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Using graph-based visualizations to explore key performance indicator relationships for manufacturing production systems

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Abstract

Key Performance Indicators (KPIs) are crucial for measuring and improving the performance of a manufacturing process. An especially critical aspect of developing balanced process performance improvement strategies across all critical objectives is the need to discover the inherent relationships between all KPIs assigned to a targeted manufacturing process. This paper explores graph-based visual representations of the analytic relationships between KPIs and their underlying metrics to uncover and describe KPI relationships. Lessons learned are summarized as a list of requirements for the development of an interactive prototype that will allow users to dynamically explore KPI-related interdependencies through graph-based visualizations.

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Keywords: Key Performance Indicators; Information Visualization; ISO 22400; Interdependencies; KPI Relationships; Manufacturing Process Improvement

1. Introduction

Manufacturers strive to monitor and improve the performance of production operations through the use of Key Performance Indicators (KPIs). KPIs indicate the level of performance a system is achieving through measurable attributes, such as the amount of material, energy, or time consumed in a process. With the advent of the Internet of Things (IoT) and the increasing availability of data in real time, manufacturers now have the opportunity to calculate a broad range of KPIs. KPIs are often interdependent; a common observation is that improving one KPI leads to a decrease in performance as indicated by another KPI, often inadvertently. Understanding these interdependencies can be a challenge due to their complexity. One would like to improve specific KPI performance without adversely affecting other KPIs. One of the challenges of IoT is navigating through an abundance of data but where the context for that data is often hard to ascertain. Often times, performance-related data is displayed on dashboards that do not provide sufficient details or the tools to properly explore KPIs and underlying metrics to drive improvement decisions.

While the relationships between various KPIs and their associated metrics are explored in literature [1], visualizations of these interrelationships are often an afterthought with basic tables providing a brief overview of pairwise metric/KPI relationships. Without a proper understanding of the complex relationships among KPIs, humans struggle to make the optimal improvement decisions. Furthermore, implementing KPI-related improvement strategies involves a wide range of organizational perspectives. A rich platform to explore KPI interdependencies will support multiple perspectives.

This paper proposes the use of graph-based visualization methods along with inputs from manufacturing process experts to address the above-mentioned challenges. The visualization techniques, both matrix- and network-based, are applied to select subsets of the 34 KPIs described in ISO 22400 [2] to highlight the interrelationships between various metrics and the associated KPIs. Best practices from the information visualization (InfoVis) community are evaluated for their suitability for KPI-related decision making. Lessons learned from the application of these practices will be used to develop a prototype interface for the exploration of KPI interdependencies.

The rest of the paper is structured as follows. Section 2 provides background on KPIs and visualization techniques. In Section 3, two graph-based visualization techniques—node-link diagrams and matrix-based layouts—are applied to illustrate the interrelationships of the KPIs. The different techniques are analyzed for their strengths and weaknesses, and lessons learned for visualizing KPI interdependencies are discussed. A prototype interface is presented that exploits advantages from both visualization techniques. Section 4 summarizes requirements for a hybrid visualization tool supporting dynamic exploration of KPI interdependencies and discusses requirements for KPI exploration where visualization may be effective.

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Table 1: KPIs and metrics used in this paper. Type includes KPIs (K), mid-level metrics (M), and low-level metrics (L). Shaded cells correlate to appearance in respective figure.

Abbr.	Name	Type	F1	F2	F3	F4	F5	F6
A	Availability	K	■	■	■	■	■	■
ADET	Actual Unit Delay Time	M	■			■		
ADOT	Actual Unit Down Time	L	■	■	■	■	■	■
AE	Allocation Efficiency	K	■	■	■	■	■	■
APT	Actual Production Time	L	■	■	■	■	■	■
AQT	Actual Queueing Time	M	■			■		
ATT	Actual Transportation Time	M	■			■		
AUBT	Actual Unit Busy Time	M	■			■		
AUOET	Actual Order Execution Time	M	■			■		
AUPT	Actual Unit Processing Time	M	■			■		
AUST	Actual Unit Setup Time	L	■	■	■	■	■	■
BL	Blockage Ratio	K	■	■	■	■	■	■
BLT	Blocking Time	L	■	■	■	■	■	■
CMR	Corrective Maintenance Ratio	K	■	■		■		
CMT	Corrective Maintenance Time	L	■	■		■		
E	Effectiveness	K	■	■		■		
FR	Fall of Ratio	K	■	■		■		
FTQ	First Time Quality	K	■	■		■		
GQ	Good Quantity	L	■	■		■		
NEE	Net Equipment Effectiveness	K	■	■		■		
OEE	Overall Equipment Effectiveness	K	■	■		■		
OTBF	Operating Time Between Failures	M	■			■		
PBT	Planned Busy Time	M	■			■		
PDOT	Planned Downtime	M	■			■		
PMT	Preventative Maintenance Time	L	■	■		■		
POT	Planned Operation Time	M	■			■		
PQ	Processed Quantity	M	■			■		
PQF	Produced Quantity in 1st Operation	M	■			■		
PRI	Planned Run time per Item	L	■	■		■		
PSQ	Planned Scrap Quantity	L	■	■		■		
PUOET	Planned Order Execution Time	M	■			■		
PUST	Planned Unit Setup Time	M	■			■		
QBR	Quality Buy Rate	K	■	■		■		
RR	Rework Ratio	K	■	■		■		
RQ	Rework Quantity	L	■	■		■		
SeR	Setup Ratio	K	■	■	■	■	■	■
SQ	Scrap Quantity	L	■	■		■		
SQR	Actual to planned Scrap Ratio	K	■	■		■		
SR	Scrap Ratio	K	■	■		■		
ST	Starvation Ratio	K	■	■	■	■	■	■
STT	Starvation Time	L	■	■	■	■	■	■
TE	Technical Efficiency	K	■	■	■	■	■	■
TTF	Time to Failure	M	■			■		
UE	Utilization Efficiency	K	■	■	■	■	■	■

2. Background

2.1. Understanding the Interdependencies of KPIs

KPIs are fundamental to addressing an organization's strategic goals [3] and to continuous improvement processes [4]. KPIs are based on measures of physical characteristics of a manufacturing system or process, such as the amount of resources consumed, the amount of output produced, and the time taken to execute a process. These measures, or metrics, are an index of an aspect of the system's performance, e.g. its efficiency or environmental impact. KPIs can exist at many levels of an organization, are debated within communities of interest, or may be tightly held as trade-secrets.

To illustrate this point, consider a set of KPIs related to equipment efficiency. These KPIs aggregate multiple goals into one indicator to measure performance of equipment or at the factory level. An example is the overall equipment effectiveness (OEE) indicator, which was created to measure equipment efficiency across three areas: availability, performance, and quality [3]. The OEE was extended further at the equipment level with the Production Equipment Efficiency (PEE) and Total Effective Equipment Performance (TEEP) indicators and at the factory-level with Overall Factory Effectiveness (OFE), Overall Throughput Effectiveness (OTE), Overall Production Efficiency (OPE), and Operational Asset Effectiveness (OAE) [5].

Other studies show similar relationships between metrics and sets of KPIs. Brundage et al. studied the interrelationship between production performance and energy consumption through cost explorations [6]. The interrelationships between various performance KPIs in the ISO 22400 standard were also explicitly studied in [1]. Further, IBM investigated correlations between various KPI networks and determined influential chains of metrics [7]. Chen and Zhou investigate the relationship between cycle time and throughput rates through quantile regression [8]. While these works examine different KPIs and their interrelationships within the manufacturing industry, they do not focus on visualizing KPI-related data in an understandable manner. This paper addresses that issue by exploring different visualization techniques and describing a prototype for understanding the KPI interdependencies that integrates the multiple visualization techniques. Table 1 lists the KPI and metrics studied in this paper. Each metric and KPI are classified based on which figures they appear as well as their type, including KPI (K), mid-level metric (M), and low-level metric (L).

2.2. Visualizations in Manufacturing

The fields of InfoVis and visual analytics provide evidence that presentation of and human-interaction with data simplifies decision-related scenarios for engineers. One of the earliest, most widely studied uses of InfoVis in the manufacturing domain is the process control chart, first proposed in 1932 by Shewhart as a statistical technique to make sense of individual process samples [9]. Production facilities around the world display process data, codified in color to represent different system states. Though such lean production tools have improved current engineering practice, other InfoVis-inspired techniques are not yet commonplace.

However, researchers are beginning to further explore the benefits of InfoVis for decision support in engineering practice. With respect to conceptual product design, Konigseder and Shea presented a visualization method for exploring a design space through grammar-based representations [10]. Ramanujan et al. developed a visualization prototype for exploring design characteristics of existing designs in the context of environmentally efficient decision making [11]. Others have implemented similar ideas