{AE} = \frac{\mathrm{AUBT}}{\mathrm{PBT}} \cdot 100\% = \frac{\mathrm{MTTF}}{\mathrm{MTTF} + \mathrm{MTTR}} \cdot 100\%. \tag{41}$$

4.2 *Pairwise relationships*

The pairwise relationship can be derived by checking whether the measuring element appears on the dividend or divisor. Figure 5 summarizes these relationships. The KPIs are shown in the rows and columns of the table. If two KPIs have a direct relationship through a measuring element, this element will appear in the intersection cell of corresponding row and column. The symbol + (or −) in the lower left (respectively, top right) means this element has a positive (respectively, negative) relationship with the KPI of this row (respectively, column). Some cells contain only one symbol +, which implies the KPIs in the corresponding row and column only have positive relationship. Therefore, Figure 5 clearly indicates the pairwise relationships of KPIs, either positive or negative, and their intermediate elements.

5. Dependencies between KPIs and their supporting elements

Since KPIs are defined based on the elements, the change of an element may cause corresponding variation in KPIs. In this section, we investigate the impact of one element on KPIs and present examples. Such investigation is carried out using the formulas presented in Section 3.

	AR	TR	AE	UE	OEE	NEE	A	E	QR	SeR	TE	PR
AR	*	AOET− / AOET−	AUBT+ / AUBT+	AUBT− / AUBT+								AOET− / AOET−
TR	AOET− / AOET−	*						PQ+ / PQ+	PQ− / PQ+			AOET− / AOET−
AE	AUBT+ / AUBT+		*	AUBT− / AUBT+	PBT− / PBT−	PBT− / PBT−	PBT− / PBT−					
UE	AUBT+ / AUBT−		AUBT+ / AUBT−	*		APT− / APT+	APT+ / APT+	APT− / APT+			APT+ / APT+	APT+ / APT+
OEE			PBT− / PBT−		*	E+ / E+	+	+	+			
NEE			PBT− / PBT−	APT+ / APT−	E+ / E+	*	PBT− / PBT−	+	+	AUPT− / AUPT+	APT+ / APT−	APT+ / APT−
A			PBT− / PBT−	APT+ / APT+	+	PBT− / PBT−	*	APT− / APT+			APT+ / APT+	APT+ / APT+
E		PQ+ / PQ+		APT+ / APT−	+	+	APT+ / APT−	*			APT+ / APT−	APT+ / APT−
QR		PQ+ / PQ−			+	+			*			
SeR						AUPT+ / AUPT−				*		
TE				APT+ / APT+		APT− / APT+	APT+ / APT+	APT− / APT+			*	APT+ / APT+
PR	AOET− / AOET−	AOET− / AOET−		APT+ / APT+		APT− / APT+	APT+ / APT+	APT− / APT+			APT+ / APT+	*

Figure 5. The pairwise relationships between KPIs.

5.1 *Production KPIs and time elements*

Examples of dependencies between production KPIs and supporting time elements are presented below. First, consider time elements from a machine or a work unit point of view.

- When AUST is increasing, we obtain:
  - The following time elements will also increase: AUPT, AUBT, AOET, and PBT.
  - However since APT will remain the same. As a consequence, we have:
    - The following KPIs are also increasing: AE, AR, SeR and NEE.
    - While the following KPIs are decreasing: A, TR, UE and OEE.
    - Then other KPIs will remain the same: E, PR and TE.
- When ADOT is increasing, this implies:
  - The following time elements will increase: AOET, AUBT and PBT
  - It will result in:
    - Increase of the following KPIs: AR and AE.
    - Decrease of other KPIs: A, PR, TE, TR and UE, as well as OEE and NEE.
- When APT is increasing, then:
  - The following time elements will increase: AOET, AUBT, AUPT and PBT
  - This will lead to:
    - Increase of the following KPIs: A, AR, AE, TE, UE and PR.
    - Decrease of other KPIs: E, SeR, TR, OEE and NEE.
- When AUBT (actual unit busy time) is increasing, then we obtain:
  - The following time elements will increase: AOET and PBT.
  - This will result in changes in the following KPIs as well.
    - These KPIs will increase: AE and AR.
    - While these KPIs will decrease: A, PR, TR, UE, OEE and NEE.
- When AUPT is increasing, it implies:

  - Increases for the following time elements: AUBT, AOET and PBT.
  - As a consequence, KPIs will change.
    * The following KPIs will increase: AR, AR and NEE.
    * While other KPIs will decrease: A, PR, SeR, TR, UE and OEE.
- When PBT is increasing, then these KPIs will decrease: A, AE, OEE and NEE.

From a production order or an operator point of view, we obtain:

- When AOET is increasing, the following KPIs will also increase: AE and TR.
- When APAT is increasing, then WE is decreasing.
- When APWT is increasing, then WE is also increasing.

5.2 *Quality KPIs and quantity elements*

Examples of quantity elements' impact on quality KPIs are given below.

- When SQ is increasing, it will cause SQR and SR to increase. Moreover, it would take more production time to meet the order demand. Thus APT will increase and all relative KPIs will change according to Section 5.1.
- When PSQ is increasing, it will lead SQR to decrease.
- When GQ is increasing, it will make QR to increase. As a result, FR will decrease, but both OEE and NEE will increase.
- When RQ is increasing, RR will increase. Moreover, it would take more production time to meet the order demand. Thus APT will increase and all relative KPIs will change according to Section 5.1.

5.3 *Maintenance KPIs and time elements*

Finally, for maintenance elements, when TTF is increasing or TTR is decreasing for a given time interval, it will lead to an increase in OEE and NEE.

5.4 *Pairwise dependencies*

The above dependency relationships can be summarized into a table, shown in Figure 6. In such a table, the rows are measuring elements and the columns are KPIs. If a KPI is positively (or negatively) correlated with an element, the intersection of corresponding row and column will be marked with a symbol $+$ (or $-$). Note that for direct relationship, symbols $+*$ or $-*$ are used, while for non-direct relationships, $+$ or $-$ are marked.

6. Case study

To illustrate the CI process of using KPIs, a case study at a door manufacturing line in an automotive assembly plant is carried out. As shown in Figure 7, the door line includes a series of 10 operations (shown as circles), including inner part loading, spot welding & inner marriage, rack, PED (Pressure Equipment Directive) welding, inner & outer marriage, outer hemming, rack, inner hemming, punching and hang on. There are 9 buffers (shown as rectangles) with finite capacity between each pair of consecutive machines.

The line is synchronized with 39 sec cycle time (AUPT per one part). But the machines are unreliable, subject to random failures. Thus, there is no setup time, but with breakdown (or repair) time and idle (blockage or starvation) time. Denote the average downtime (i.e. mean time to repair – MTTR) of machine i, $i = 1, \ldots, 10$, as $T_{down,i}$, and the average uptime (i.e. mean time between failure – MTBF) as $T_{up,i}$. These KPI data are continuously evaluated through monitoring and collecting time elements TTR and TBF and FEs on the production line. Table 1 provides such KPIs as well as the buffer capacity B_i, $i = 1, \ldots, 9$.

The goal of this study is to continuously improve the productivity of the manufacturing line. To achieve this, a bottleneck-based improvement approach is used. In other words, by repeatedly identifying and mitigating the bottleneck machine's efficiency (e.g. A) and OEE, the LTR can be improved.

Bottleneck analysis is viewed as the most effective way to improve system performance. A bottleneck machine is the one whose improvement will lead to the largest improvement of the whole line, i.e. it impedes line performance in the strongest manner. As introduced in Li and Meerkov (2009), by measuring and comparing ratios of blockage BL_i and starvation ST_{i+1}

	WE	AR	TR	AE	UE	OEE	NEE	A	E	QR	SeR	TE	PR	SQR	SR	RR	FR	MOTBF	MTTF	MTTR	CMR
PBT				−*		−*	−*	−*													
PRI						+*	+*		+*												
APWT	+*																				
AUPT		+	−	+	−	−	+*	−			−*		−								
AUBT		+*	−	+*	−*	−	−	−					−								
AOET		−*	−*										−*								
APAT	−*																				
APT		+	−	+	+*	−	−	+*	−*		−	+*	+*								
ADET		+	−	+	−	−	−	−				−*	−								
AUST		+	−	+	−	−	+	−			+*		−								
SQ						−	−			−				+*	+*						
PSQ														−*							
GQ						+*	+*			+*					−	−	−*				
RQ						−	−			−					−	+*					
PQ			+*						+*												
TTF																			+*		
OTBF																		+*			
TTR																				+*	
FE																		−*	−*	−*	
CMT																					+*
PMT																					−*

Figure 6. The pairwise dependencies of KPIs on measuring elements.

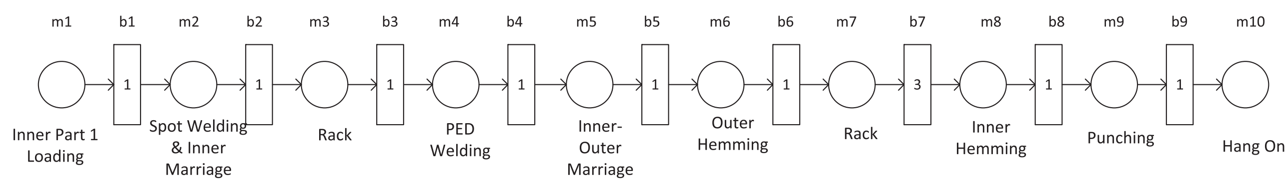

Figure 7. Doorline layout.

Table 1. Machine and buffer KPIs.

m_i	$T_{up,i}$ (min)	$T_{down,i}$ (min)	B_i
1	155.917	2.733	1
2	74.883	4.8	1
3	17.567	1.683	1
4	268.067	4.042	1
5	492.3	41.23	1
6	836.583	27.15	1
7	628.742	4.242	3
8	249.05	1.7	1
9	479.05	17.133	1
10	789.783	14.383	–

of consecutive machines i and $i+1$, $i = 1, \ldots, 9$, an arrow assignment rule can be applied. Specifically, the arrows are assigned from the upstream machine to the downstream if $BL_i > ST_{i+1}$, otherwise, the direction should be reversed. Then the machine that has no emanating arrows is the bottleneck machine. Such an approach has been used in many manufacturing

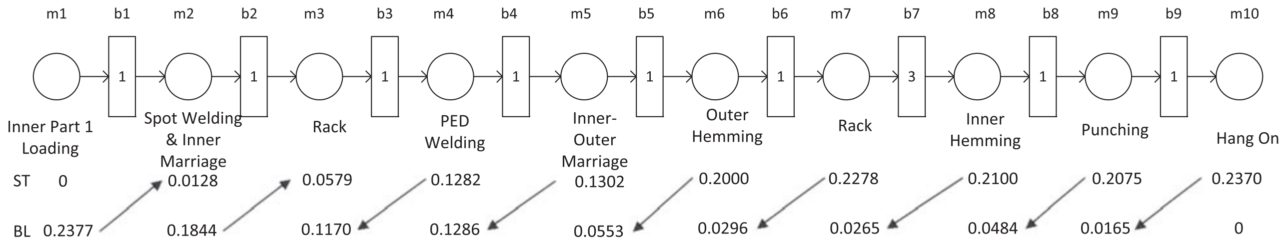

Figure 8. Bottleneck identification of door line.

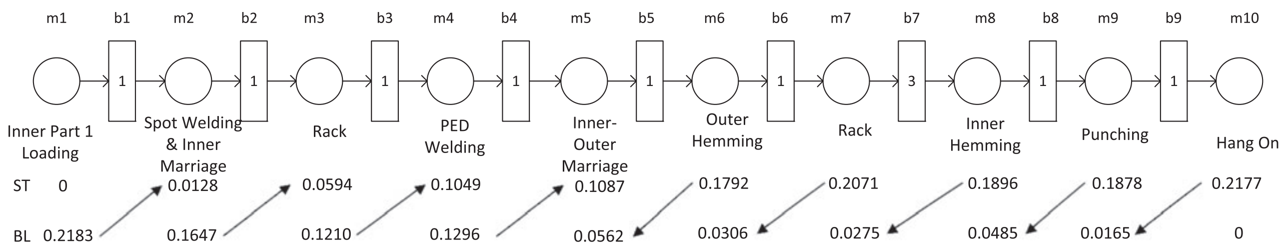

Figure 9. Bottleneck identification of door line with 30% downtime reduction of m_3.

systems studies, see examples and case studies introduced in Li and Meerkov (2009), Kuo et al. (1996), Chiang, Kuo, and Meerkov (2001), Li (2004a), Li (2004b), Li (2013), Xie and Li (2012).

The illustration of the arrow-based bottleneck analysis approach is shown in Figure 8. As one can see, machine m_3 has no emanating arrows, which is the bottleneck machine. The line throughput rate is 1.146 parts/min. Thus, as mentioned in Section 3, blockage and starvation ratios are the most critical KPIs for CI.

In order to enhance throughput of the door line, what-if analysis could be performed to mitigate the impact of bottlenecks. Specifically, based on the KPI dependency study in Section 5, the line throughput rate is monotonically decreasing with respect to downtime. Thus, reducing $MTTR$ could lead to an increase of LTR. Then, using the performance analysis method for synchronous exponential line introduced in Li and Meerkov (2009), applying the KPI data in Table 1 with a 30% downtime reduction of bottleneck machine m_3, we obtain that the system throughput increases to 1.176 parts/min, which is a 2.6% improvement. Consequently the bottleneck machine has been switched to m_5 (see Figure 9). Further improvement can be achieved through repeating this process by focusing on machine m_5.

To graphically represent such a CI procedure, Figure 10 presents the steps involved, from supporting elements monitoring, basic and comprehensive KPI evaluation, to bottleneck identification, operation improvement, and KPI re-evaluation. The process goes back to bottleneck identification and repeats the steps.

7. Conclusions

In this paper, a hierarchical structure is proposed to categorize KPIs and to identify and analyze the intrinsic relationships of them. The KPIs and their supporting measurement elements are defined and categorized into multi-level groups. The inherent and pairwise relationships between KPIs are explored. Examples of the dependencies between KPIs and their measurement elements are presented. A case study at an automotive door production line is introduced to illustrate the CI procedure using the KPIs and their relationships. Such a structure provides a useful tool for manufacturing engineers and managers to measure, analyze, and utilize KPIs for CI.

In future work, the following directions can be pursued:

- More useful KPIs and their supporting elements need to be introduced. In particular, most of the KPIs presented here are for single machine only. Studying KPIs for a multi-stage production system is important. Similarly, energy related KPIs also deserve in-depth study.
- Further investigation on the relationships between KPIs and their dependencies to supporting elements should continue. The current paper only provides a portion of such relationships, and more comprehensive studies are needed.

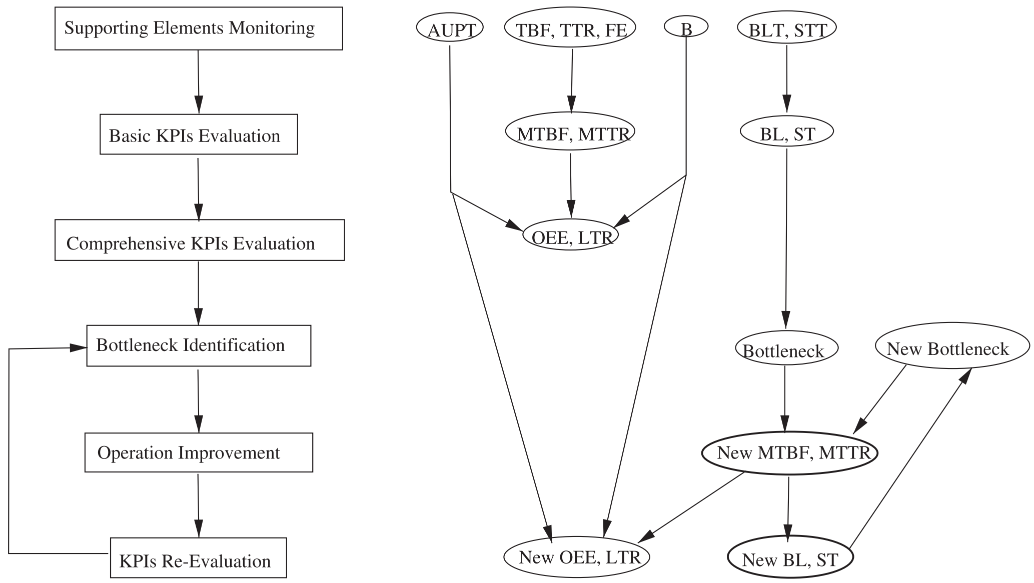

Figure 10. Illustration of CI procedure.

- Apply the developed KPIs on the factory floor. Use the collected data to verify and validate the results obtained from the study, and to refine KPIs and their relationships. More case studies using different aspects of KPIs and supporting elements should be carried out.

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References

Ahmad, M. M., and N. Dhafr. 2002. “Establishing and Improving Manufacturing Performance Measures.” *Robotics and Computer-Integrated Manufacturing* 18 (3): 171–176.

Arinez, J., S. Biller, K. Lyons, S. Leong, G. Shao, B.E. Lee, and J. Michaloski. 2010a. "Benchmarking Production System, Process Energy, and Facility Energy Performance Using a Systems Approach." Proceedings of the 10th Performance Metrics for Intelligent Systems Workshop, 88–96, Baltimore, MD.

Arinez, J., S. Biller, S. M. Meerkov, and L. Zhang. 2010b. “Quality/Quantity Improvement in an Automotive Paint Shop: A Case Study.” *IEEE Transactions on Automation Science and Engineering* 7 (4): 755–761.

Biller, Li, and J. Marin, S. Meerkov, and S. M. Zhang. 2010. “Bottlenecks in Bernoulli Serials Lines with Rework.” *IEEE Transactions on Automation Science and Engineering* 7 (2): 208–217.

Buzacott, J. A., and J. G. Shantikumar. 1993. *Stochastic Models of Manufacturing Systems*. Englewood Cliffs, NJ: Prentice Hall.

Chiang, S. Y., C. T. Kuo, and S. M. Meerkov. 1998. “Bottlenecks in Markovian Production Lines: A Systems Approach.” *IEEE Transactions on Robotics and Automation* 14 (2): 352–359.

Chiang, S. Y., C. T. Kuo, and S. M. Meerkov. 2000. “DT-bottlenecks in Serial Production Lines: Theory and Application.” *IEEE Transactions on Robotics and Automation* 16 (5): 567–580.

Chiang, S. Y., C. T. Kuo, and S. M. Meerkov. 2001. “c-Bottlenecks in Serial Production Lines: Identification and Application.” *Mathematical Problems in Engineering* 7 (6): 543–578.

Cooper, R. 1988. “The Rise of Activity-based Cost Systems: Part I – What is an Activity-based Cost System?.” *Journal of Cost Management*. (Spring):45–54.

Cooper, R. 1988. “The Rise of Activity-based Cost Systems: Part II - When do I Need an Activity-based Cost System?.” *Journal of Cost Management*. (Fall): 41–48.

Cooper, R. 1988. “The Rise of Activity-based Cost Systems: Part III – Howmany Cost Drivers do You Need and How You Select Them?.” *Journal of Cost Management*. (Winter):34–46.

Cooper, R. 1989. “The Rise of Activity-based Cost Systems: Part IV – What do Activity-based Cost System Look like?.” *Journal of Cost Management*. (Spring):34–46.

Cross, K. F., and R. L. Lynch. 1988. “The SMART way to Define and Sustain Success.” *National Productivity Review* 8 (1): 23–33.

Dallery, Y., and S. B. Gershwin. 1992. “Manufacturing Flow Line Systems: A Review of Models and Analytical Results.” *Queuing Systems* 12 (1): 3–94.

Dixon, J. R., A. J. Nanni, and T. E. Vollman. 1990. The New Performance Challenge: Measuring Operations for World Class Competition, Dow Jones-Irwin, Homewood, IL.

Eccles, R. G. 1991. “Performance Measurement Manifesto.” *Harvard Business Review* 69: 131–137.

Fisher, J. 1992. “Use of Non-financial Performance Measures.” *Journal of Cost Management*. (Spring): 31–38.

Gershwin, S. B. 1994. *Manufacturing Systems Engineering*. Englewood Cliffs, NJ: PTR Prentice Hall.

Ghalayini, A. M. 1997. “An Integrated Dynamic Performance Measurement System for Improving Manufacturing Competitiveness.” *International Journal of Production Economics* 48 (3): 207–225.

Gomes, C. F. 2004. “A Literature Review of Manufacturing Performance Measures and Measurement in an Organizational Context: A Framework and Direction for Future Research.” *Journal of Manufacturing Technology Management* 15 (6): 511–530.

Hayes, R. H., S. C. Wheelwright, and K. B. Clark. 1988. *Dynamic Manufacturing: Creating the Learning Organization*. New York, NY: Free Press.

International Standard ISO 22400–1. 2014. *Automation Systems and Integration – Key Performance Indicators (KPIs) for Manufacturing Operations Management - Part 1: Overview, Concepts and Terminology*. Geneva: International Standard Organization (ISO).

International Standard ISO 22400–2. 2014. *Automation Systems and Integration - Key Performance Indicators (KPIs) for Manufacturing Operations Management - Part 2: Definitions and Descriptions*. Geneva: International Standard Organization (ISO).

Jacobs, D., and S. M. Meerkov. 1995. “A System-theoretic Property of Serial Production Lines: Improvability.” *International Journal of Systems Science* 26 (4): 755–785.

Ju, F., J. Li, G. Xiao, and J. Arinez. 2013. “Quality Flow Model in Automotive Paint Shops.” *International Journal of Production Research* 51 (21): 6470–6483.

Ju, F., J. Li, G. Xiao, N. Huang, and S. Biller. 2014. “A Quality Flow Model in Battery Manufacturing Systems for Electric Vehicles.” *IEEE Transactions on Automation Science and Engineering* 11 (1): 230–244.

Kaplan, R. S. 1983. “Measuring Manufacturing Performance: A New Challenge for Manageria.” *Accounting Research. The Accounting Review* 58 (4): 686–705.

Kaplan, R. S. 1984. “Yesterday’s Accounting Undermines Production.” *Harvard Business Review* 62: 95–101.

Kaplan, R. S., and D. P. Norton. 1996. *Translating Strategic into Action – The Balanced Scorecard*. Boston, MA: Harvard Business School Press.

Kuo, C. T., J. T. Lim, and S. M. Meerkov. 1996. “Bottlenecks in Serial Production Lines: A System-theoretic Approach.” *Mathematical Problems in Engineering* 2 (3): 233–276.

Li, J. 2004a. “Performance Analysis of Production Systems with Rework Loops.” *IIE Transactions* 36 (8): 755–765.

Li, J. 2004b. “Throughput Analysis in Automotive Paint Shops: A Case Study.” *IEEE Transactions on Automation Sciences and Engineering* 1 (1): 90–98.

Li, J. 2013. “Continuous Improvement at Toyota Manufacturing Plant: Application of Production Systems Engineering Methods.” *International Journal of Production Research* 51 (23–24): 7235–7249.

Li, J., D. E. Blumenfeld, N. Huang, and J. A. Alden. 2009. “Throughput Analysis of Production Systems: Recent Advances and Future Topics.” *International Journal of Production Research* 47 (14): 3823–3851.

Li, J., D. E. Blumenfeld, and S. P. Marin. 2008. “Production System Design for Quality Robustness.” *IIE Transactions* 40 (3): 162–176.

Li, J., and S. M. Meerkov. 2000. “Bottlenecks with Respect to Due-time Performance in Pull Serial Production Lines.” *Mathematical Problems in Engineering* 5 (6): 479–498.

Li, J., and S. M. Meerkov. 2009. *Production Systems Engineering*. New York, NY: Springer.

Little, J. D. C., and S. C. Graves. 2008. “Little’s law. in Building Intuition: Insights from Basic Operations Management Models and Principles, D. Chhajed and T.J. Lowe Ed.” *International Series in Oprations Research and Management Science* 115: 81–100.

Maskell, B. H. 1992. *Performance Measurement for World Class Manufacturing: A Model for American Companies*. Cambridge, MA: Productivity Press.

Meerkov, S. M., and L. Zhang. 2010. “Product Quality Inspection in Bernoulli Lines: Analysis, Bottlenecks, and Design.” *International Journal of Production Research* 48 (16): 4745–4766.

Meerkov, S. M., and L. Zhang. 2011. “Bernoulli Production Lines with Quality-quantity Coupling Machines: Monotonicity Properties and Bottlenecks.” *Annals of Operations Research* 182 (1): 119–131.

Neely, A. 1995. “Performance Measurement System Design.” *International Journal of Operations & Production Management* 15 (4): 80–116.

Papadopoulos, H. T., J. Browne, and C. Heavey. 1993. *Queueing Theory in Manufacturing Systems Analysis and Design*. London, UK: Chapman & Hall.

Papadopoulos, H. T., and C. Heavey. 1996. "Queueing Theory in Manufacturing Systems Analysis and Design: A Classification of Models for Production and Transfer Lines." *European Journal of Operational Research* 92 (1): 1–27.

Rakar, A., S. Zorzut, and V. Jovan. 2004. "Assesment of Production Performance by Means of KPI." *Proceedings of the Control* 6–9.

Rodriguez, R. R. 2009. "Quantitative Relationships between Key Performance Indicators for Supporting Decision-making Processes." *Computers in Industry* 60 (2): 104–113.

Ross, S. M. 2014. *Introduction to Probability Models*. 11th ed. Amsterdam, Netherland: Academic Press.

Sarkis, J. 1997. "An Empirical Analysis of Productivity and Complexity for Flexible Manufacturing Systems." *International Journal of Production Economics* 48 (1): 39–48.

Suwignjo, P. 2000. "Quantitative Models for Performance Measurement System." *International Journal of Production Economics* 64 (1): 231–241.

Tempelmeier, H., and H. Kuhn. 1993. *Flexible Manufacturing Systems: Decision Support for Design and Operation*. New York, NY: John Wiley & Sons.

Viswanadham, N., and Y. Narahari. 1992. *Performance Modeling of Automated Manufacturing System*. Englewood Cliffs, NJ: Prentice-Hall.

Wang, J., J. Li, J. Arinez, S. Biller, and N. Huang. 2010. "Product Sequencing with Respect to Quality in Flexible Manufacturing Systems with Batch Operations." *IEEE Transactions on Automation Science and Engineering* 7 (4): 776–790.

Wang, J., J. Li, and N. Huang. 2012. "Indicators for Quality Improvability and Bottleneck Sequence in Flexible Manufacturing Systems with Batch Productions." *International Journal of Production Research* 50 (22): 6388–6402.

Wang, J., J. Li, J. Arinez, and S. Biller. 2013. "Quality Bottleneck Transitions in Flexible Manufacturing Systems with Batch Productions." *IIE Transactions* 45 (2): 190–205.

Xie, X., and J. Li. 2012. "Modeling, Analysis and Continuous Improvement of Food Production Systems: A Case Study at a Meat Shaving and Packaging Line." *Journal of Food Engineering* 113 (2): 344–350.

Zhou, M., and K. Venkatesh. 1999. *Modeling, Simulation and Control of Flexible Manufacturing Systems: A Petri Net Approach*. Singapore: World Scientific Publishing Company.