Chinese Journal of Chemical Engineering 22 (2014) 805–811

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJCHE

Process Monitor

Coordinating and Evaluating of Multiple Key Performance Indicators for Manufacturing Equipment: Case Study of Distillation Column☆

Li Zhu, Hongye Su *, Shan Lu, Yue Wang, Quanling Zhang

State Key Laboratory of Industrial Control Technology, Institute of Cyber-Systems and Control, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 24 January 2014
Accepted 3 March 2014
Available online 20 June 2014

Keywords:
Key performance indicator
Coordination
Manufacturing equipment
Evaluation

ABSTRACT

Manufacturing equipment takes the task of operation and directly effects on the manufacturing process. One single Key Performance Indicator (KPI) is mainly employed to evaluate equipment in most studies, neither integrating the KPIs into a completed evaluation system nor considering the impact and conflict among KPIs. In this paper, a KPI evaluation architecture is presented to define and analyze KPIs, and then a common structure for KPI to obtain the KPI set of manufacturing equipment is introduced. An available multi-KPI coordination model is proposed to discern and balance the relationship among multi-KPI. Finally, a case study is introduced to illustrate the applicability of the coordination model by using multi-objective optimization strategy and an efficient solution is obtained.

1. Introduction

Manufacturing equipment plays a principal role in the manufacturing process and directly influences the yields and profits of manufacturing companies. There are manufacturing equipment design, operation and maintaining all the way through the entire manufacturing process. To ensure the stability and efficiency of production process, it is necessary to evaluate the performance of manufacturing equipments.

Many investigations have been reported in the literatures about equipment evaluations. Ljungberg [1] introduced overall equipment effectiveness in the formulation and execution of a total productivity maintenance strategy to measure the performance of equipment as a metric. Yacoub and MacGregor [2] presented a data analysis method to assess the equipment performance in manufacturing processes. Chen *et al.* [3] proposed a performance indicator of process manufacturing time, which can be transformed to production capacity and to evaluate equipment performance. Geng *et al.* [4] developed a fuzzy analytic hierarchy process method to get energy efficiency indices to assess energy utilization states of different equipments. Shen *et al.* [5] made a determination on the benchmark of manufacturing equipment and took production ratio as an instance. Younes *et al.* [6] presented the application of parameters design to improve both the product quality and equipment performance in a hot sheet rolling plant. Irshad *et al.* [7] provided total quality model and applied productivity and quality indicators to evaluate performance. Garza-Reyes *et al.* [8] investigated the relationship between overall equipment effectiveness and process capability for measuring the performance.

However, most studies pay attention to use a single performance indicator to measure the manufacturing equipment without integrating the key performance indicators into a completed evaluation system. And qualitative analysis methods of equipment performance are in the majority, which lacks systematicness, generality and accuracy. In addition, there are conflicts and inconsistence in the relationship of multi-KPI, thus it is helpful and essential to find out the trade off compromises to balance the multi-KPI, which is useful to narrow down the choices in decision-making in the manufacturing process [9].

Considering these aspects for evaluating the performance of manufacturing equipment, evaluation architecture of key performance indicators for manufacturing executive system is introduced to define and analyze KPIs in this study. Based on the common structure of KPIs proposed by the international standard ISO 22400 [10], a set of KPIs to measure manufacturing equipment performance is established and described. To discern and coordinate the relationships among the multi-KPI in this KPI set, a multi-KPI coordination model is proposed, which takes into account coordinating objectives selected, mass balance, energy balance, quality and safety constraints, *etc*. The trade off among the multi-KPI is explored by collaboration model, which is not limited to evaluate the special manufacturing equipment, but also accounts for the evaluation of different levels in manufacturing process. To demonstrate the effectiveness of the presented model, the

☆ Supported by the National Natural Science Foundation of China (61134007, 61320106009).

* Corresponding author.
E-mail address: hysu@iipc.zju.edu.cn (H. Su).

http://dx.doi.org/10.1016/j.cjche.2014.05.007
1004-9541/

methanol–water packed distillation column is taken as a real case study. The trade off compromise between production rate and unit energy consumption is obtained by using multi-objective optimization strategy.

2. KPI Evaluation Set of Manufacturing Equipment

Key performance indicators (KPIs) are defined as quantifiable and strategic measurements that reflect the critical success factors in the manufacturing process. KPIs are very important for understanding, benchmarking and improving the performance of manufacturing executive system from both the manufacturing process perspective of eliminating waste and the corporate perspective of achieving strategic goals [10]. Zhu, *et al.* [11] proposed KPI evaluation architecture and divided KPI analysis into two parts including KPI definition and KPI utility, as shown in Fig. 1. The International Organization for Standardization (ISO) 22400 Automation systems and integration—key performance indicators for manufacturing operations management [10] established a set of general evaluation system to express the objectives and critical factors, and proposed a common structure for standardizing KPI definition. The performance of manufacturing equipment directly influences production security, quality and efficiency, so it is necessary to evaluate manufacturing equipment from many aspects. There are different key performance indicators from different evaluation aspects, such as production ratio, unit energy consumption, quality ratio, equipment load rate, and overall equipment effectiveness, which form the KPI evaluation set of manufacturing equipment. According to KPI evaluation architecture and KPI common structure, Tables 1 and 2 give the definition and description of production ratio, and unit energy consumption.

Production rate indicator is defined as output–input ratio and higher ratio means the efficiency is better. However, it is complicated to compute the production rate because of the interaction among the quantity of different products in the multi-input and multi-output process. For the manufacturing equipment, the ratio of target product and produced quantity is used to evaluate the operating state and production efficiency.

Unit energy consumption indicator is used to evaluate energy consumed by equipment for energy savings, environmental protection and cost reduction. Though energy can be considered as a form of raw material, it helps to evaluate the consumption of energy using distinct indicators.

The relationship between the good quantity and the produced quantity is denoted as quality ratio. The higher the quality ratio, the more products meet the quality requirement. The information about the ratio of produced quantity in relation to the maximum equipment production capacity is provided by equipment load rate indicator, which reflects production efficiency, technical performance, equipment production state and equipment utilization by researching the usage of equipment. The value of equipment load rate impacts the production cost and profit. The optimal results of manufacturing process in the non-disturbance condition assess production loss and improve product quality represented by overall equipment effectiveness, which could be applied to evaluate either single production equipment or production unit which consists of multiple production equipments. These indicators could be defined and described on the basis of KPI common structure, and form the KPI set for manufacturing equipment with other indicators.

3. Multi-KPI Coordination Model of Manufacturing Equipment

According to the KPI evaluation architecture and common structure, one single KPI reflects the effectiveness of the certain concern point in the equipment operation state. However, due to managing the manufacturing equipment more effectively and efficiently, it is necessary to analyze and coordinate the relationships among multi-KPI in the KPI evaluation set, as shown in Fig. 2.

The relationships of KPIs are complicated and they interact and impact each other in the KPI set, which affects decision making. For instance, production rate may have a direct effect on the overall equipment effectiveness of the manufacturing equipment [8]. Raising production rate while simultaneously reducing unit energy consumption is often conflicted and inconsistent. Therefore, finding out the trade off compromises to keep the multi-KPI balance is crucial. According to the multi-objective optimization methodology, the multi-KPI coordination model of manufacturing equipment contains two parts: coordinate objectives and constraint condition.

3.1. Coordinate objectives

Minimizing or maximizing the focused KPIs is the coordinate objectives. The optimal overall objective is obtained by balancing the relationship among KPIs.

$$\min\begin{cases} KPI_1 = g_1(x_1, x_2, \cdots, x_m) \\ KPI_2 = g_2(x_1, x_2, \cdots, x_m) \\ \cdots \\ KPI_M = g_M(x_1, x_2, \cdots, x_m) \end{cases} \text{ or } \max\begin{cases} KPI_1 = f_1(y_1, y_2, \cdots, y_n) \\ KPI_2 = f_2(y_1, y_2, \cdots, y_n) \\ \cdots \\ KPI_N = f_N(y_1, y_2, \cdots, y_n) \end{cases} \quad (1)$$

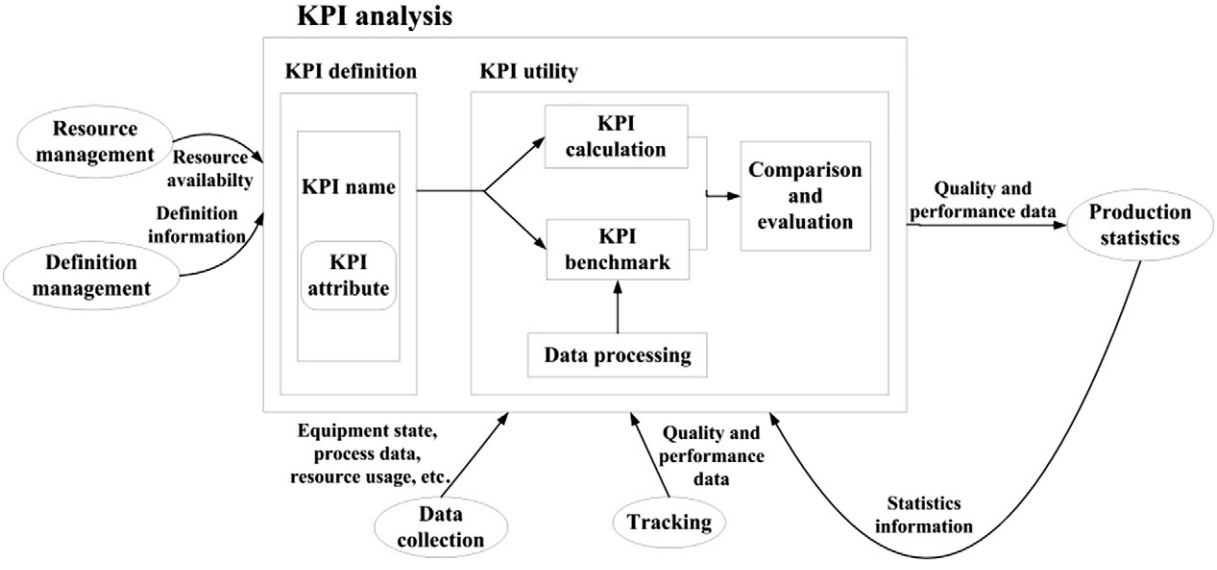

Fig. 1. Evaluation architecture of key performance indicators.