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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 for visually assessing supply chain representations [12-13]. Within the manufacturing domain, InfoVis techniques have been mainly limited to performance dashboards. Mazumdar et al. proposed a knowledge-based visualization dashboard to allow users to quickly identify problems on the manufacturing floor [14]. Groger and Stach studied the feasibility of a mobile manufacturing dashboard, which allows both shop floor workers and production supervisors to understand performance in real-time [15]. In general, there is limited work in visually representing KPI-related data, and we have not found any directed work at visualizing KPI-related interdependencies.

3. Exploring KPI Visualization Methods

This paper explores the use of graph-based visualizations to enhance stakeholders' understanding of KPIs. The strengths and weaknesses of each technique are studied both in the context of (1) visualizing a large group of KPIs and their associated metrics and (2) a small, more focused subset of KPIs. The figures presented will not be the same for all sets of KPIs, however the weighting of the elements (nodes and links) are described in detail to reproduce the visualization method. Before discussing these techniques, we describe the data used in this work and related challenges.

3.1. Data Preparation and Challenges

The data used in this paper was derived from ISO 22400: Automation systems and integration - Key performance indicators (KPIs) for manufacturing operations management [2]. The relationships between the metrics and indicators defined in the above standard are investigated in the work presented by Kang et. al [1]. One challenge in visualizing the information is the discrepancy between units of KPIs and the metrics. For example, Actual Production Time (APT) is in units of time, while Good Quantity (GQ) is the number of good products produced and Overall Equipment Effectiveness (OEE) is represented as a percentage and, hence, unit-less. This becomes a barrier when performing what-if analysis to study the effect of changing a metric on different KPIs. We must understand how the value of change in one metric relates to the value of change of another metric (e.g. how does a change in unit time relate to a change in unit quantity?). This paper does not directly address this issue. Instead, subsets of KPIs with similar units are handled independently.

An important design consideration for developing visualizations is the appropriate mapping of visual variables to data. According to Jacque Bertin, visual variables include position, size, shape, value, color, orientation, and texture [16]. One guiding principle for visual variable selection is the resolution. A variable's resolution value is defined through experimentation and observation of human performance, i.e. perception and cognition. As an example, the possible combinations of color are theoretically infinite. However, humans can only distinctly perceive about 10 different colors in one visual field [17]. In this case, the functional resolution of color is equal to about 10. As a result, color should be assigned to denote no more than about 10 different data types. In the following examples, the assignment of visual variables was designed based on best practice.

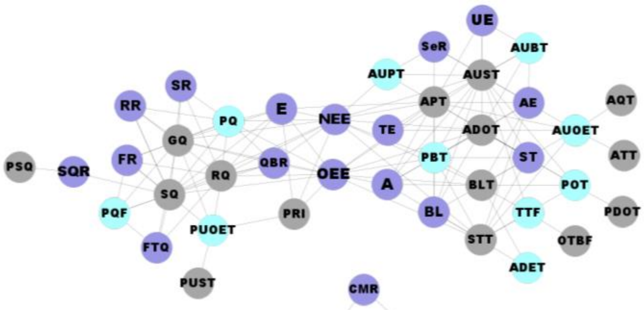

Figure 1: Undirected graph of relationships between all metrics and KPIs, generated using a force-directed layout algorithm. The purple nodes represent the KPIs, the blue nodes represent the mid-level metrics, which are dependent on the lower level metrics and are represented by the grey nodes. The labels on the graph nodes are the metrics and KPIs defined in [1].

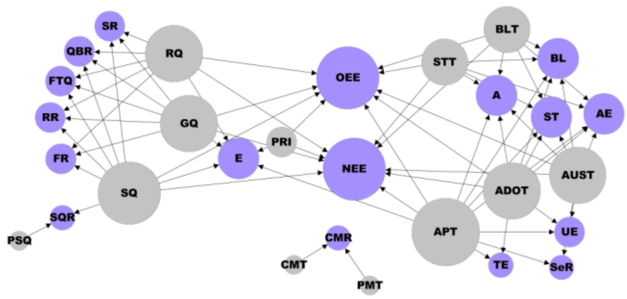

Figure 2: Graph of relationships between low level metrics and KPIs, produced through a force-layout algorithm. The size of the node is scaled based on the its degree (or the number of connections with other nodes). The purple nodes are KPIs, while the grey nodes are the low level metrics.

3.2 Node-Link Diagrams

Node-link diagrams illustrate the relationships, represented by lines, between different entities, represented by circles. Node-link diagrams are used to show the relationships between KPIs and the corresponding metrics. Figure 1 illustrates a network visualization representing an undirected graph, capturing all known functional relationships between low-level metrics, mid-level metrics, and KPIs. The mid-level metrics are dependent on low-level metrics and the KPIs can be dependent upon either mid-level or low-level metrics. Edges in this graph are defined as functional relationships between a metric and a KPI. The diagram shows two distinct node groups, a group that relates to time-based measurements and indicators (on the right side of the network) and the other that shows all elements related to quality-based measurements

Table 2: Summary of Lessons Learned for Node-Link and Matrix Based Visualizations

	Node-Link Diagram	**Matrix-Based**
Overview of KPI Relationships	Works well for sparse networks	Works well for dense networks
Presentation/Layout	Force-based layout	Clustering algorithm (e.g. Voor Hees)
What-if Analysis	Line thickness shows percent improvement	Colormap shows percent improvement
Degree of Connectivity	Quickly depicts connections	More difficult for human to decipher
Neighborhood Detection	Works for space networks with physics layout	Lots of flexibility, even with dense networks
Visual Variable Issues	Resolution of line thickness	Resolution of colors and alpha levels

(on the left side of the network). Overall equipment effectiveness (OEE) and net equipment effectiveness (NEE) fall in the middle as they measure both quality and time efficiency. This graph shows a general overview, but fails to illustrate the influence of any given metric on different KPIs.

In Figure 2, the mid-level metrics are removed and the relationships between the low-level metrics and the corresponding KPIs are shown. Here, node diameters are scaled based on node degree, or the number of connections. In other words, the more connections, the larger the node; the less connections, the smaller the node. As in Figure 1, Figure 2 groups both the quality metrics and KPIs (left) and the time based metrics and KPIs (right). In Figure 2, the metrics that have the highest influence on multiple KPIs and the KPIs that are dependent on the most metrics can easily be identified.

Lastly, improvement strategies through what-if scenarios with the node-link diagrams are shown. Figure 3 focuses on the time-based metrics and KPIs and can be used to study the effect of improving a metric (e.g., by a time unit of 10) on the KPIs. The node color represents whether a KPI meets a threshold as defined by system experts: orange means the KPI is not meeting the threshold; blue means the KPI is performing better than the threshold. The size of the nodes represents how far the KPI is from the threshold: the larger the node, the further the KPI is from the threshold. The edge color represents a positive (green) or negative (red) influence on the KPI and the edge weight is proportional to the change in the KPI when improving the metric. In this example, it can be seen that improving actual production time (APT) will lead to the biggest improvement across all KPIs since APT has the heaviest lines extending from it.

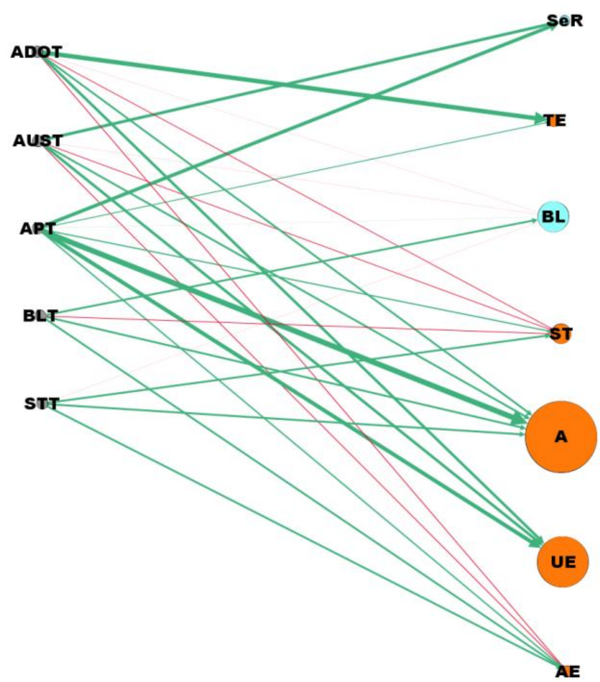

Figure 3: Node-link diagram of time-related KPIs and their metrics. The metrics are the nodes on the left, while the KPIs are the nodes on the right.

Lessons Learned

Node-link diagrams are useful for a quick general overview of the connections of metrics and KPIs, but can fail when trying to show the influence of a large set of metrics on their KPIs. Since node-link diagrams are better suited for sparse networks, it is necessary to narrow down the targeted data to best illustrate relationships using node-link diagrams. Additionally, the position of the nodes is dictated by the designer, and hence, the nodes are not fixed with respect to the field. This provides the designer with flexibility in visualizing the nodes based on their needs. In this case, position is used to depict communities of metrics and KPIs.

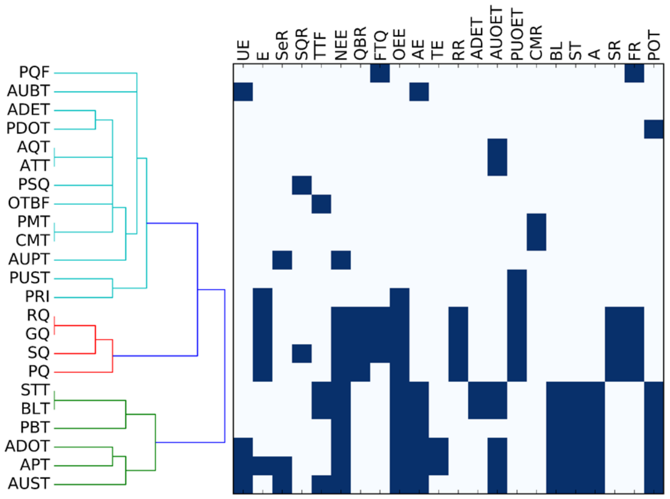

Figure 4: Matrix-based visualization of metrics relationships to KPIs. A functional relationship between a metric and a KPI is shown as a blue box on the right. The dendrogram (left) shows the similarity in functional interdependencies of the metrics to each other.

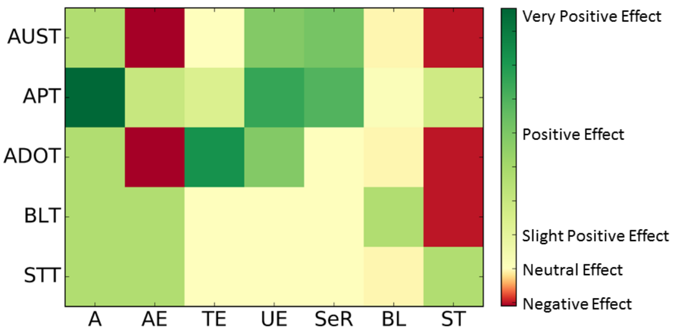

Figure 5: Heat map corresponding to the sensitivity of key performance indicator relative to a change in an underlying metric.

3.3 Matrix-Based Visualizations

The same adjacency matrices that were developed to generate the node-link diagrams were used to explore the efficacy of matrix-based visualization in the context of KPI interdependencies. Matrix-based visualizations are known to be effective for dense networks. Furthermore, another advantage lies in their ability to illustrate advanced analytics performed on the graph. For example, Figure 4 presents the results from a hierarchical clustering of the interdependencies between metrics and KPIs. Based on the Voor Hees Algorithm, groups of KPIs are defined and arranged based on the number of shared metrics [18]. The dendrogram to the left of the matrix is codified with the cluster distances represented by the length of the branches. For clarity, shorter branches in the dendrogram correspond to tighter clusters. This form of information visualization effectively reflects the relative difference in cluster distance. The matrix to the right of the diagram presents the adjacency matrix representing the KPI interdependencies. If a metric (represented as a row) has a functional effect on a KPI (represented as a column), its corresponding cell in the matrix is highlighted blue.

Figure 5 illustrates another way of visualizing the same information as in Figure 3 but using a matrix-based layout. Instead of presenting the degree of change in a KPI by exploiting node diameter, in this diagram, sensitivity is codified by color (yellow as no effect on the KPI, red indicates a negative effect on the KPI, and green illustrates a positive effect on the KPI). This is similar to a heat map.

Lessons Learned:

A prominent advantage of using matrix-based representations compared with network visualization is the avoidance of occlusion issues. In other words, when interacting with the cells of a matrix, the rules that dictate the layout of information do not allow for entities to lie on top of one another. This characteristic also contributes to being a more appropriate option for dense networks as well as a better representation of clustering interdependencies (e.g. for large sets of KPIs and metrics). Also, the compactness of a matrix-based visualization lends itself to incorporating supporting diagrams, e.g. the dendrogram beside the matrix in Figure 4. On the contrary, matrices do not easily lend itself to human interaction. The tabular form imposes strict convention to data presentation and layout, which makes it difficult for a user to perform what-if analysis when determining which metrics to improve.

3.4 Coordinated Visualizations through Small Multiples

The observations summarized in Table 2 guided the development of a customized visualization interface to enable the exploration of metric-KPI independencies. One main goal was to align the advantages of node-link diagrams and matrix-based visualizations in order to enhance human understanding of KPI interdependencies. Small multiples are used, which use multiple graphs with similar scales to show the effect of changing metrics on the different KPIs. Figure 6 provides a screenshot of the prototype visualization tool. The prototype comprises of four primary elements:

Control Sliders (A): Sliders allow users to permute control variables (i.e. a chosen set of metrics) and dynamically view changes in the other mutually coordinated visualizations.

Dependent Metric Readout (B): Some KPIs in ISO 22400 are derived from lower level metrics. Here, these mid-level metrics are computed in accordance with the control sliders.

Sensitivity Matrix (C): Since one wants to understand the effect of individual control variables on each indicator value, a coordinated matrix visualization is provided that displays the effect of changing each individual metric on the indicators to which it is functionally related. An additional row is included below the matrix to summarize the overall change of the indicator with respect to the set of control variables.

Node-Link Diagram (D): Based on observation and common practice, sparse networks (or networks that exhibit low density) are readily visualized using a node-link diagram. Here, indicators and their low-level metrics are represented as nodes and any functional relationships as edges.

Nodes (E): Two different node types are defined corresponding to indicators and low-level metrics. Indicator nodes are represented as a small multiple, wherein its value is displayed on the outer margin of the box. At the center of the node, all low-level measures are displayed relating to the indicator with their normalized values.

Lessons Learned

The prototype is built on the concept of using independent elements combined with mutually coordinated small multiples as an intuitive interface. The prototype interface presented here is the first step to developing a fully functional interactive interface for decision makers to explore the interdependencies between KPIs and their underlying metrics. One lesson is that there is a danger that the system interface could suffer from scope creep. With each addition of a visualization feature, the interface becomes much more complex and less intuitive. For example, including the functions of the interrelationships between low-level and mid-level metrics in Figure 6 might make using the tool more complicated. However, the mutual coordination of multiple representations could provide more detailed and well-described exploration.

4. Discussion and Future Work

The purpose of this work is to identify methods to help guide decision makers in understanding the implications of varying manufacturing-related performance parameters, and visualizing their impact on multiple KPIs. For these relationships to be intuitively displayed, guiding principles from the fields of information visualization and visual analytics are used. Based on lessons learned from exploring node-link diagrams and matrix-based visualizations, we presented an initial prototype interface which emphasized mutually coordinated elements. As has been discussed, both graph-based visualizations, matrices and node-link diagrams, can provide an overview of all KPIs, metrics, and their relationships. These benefits will be further extended in the next prototype and it will become necessary to properly scale the system as a larger set of KPIs and metrics are integrated.

Several additional requirements for visualization to support

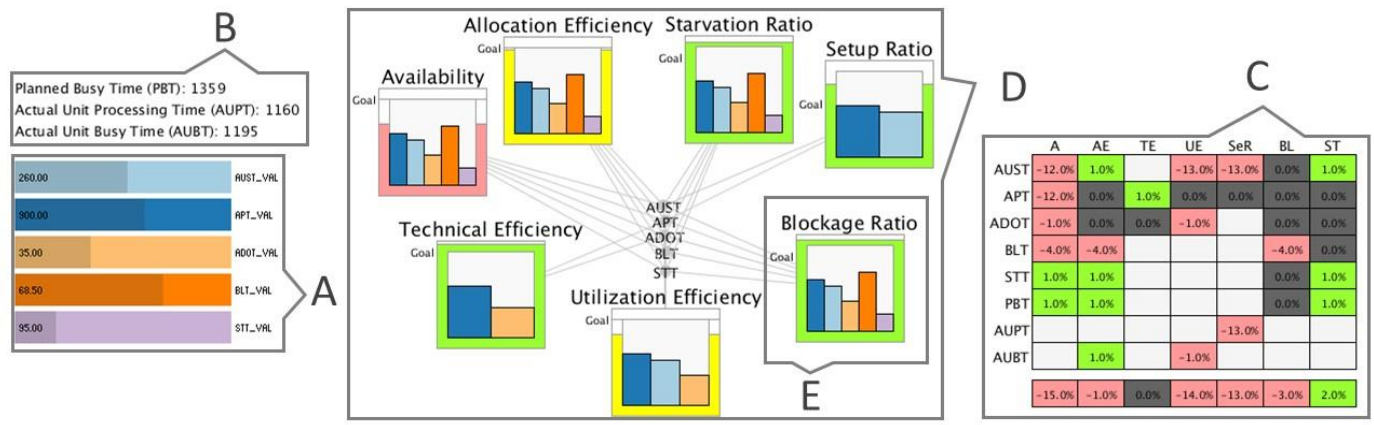

Figure 6: Mutually coordinated visualization enabling the exploration of the interdependencies between metrics and key performance indicators. Callouts to the primary elements denoted by their own character are described in the text.

KPI exploration that have yet to be explored are identified here. First, the study of KPIs and their metrics lends itself to Shneiderman's visualization mantra, "overview first, zoom and filter, then details-on-demand" [19]. The current prototype does not address the functions of filtering or zooming. Filtering and zooming will be fundamental to KPI exploration as many organizations track very large sets of KPIs [4]. Filtering provides a method for emphasizing a particular set of metrics and/or KPIs. For example, in the current prototype, to narrow the scope, only time-based metrics were considered. In the next prototype, we will explore additional features, such as radio buttons or drop-down menus, and add the context of other communities of metrics and KPIs, e.g. quality-based metrics.

The second key requirement for KPI exploration will be the ability to perform what-if analysis on the effect of improving certain metrics on the various KPIs. This capability was initially illustrated in the prototype through the use of sliders to examine the effects of changing metrics. However, more sophisticated support for what-if analysis should be possible. Such capabilities may influence the way in which stakeholders prioritize the KPIs.

A third consideration for improving the prototype includes the use of visualization to represent non-functional relationships as well as environmental and human-related conditions (and their effect). For example, the range of certain metrics will vary based on the differences between human operators who inherently operate at different skill levels and as such may require different amounts of time for activities such as set-up, cleaning, unloading and loading time during machining. These variations greatly affect the bounds for certain control variables. For example, it might not be feasible to anticipate that an operator can decrease their set-up time by 5 mins. When non-functional relationships are quantified, the usefulness of the visualization tool will be enhanced, which can help managers better understand such abstract relationships. We also intend to address variations in human preference and its effect on human-based KPI prioritization. As of now, the importance of KPIs are prioritized based on the number and effective change of their interdependencies. We have yet to explore how interactive visualizations could help overcome differences of intuition.

Another consideration to which visualization may lend itself is in the reflection of trade-offs between different KPIs across multiple goals. For example, analyzing the relationships between throughput, quality, and energy consumption to find the interdependencies between these KPIs and relative contributions of associated metrics to competing goals should be explored. This is the essence of a multi-objective optimization for which intuition alone may be suboptimal or multi-objective optimization may not be feasible. Whether visualization can assist intuition to produce more optimal results should be explored. Our current prototype does not include any optimization problem formulation and we plan to explore this improvement.

Finally, we also plan incorporate multi-machine or multi-line scenarios. The interrelationships of KPIs at different machines or different production lines fundamentally change the underlying models, e.g. altering a metric at one machine might affect performance at another machine.

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