Survey of recent advances on the interface between production system design and quality

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Survey of recent advances on the interface between production system design and quality

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Product design’s impact on quality is widely recognized. Less well recognized is the impact of production system design on quality. As quality can be improved by integrating it with the design of the product, so it can be improved by integrating quality with the design of the production system. This article provides evidence of the production system’s influence on quality and surveys recent advances on the interface between quality and production system design including the design of the production system’s quality control process. After mapping the literature, we identify opportunities for future research.

Keywords: Manufacturing, supply chain, tolerance, andon, inspection, statistical process control

1. Introduction

This article surveys the interface between production system design and quality. Production system design can impact quality. It is too much to ask of a production system to guarantee good quality of a poorly designed product. However, a poorly designed production system can foul the quality of even well-designed products. Also, production system design’s role in quality applies to a broad range of industries. For example, Table A1 in the Appendix cites an example where the production system is identified as either the cause of a lapse in quality or an enabler to improve quality for each the U.S. Census Bureau’s 2007 North American Industry Classification System’s (NAICS) subcategories of manufacturing. It shows that a production system’s impact on quality is pervasive; it touches virtually every type of manufacturing. Although product design administered plays a major role in quality, production system design can also impact quality. Neglecting the interface between production system design and quality can damage even the best designed product’s reputation.

The examples in Table A1 (see Appendix) emphasize the relationship between the production system and quality. This article discusses production system design. The scope we define as production system design covers the various stages needed to set up a complete system for manufacturing one or more products. These stages include the supply chain network, production planning to meet product and process specifications, system layout on the plant floor, equipment selection and tooling, and production management to ensure efficient operations. While many of the examples in Table A1 refer to operational lapses in production, three of the examples highlight the importance of production system design on quality. First, in the textile mills category, the Market News Publishing (2008) report shows that the production system design decision of equipment upgrades can improve quality. Second, in the leather and allied product manufacturing category, the Science Letter (2009) report indicates that applying production system design optimization of the fatliquoring stage can improve quality. Third, in the primary metal manufacturing category, the Modern Casting (2009) report shows that the production system design tasks of improving the process with new cleaning and degassing techniques can improve quality. These examples demonstrate that production system design can improve quality.

Despite the importance of production system design to quality, historically there has been relatively little research on the interface between production system design and quality. Figure 1 displays a version of a figure from Early and Coletti (1999) that categorizes the gaps between customer expectations and perceived delivery. The quality gap’s components are cumulative. Any of the gaps can lead
to perceived poor quality. Quality cannot be inspected into a poorly designed product. However, even a perfectly conceived and perfectly designed product can leave customers dissatisfied if there are large process and operations gaps; all quality gap components are important. This article focuses on the process and operations quality gaps. Both the design of effective production systems and the design of quality control processes are essential to closing the overall quality gap.

Figure 2 displays research areas on a two-by-two matrix to put this article in context. The two rows display the two separate phases (design and operation) in the production system development process. The two columns display two different objectives: productivity and quality. Historically, considerable research has been devoted to the areas in dark gray shading—production system design for productivity, production system operation for productivity, and quality control for operations. This article reviews recent research contributions that help close the research gap (depicted by an empty white square) of the interface between production system design and quality. The horizontal arrow represents the contributions that are extensions of production system design for productivity research that consider quality as an important factor. The vertical arrow represents contributions that are extensions of quality control for operations that consider production system design issues.

We argue that quality can be improved by considering it during production system design. Inman et al. (2003) suggest research areas to close the research gap on designing production systems for quality. This article reviews recent advances in the literature that help incorporate quality in the production system design process and explicitly addresses the role of designing the quality control system.

Figure 3 displays a conceptual product development flow-chart showing the parallel processes of designing the production system and designing the quality control system. Production system design can generically be categorized into five stages: designing the supply chain, production planning, system layout, equipment selection, and production management. For expository purposes, we divide quality control design into quality function deployment, failure mode and effects analysis, inspection planning, design of experiments, and statistical process control. The solid black lines connecting elements of production system design with quality control system design indicate recognized linkages in the literature—but these linkages have room for more work. The red dashed lines indicate new opportunities for integrating quality control system design with production system design. The existing connections will be discussed in the course of the literature review; the proposed connections will be discussed in the future research section.

The boundaries in Fig. 3 are fluid and many research areas cross boundaries; nonetheless, the figure provides a framework for organizing the literature. Figure 3 is a roadmap for this article where the numbers under each stage refer to a subsection in this article’s literature review. Section 2 progresses through the production system design stages, and Section 3 describes the design of quality control systems. Section 4 concludes with suggestions for future research.

2. Literature review of designing production systems for quality

This section surveys recent advances in production systems design for quality. As shown in Fig. 3, we consider five main categories: supply chain, production planning, system
layout, equipment selection, and production management. These categories are arranged roughly in the coarse-to-fine order that they are performed by a firm. The production system design process begins with the overall supply chain network (where to produce and where to source), followed in turn by production planning, system layout, equipment selection and ending with production system management once the supply chain, planning, layout, and equipment decisions have been made.

### 2.1. Supply chain

A broad view of production system design includes the supply chain. For recent survey articles regarding quality in supply chain management, see, for example, Sila et al. (2006) and Talib et al. (2011). Li and Warfield (2011) pref ace a special issue on quality coordination and assurance in supply chains. This article focuses on production system design, and we now turn our attention to so supply chain design for quality.

Supply chain design begins with supplier selection. Quality has long been a part of the supplier selection and contract specification and is supported by a rich literature. For recent literature reviews see Lo and Yeung (2006), Wu and Weng (2010), and Kumar et al. (2011). Another element of supply chain design is implementing advances in information technology. Xu (2011) argues that the supply chain’s information architecture can be designed to improve quality and Tse and Tan (2011) argue that providing supply chain visibility mitigates the threat of poor quality.

Supply chain design also includes choosing the shipping mode and warehouse locations that can impact the quality of perishable goods. Blackburn and Scudder (2009) analyze supply chain design for perishable products and recommend a responsive supply chain for the stage between harvest and cooling and an efficient supply chain for the stage from cooling to delivery. Dabbene et al. (2008) propose a method that trades off logistic costs with indices measuring perceived product quality. Gong et al. (2007) optimize the location of perishable food distribution centers.

### 2.2. Production planning

Production planning is an early step of production system design that sets the boundary conditions (such as the requirements of perishable products that need the special consideration of time sensitivity) and first-order system design (such as tolerance analysis, process planning, and process capability indices).

#### 2.2.1. Perishable products

In food and many other industries, products are perishable. When a product’s quality degrades with time, it must be degraded or scrapped after a certain time span. Liberopoulos et al. (2007) develop a model for a failure-prone, bufferless, paced, automatic transfer line, where the quality of the material trapped in the stopped workstations deteriorates with time. If this material remains immobilized beyond a certain critical time, its quality becomes unacceptable and it must be scrapped. Similarly, Liberopoulos and Tsarouhas...
(2002) present a case study of increasing a croissant production line’s speed by inserting an in-process buffer in the middle of the line to absorb some of the downtime. Hu and Zong (2009) propose an extended product inspection policy for a deteriorating production system, where product inspections are performed in the middle of a production cycle and, after the inspection, all products produced until the end of the production run are fully reworked. Wang, Hu, and Li (2010) develop a transient analysis to study the buffer capacity needed in dairy filling and packing lines.

Teunter and Flapper (2003) study a single-stage–single-product system where produced units may be non-defective, reworkable defective, or non-reworkable defective and the reworkable defects are perishable or can become technologically obsolete. Soman et al. (2004) consider make-to-order and make-to-stock production with limited product shelf life and sequence-dependent setups. Subbaiah et al. (2011) develop an inventory model for perishable items with alternating production rates and random perishability. Panda and Saha (2010) optimize the production rate and stopping time for a perishable seasonal product with increasing–steady–decreasing time-dependent demand over the sales season.

2.2.2. Process planning

Process planning is the systematic determination of the steps by which a product is manufactured. A key element is setup planning, whose purpose is to arrange manufacturing features in a sequence of setups that ensures quality and productivity (see Huang and Liu (2003)). Research in assuring quality in the setup planning process includes the following. Zhang et al. (1996) discuss the importance of setup planning to tolerance control and propose a graphical approach to generate optimal setup plans based on tolerance specifications. Mantripragada and Whitney (1998) propose the “datum flow chain” concept to explicitly relate datum logic to key product characteristics and assembly sequences and provide information for tolerance analysis. Rong and Bai (1996) propose a machining accuracy analysis for fixture design verification, considering the dependency of variations of multiple dimensions for better identification of machining errors. Song et al. (2005) use a Monte Carlo simulation method to analyze the quality impact of production planning. Xu and Huang (2006) present a setup plan evaluation system recognizing that setup planning is a multiple attributes problem associated with uncertainties and involves human inputs. For a given setup plan, stream of variation methodologies (Shi, 2006) and state-space modeling techniques model the dimensional variation propagation along different setups. Liu et al. (2009) propose a method to realize cost-effective, quality-assured setup planning for multistage manufacturing processes. Finally, Shi and Zhou (2009) survey research in quality control for multistage systems.

2.2.3. Tolerance analysis

While tolerance design and allocation (determining the tolerance for each product component) is an element of product design, considering manufacturing’s tolerance is as an element of the production system design. Hong and Chang (2002) review the broader literature on tolerance design. The following contributions integrate the manufacturing process selection with tolerance allocation. Robles and Roy (2004) incorporate the manufacturing cost to attain a given tolerance in addition to manufacturing capacity constraints, measurement errors, and process capabilities. Etienne et al. (2008) allocate tolerance to provide the best ratio between functional performance and manufacturing cost following Boeing’s “Key Characteristics” approach. Sivakumar et al. (2011) consider both the manufacturing cost and quality loss for each candidate manufacturing process in a multi-objective optimization that distributes tolerances among components. Abdul-Kader et al. (2010) optimize the cost of reworking or scrapping off-specification items and the cost of adjusting manufacturing processes to reduce or eliminate rejected pieces to find the best production specification.

2.2.4. Process capability indices

While process capability indices (see Stoumbos (2002) and Anis (2008) for recent reviews) attempt to measure a current process’s capability, process capability indicators attempt to predict a proposed production system’s performance. By identifying key drivers of quality in the production system, these indicators can serve as guidelines for designing production systems for quality. Recent work in this area includes Nada et al. (2006), who develop a configuration capability indicator to predict the quality performance of manufacturing system designs. They use a hierarchical fuzzy inference to relate manufacturing design parameters to quality. The design parameters are the number of flow paths, the number of stations, overall process capability, level of mistake-proofing, inspection error, allocation of inspection stations, level of intelligent automation (Jidoka) implementation, and buffer size. The intermediate predicted quality measures are the quality of the configuration, morphological structure, error detection responsiveness, defect prevention capability, and defect detection capability, which they aggregate into an overall configuration capability indicator.

2.3. System layout

System layout is a production system design step that follows production planning. Since the layout often impacts the system’s flexibility and robustness, we discuss manufacturing flexibility, production complexity and entropy, and robustness in this subsection.
2.3.1. Manufacturing flexibility

Manufacturing flexibility is the capability of building several different products in one system with no interruption in production due to product differences. Flexibility enables mass customization and high manufacturing utilization. Most companies treat quality as a constraint and only increase flexibility in cases where it will not harm quality (Hallgren et al., 2011). In other words, they are unwilling to sacrifice quality for flexibility (Rosenzweig and Eston, 2010). Nevertheless, flexibility and quality can be related.

Several studies seem to indicate that flexibility can improve quality. For example, Weber (2004) reports that flexible modular assembly systems help achieve better product quality. Dangayach and Deshmukh (2005) surveyed 122 Indian companies regarding advanced manufacturing technologies and found that flexibility and quality are positively correlated with a Pearson’s correlation coefficient of 0.25. In Europe, BMW invested in additional robots to improve both flexibility and quality (Kochan, 2005). On the other hand, Inman et al. (2003) suggest that flexibility could impact quality, but that the relationship has not been thoroughly analyzed. Li and Huang (2007) use a Markovian model to investigate the relationship between machine flexibility and product quality. Pinker and Shumsky (2000) argue that cross-training workers to increase flexibility can degrade quality. Similarly, McDonald et al. (2009) model worker cross-training and assignment and observe that increased cross-training reduces quality primarily because a newly cross-trained worker will not perform as well as an experienced specialized worker.

2.3.2. Production complexity and entropy

Globalization and the demand for more product functionality and variety are driving the incorporation of more complexity into production systems. Although the definition of manufacturing complexity varies, it typically includes mixed product lines, a large number of materials at one location, and a complex supply network. In exploring complexity’s impact on quality, considerable attention is paid to the behavior of operators. Studies have found that operators tend to make more mistakes if their jobs involve making more choices, such as different parts, tools, or procedures. Rao et al. (2010) use a neural network to analyze the relationship between the error rate and the number of choices. Abad et al. (2011) model “think time” (when making choices), job complexity, and operator’s experience. Hinkley (1993) and Shibata (2002) present models to predict defects based on the number of assembly operations in the semiconductor industry. Su et al. (2010) apply a similar concept to predict defects in copier manufacturing. These models all positively link the operator’s work complexity (number of job elements, task difficulty, think time, and so forth) with product defects. In addition to these studies on operators, Bozarth et al. (2009) explored supply chain complexity and found that internal manufacturing complexity (including the number of parts and products, the types of processes, and the schedule stability) negatively impacts manufacturing performance measures (customer satisfaction and competitive performance). Huang and Inman (2010) analyze automotive plant build complexity’s negative impact on quality and investigate how complexity impacts assembly line work. In mixed-model assembly systems, the station configurations may be highly complex because different product variants follow different production paths in the same assembly system. Several papers develop methods to link station configurations and product mix with quality; see, for example, Webbink and Hu (2005) and Abad and Jin (2011).

2.3.3. Robustness

Robust production system design is an important research topic. Fluctuations in operations can damage product quality, and robust production system design seeks to minimize this damage. The considerable literature on the trade-offs between productivity, flexibility, and quality includes Son and Park (1987), Jacobs and Meerkov (1991), Bulgak (1992), and Han et al. (1998). There is less research, however, on quantifying the effects of random production variability on quality.

In the system design phase, many system parameters are either uncertain or inaccurate. Li et al. (2008) introduce the notion of quality robustness in manufacturing system design and analyze the impact of random variability in repair and rework operations. The results are used to ensure robustness by identifying which system parameters most impact quality.

Chincholkar and Herremann (2008) present a queuing network model to estimate the manufacturing cycle time and throughput in a production system with process drift, which will lead to producing defective parts before the drift can be detected at the downstream station. Sensitivity analyses with respect to machine processing time and arrival rate are carried out to provide insights. Such a model can be used to evaluate system performance of alternative designs, such as inspection allocation and selecting equipment with different yields and drift rates.

2.4. Equipment selection

Equipment selection, which determines machine operating characteristics and reliability, can impact a production line’s quality. If machines have flexibility, lines can be run at different speeds, resulting in trade-offs between productivity and quality. Most machines are also subject to quality failures, which can lead to production loss and defective products. This subsection reviews the literature related to the interface between equipment selection and quality.

2.4.1. Operating speed

The relationship between production line speed and quality has been identified as an important consideration in production system design and operation (see Khouja et al. (1995), Mehrez et al. (1996), and Lin et al. (2001)). The line
Operational failures and quality failures exist in production processes. Both operational and quality failures lead to both quality and operational failures. They identify cases in which the effective production rate increases with larger buffers and also cases in which the effective production rate decreases with larger buffers. Kim and Gershwin (2008) extend this two-machine model by developing approximation methods for analyzing long lines that have both quality and operational failures and discuss inspection allocation and remote quality information feedback. Similarly, Korugan and Ates (2007) model a two-machine–one-buffer line subject to both operational and quality failures to study the quality impact of manufacturing new parts and remanufacturing returned parts on the same machines. Tan and Gershwin (2011) introduce a methodology to analyze a general Markovian continuous-flow system with a finite buffer. The method applies to a range of general models, such as systems with phase-type distributions, multiple unreliable machines in series or parallel in each stage, and can also be used to model systems with quality–quantity relationships.

2.5. Production management

This subsection addresses the continuous improvement of product quality by managing production. It includes quality improvements that can be achieved by identifying and mitigating quality bottlenecks, implementing an andon system to correct defects online, batching products to reduce the negative impact of changeovers, managing the workforce to reduce variations caused by absentee workers, and effective planning of preventive maintenance to mitigate machine deterioration.

2.5.1. Quality bottleneck

Throughput bottleneck identification and elimination have been used as an effective way to improve throughput. Analogous to productivity bottlenecks, quality bottlenecks also deserve study. From a system’s point of view, a quality bottleneck is the factor (operation, ratio, sequence, inspection or other performance metric) that most impedes product quality. Improving the bottleneck factor will lead to the largest improvement in product quality compared with improving all other factors. From this perspective, Wang and Li (2009) investigate the impact of product sequencing on quality, introducing the notion of a quality bottleneck sequence, which is the sequence that impedes quality in the strongest manner. Wang, Li, Arinez, and Biller (2010a) extend this work by defining and analyzing the quality bottleneck transition, which is the transition whose improvement will lead to the largest improvement in quality.

Meerkov and Zhang (2010) consider serial production lines consisting of producing and inspection machines that follow Bernoulli reliability and quality assumptions to gain insight into the nature of both production and quality bottlenecks. Meerkov and Zhang (2011) extend the study to serial production lines with quality–quantity coupling machines, where product quality is interrelated with machine efficiency. Using this methodology, Arinez et al. (2010) describe a continuous improvement project to improve production quality and throughput at an automotive paint shop. By identifying the quality bottleneck, the operation speed can be reduced while maintaining capacity by adding a parallel operation leading to a significant improvement in the throughput of non-defective jobs.

2.5.2. Andon production systems

Derived from the Japanese word for “paper lantern,” andon is a term for a visual control device for monitoring assembly line quality. An andon cord along the assembly line allows workers to signal a request for help. When a worker pulls the andon cord, it triggers a light as a call for help, and the line can be stopped if needed to correct the problem (Monden, 1997; Liker, 2004). Originating with
the Toyota Production System, it has been used in many manufacturing plants worldwide as an effective approach to improve quality (Mayne et al., 2001; Strozniak, 2001; Inman et al., 2003; Tierney, 2004).

In a quantitative analysis, Li and Blumenfeld (2006) examine the benefits of andon systems and determine conditions for successful use. The study develops analytical models to quantify the production rate of quality jobs for different types of transfer production lines. It derives practical rules to guide operations management on the factory floor. Subramaniam et al. (2009) show how andon display data can be used to improved production performance. They present a production monitoring system that automates data collection to provide reliable performance information.

2.5.3. Production batching

Many multiple-product manufacturing systems use batching to reduce changeover time and cost and improve quality. Most studies addressing batching focus on improving productivity (e.g., by minimizing setups) and only a few consider quality. However, production batching may impact quality. Cao et al. (2009) account for the production run length’s impact on quality in their model of splitting lots into alternative routes in a cellular manufacturing environment. They suggest that if a production route is subject to deterioration, then shortening the route by lot splitting will improve quality. Also, if a longer production run improves quality, then merging sub-lots can lengthen production runs to improve quality.

Wang, Li, Arinez, Biller, and Huang (2010) analyze the quality of a manufacturing system with batch operations. They present a production monitoring system that automates data collection to provide reliable performance information.

2.5.4. Maintenance planning

Planning for maintenance can improve productivity and quality. One type of planning is preventive maintenance. Most preventive maintenance research is focused on productivity but some incorporates the impact of quality. For example, Radhoui et al. (2009) introduce a joint quality control and preventive maintenance policy for a manufacturing system with random failures and non-conforming production. The maintenance action will be taken if the proportion of non-conforming units in each lot exceeds a threshold value. A buffer stock is built up to ensure the continuous supply during maintenance. A mathematical model combined with simulation is developed to determine the optimal threshold value and buffer size simultaneously to minimize the total cost due to maintenance, quality, and inventory.

Colledani and Tolio (2012) provide a general theory encompassing preventive maintenance to analyze a production system with progressively deteriorating machines. They show that by a joint analysis and design of functions of quality, maintenance, and production control at the system level in a multistage manufacturing system, the system performance can be improved. The industrial benefits are shown through application of the method to a real manufacturing context.

ElMaraghy and Meselhy (2009) present a framework to investigate the complex relationship between quality and maintainability in reconfigurable manufacturing. They show that manufacturing system changeability affects product quality in two respects: manufacturing system design and maintenance. Maintainability is an important concern in choosing the manufacturing system parameters. This article presents a maintainability strategy using the relationships between the manufacturing system parameters and the multi-objectives for optimizing quality, cost, and availability, which makes the maintenance systems less complex and adaptive to manufacturing changes.

2.5.5. Absenteeism

An assembly line’s operation depends on all workers being present. When any are absent, the line does not function optimally and this can impact product quality. Absenteeism’s effects on productivity and quality have been noted by several authors (Gatchell, 1979; Mefford, 1986; Womack et al., 1991; Oliver et al., 1994; Conti, 1996; Connelly, 2003; Chang, 2004; Mayne and Clanton, 2004; Terlep, 2007). In a case study of lean manufacturing, Brondo and Baba (2010) analyze attendance data for an assembly plant. They point out that lean production systems are team based and explain how absenteeism affects the work environment for the team leader and other team members.

Blumenfeld and Inman (2009) develop an analytical model of an assembly line’s operation to quantify how absenteeism can affect product quality. The model incorporates the increased demand for assistance from a team leader when absent workers must be replaced with less experienced substitutes. A related model that includes team sizing delineates how the throughput of defect-free jobs decreases with team size and absenteeism (Inman and Blumenfeld, 2010). Specific cross-training strategies for addressing assembly line absenteeism are examined in Inman et al. (2004). Their workforce reliability model shows how cross-training can help maintain quality and productivity under absenteeism. Other approaches to reducing absenteeism include attendance bonuses, warning letters, and counseling (Barmby, 2002; Connelly, 2003; Garsten, 2005; Terlep, 2007). There is also evidence that new and sophisticated automation may eliminate adverse effects of absenteeism on assembly line production and quality (Mateo, 2008).
3. Literature review of designing quality control systems for production

Section 2 reviewed recent advances in designing production systems for quality. This section views the interface between production system design and quality from the perspective of quality control system design. In the quality control research area, the existing research work falls into two general categories: quality control for product quality improvement and quality control for production systems. The former topic has been extensively studied, the latter less so. This section surveys research on quality control for production systems. To parallel the approximate chronological order in Section 2, we organize this section's topics roughly in the sequence (planning, design, and finally control) that they would be encountered by a firm. We now review recent advances in the quality control system design topics displayed in Fig. 3.

3.1. Quality function deployment

Quality function deployment (QFD) translates customer requirements into product attributes (to inform product design), which can then be translated to production process requirements (to inform the design of the production process and the design of the quality control process). Xu et al. (2010) provide a comprehensive review of recent QFD developments. Recent work includes Chen et al. (2006), who use a fuzzy logic approach to apply QFD to the design of a flexible manufacturing system. As depicted by the solid (PP-QFD) line in Fig. 3, QFD has been applied to production planning. For example, Lowe et al. (2000) develop a tool based on QFD to rapidly evaluate the effectiveness of the thixoforming process as a manufacturing stage. Hassan et al. (2010) apply QFD to select the process alternatives and then apply Failure Mode and Effects Analysis (FMEA) based on the resulting product and quality characteristics to identify the process with the highest quality-to-cost ratio.

3.2. FMEA

Often performed in conjunction with QFD, a step in process quality planning is to identify failure modes and analyze their effects. Based on a survey of Australian manufacturers, Karim et al. (2008) conclude that FMEA is an important tool for improving product quality. Alaa et al. (2008) present a process planning approach incorporating QFD and FMEA to improve the quality-to-cost ratio. Chin et al. (2003) incorporate QFD and FMEA in their rough quality planning process to help identify the best manufacturing process candidates. Almannai et al. (2008) incorporate QFD (to identify the most suitable manufacturing alternatives) and FMEA (to assess the risk of each) in a decision support tool. Padiyar et al. (2006) describe a supply chain information system based on the FMEA framework to reduce non-conforming parts.

Belmansour and Nourelfath (2010) present an aggregation method to evaluate the throughput of tandem production lines. They treat quality failure as an additional system state in a multi-state machine model.

The discussed studies show that FMEA plays an important role in Production Planning (PP) and Production Management (PM) to improve quality and throughput. As indicated in Fig. 3, the PP-FMEA and PM-FMEA links are recognized connections in the literature. Integrating FMEA with PP and PM can help improve both a production system's quality and productivity.

3.3. Inspection planning

A popular research area is quality inspection in production systems. There has been significant research integrating Inspection Planning (IP) with both System Layout (SL) and PM, as depicted by the solid black (SL-IP, PM-IP) links in Fig. 3. Example applications include designing the number and locations of inspection stations, designing inspection plans (e.g., full inspection or sampling), finding the best action among several options (e.g., rework, repair, or scrapping), dealing with different types of constraints (e.g., inspection time, average outgoing quality limit, or budget limit), dealing with different kinds of production systems, and developing quantitative problem-solving tools. See Raz (1986) and Mandroli et al. (2006) for nice reviews.

Determining the number and location of inspection stations is at the intersection of designing the production system and designing the quality control system. The practical importance of this research area is evidenced by Greimel (2011), who report that Hyundai Motor Company increased the number of inspection stations on its assembly lines to improve quality. Below are some of the recent research advances regarding inspection.

Gershwin and Schick (2007) describe and classify the principal issues that arise in the context of quality/quantity interactions including quality failures, quality inspection, the actions that may be taken in response to inspection, and pertinent measures of system performance. Penn and Raviv (2007) develop a profit model of unreliable serial production lines that depends on both production rates and the allocation of quality control stations. This model enables them to explicitly consider quality in the production system design. They maximize profit using a branch-and-bound approach with a dynamic programming algorithm to find the best combination of production rates and allocation of quality control stations.

Mhada et al. (2011) develop a fluid model of an unreliable production line consisting of production machines and inspection stations that reject non-conforming parts. They apply a decomposition/aggregation method to minimize the average long-term combined storage and shortage costs, while accounting for part quality and specifying the location of quality inspection stations. Korugan and Hancer (2007) study a serial production line with rework
and information feedback. They use an overlapping decomposition method to decompose the system into serial lines and analyze quality information feedback in different scenarios.

3.4. Design of experiments

Design Of Experiments (DOE) is related to the design of quality control systems for a production process. In a typical DOE, physical experiments are carried out in a production process and the experimental data are analyzed to identify key process parameters influencing quality output, which can be subsequently optimized to achieve a quality target. DOE is a very large research area conventionally applied to product quality improvement. One application of DOE is to robust production system design. Since the focus of this article is designing production systems for quality, we limit our DOE discussion to robust design because unlike other DOE topics, it is an area within DOE that does have recent work that explicitly considers production systems. We feel that the many other areas of DOE, while very important to the broader topic of quality, would be outside the scope of this article. Taguchi (1986) introduced robust design with the goal of controlling (design) parameters or factor settings to optimize quality and make output insensitive to uncontrollable (noise) factor variation. Some recent work has applied Taguchi's methods for production system design. For example, Dubey and Yadava (2007) optimize multiple quality characteristics. Wazed et al. (2011) apply the Taguchi DOE approach to a multistage production system with machine breakdowns and quality variations. Sukthomya and Tannock (2005) apply Taguchi experimental design with both historic data and a neural network model to manufacturing process optimization. These two works correspond to the linkage between PM (batch sizing and process optimization, respectively) and DOE (Taguchi methods in particular) in Fig. 3. In both works, to avoid production disruptions, Taguchi methods are not applied by conducting real experiments but through simulation and existing data, respectively.

3.5. Statistical process control

With advances in sensing technologies, automatic data acquisition has become common in production systems. With abundant online measurement data, statistical methods can be used to monitor product quality and detect changes. Statistical Process Control (SPC) is a well-known research area in which various control charts have been developed to monitor product quality and detect changes. The literature on SPC is quite large. Please refer to Woodall and Montgomery (1999) for a nice review. Design of an SPC control chart includes designing the chart's parameters, such as sample size, sampling frequency, and control limits. Control charts can be used to monitor various quality aspects such as single quality characteristics, multiple correlated quality characteristics, mean shifts and changes in variances and covariance, small versus large changes, and quality characteristics that follow particular probability (or possibly non-parametric) distributions. An interesting recent area of SPC research is profile monitoring (see Woodall et al. (2004) and Woodall (2007)). Cherif et al. (2008) apply goal programming to quality control system design by maximizing satisfaction through the setting of specification limits.

Typically, the effectiveness of an SPC design has been evaluated based on quality metrics such as the average run length; i.e., how long it takes the control chart to detect the quality change after it occurs. Little consideration has been given to productivity performance metrics. However, it is not surprising that SPC design impacts not only quality but also productivity. For example, once a control chart generates an out-of-control signal, normal production may be interrupted to allow for checking whether the signal is a false alarm or an indication of a real quality problem. In the latter case, production may be further delayed to allow for fixing the quality problem.

Nevertheless, some recent studies do analyze the impact of SPC on productivity. Colledani and Tolio (2006, 2011) propose analytic methods to incorporate SPC inspection stations and design parameters into the evaluation of production system performance. Their studies focus on SPC with online and 100% inspection policies. Colledani and Tolio (2009) focus on SPC with off-line and sampling inspection policies. Their studies extend existing knowledge regarding system productivity by incorporating SPC in the production system model. For example, one new finding is that larger buffers may not lead to higher throughput of conforming products, which differs from the prior understanding that conforming product throughput increases monotonically with buffer capacities. This result opens the possibility of identifying a buffer size that maximizes the throughput of good parts. This work corresponds to the linkage between PM (buffer capacity optimization) and SPC (for non-conforming products) in Fig. 3. Borgh et al. (2007) extend the work by Colledani and Tolio (2006) and analyze production lines with on-line SPC and rework of defective parts. The probability of rework is not fixed but depends on the quality control system parameters and the probability that machines to go out of control.

Rahim and Ohta (2005) introduce a generalized economic model to integrate inventory and quality control. By taking into account the changes in both process mean and variance and using the joint $R$ chart and $X$ chart to control the production process, the economic production quantity and inspection schedule can be determined. The production process can shift from an in-control state to an out-of-control state due to an assignable cause. The signal of shifting triggers a search for the cause within a pre-specified time, and the process is brought back to an in-control state by repair.

Cheng and Chou (2008) integrate the ARMA control chart to monitor market demand and an individual control
chart to monitor the inventory level. They use simulation to investigate the effects of demand change and autocorrelation on the inventory decisions. They use a Western Electric handbook to define decision rules to detect non-random patterns on control charts.

Some studies focus on specific production systems. Colledani and Yemane (2010) integrate SPC into production logistics modeling for closed-loop production systems such as CONWIP (CONstant Work In Progress) lines. Shanoun et al. (2010) focus on a simplified model of semiconductor production consisting of one production tool, one buffer, and one control device. Their study shows that when buffer behaviors are considered in planning the process control, the number of controls may be reduced, leading to better productivity. A test of their proposed method over a 300-mm wafer fabrication data set showed that 35% of controls can be skipped. This work also reflects the linkage between PM (buffer behaviors in particular) and SPC process control. Baud-Lavign et al. (2010) point out that in the semiconductor industry, key and costly investigations are made to reduce scrap, which should be taken into account in the design of SPC. Specifically, they propose a simulation model to infer SPC parameters, such as the sample size and sampling interval, by considering reuse of SPC data for scrap investigation and associated costs. Totondo et al. (2009) develop a prediction model using simulation for both the number of non-sampled items between two successive samples and the time between two successive samples in a multi-product, multistage parallel manufacturing system subject to sequence-disorder and multipletream effects. In addition to predicting the average performance, the analysis provides the shape of the number of non-sampled item distribution. Finally, Hajji et al. (2010) study a joint production control and product specifications decision-making problem in an unreliable manufacturing system.

4. Future research opportunities

This section presents future research opportunities at the interface between production system design and quality. We discuss integrating different aspects of system design and quality, extensions of existing work, and new applications that would address specific links between quality and production system design.

4.1. Integrating production and quality control system design elements

There is a broad opportunity in integrating the design of the production system with the design of its quality control system. Instead of designing the quality control system after the production system is already designed, there is an opportunity for designing both simultaneously. For example, Chowdhury (2005) describes the following sequential seven-step process.

1. Understand who the customers are.
2. Capture and analyze the voice of the customer.
3. Translate the voice of the customer into performance requirements.
4. Choose the best design concept to meet the performance requirements.
5. Translate the performance requirements into product/service design parameters.
6. Translate the product parameters into manufacturing conditions (this step does not apply to a service).
7. Determine activities required to maintain manufacturing conditions or service process parameters.

There may be opportunities for integrating steps (6) and (7) instead of performing them sequentially.

Though there have been significant efforts to try to incorporate productivity consideration into the design of a quality control system as reviewed in Section 3, there are still a large number of subareas in quality control that have not fully taken productivity into consideration. Examples of these subareas include root cause diagnosis of faults, tolerance allocation and synthesis, sensor selection and allocation, and reliability and maintenance scheduling. Considering productivity in traditional quality control system design topics identifies several new research directions.

Another way to view the integration of production and quality control system design is to consider the linkages between the design of production and quality control systems as shown by the dotted lines in Fig. 3. Both the solid line (recognized) and dotted line (new) integrations in Fig. 3 provide opportunities for future research. Even the areas that have been previously recognized would benefit from more research. Here we elaborate on the new connections.

**Applying QFD to supply chain design**

The proposed link between QFD and supply chain represents the opportunity of extending QFD into supplier selection, outsourcing decisions, and logistics planning by researching how to align both internal and external supplier capabilities and shipping capabilities with their impact on the most important customer requirements.

**Applying FMEA to the supply chain**

Analyzing the failure modes by which supply chains can damage quality (for example, sourcing from suppliers without demonstrated quality control, dual-sourcing’s impact on product variation, long lead times that lead to corrosion, variable lead times that allow out-of-sequence deliveries that break the first-in–first-out component usage discipline) can lead to more effective supply chain design.

**Applying FMEA to equipment selection**

The proposed link between failure mode and effects analysis and equipment selection represents an opportunity to
Production system design and quality

consider different types of equipment (for example, robotic versus manual welding) on failure modes.

Incorporating inspection during PP
The proposed link between IP and PP represents an opportunity to explore how existing inspection research results (such as optimal number and location of inspection stations) can be integrated with the PP process during the initial design phase.

Applying DOE to SL
The proposed link between DOE and SL represents an opportunity to apply DOE to different layout alternatives, to identify which layouts work best under various operating criteria.

Applying SPC to SL
The proposed link between SPC and SL represents an opportunity to apply SPC to parallel, cellular, or job-shop layouts.

4.2. Specific research opportunities

Figure 3 helps uncover the proposed research opportunities. There are, however, many other research opportunities in addition to those identified as new areas in Fig. 3. Additional opportunities can be divided into two broad categories:

- extensions of existing work (robust scheduling, human factors, propagation of quality metrics, supply chain, and competing objectives); and
- new applications (energy efficiency, product usage, product launches, and digital manufacturing)

4.2.1. Extensions of existing work

Robust scheduling
Another research opportunity is robust scheduling of multiple products to ensure quality and productivity. The scheduling policies should be robust to changes or variations in production environment, and both quality and productivity should be considered.

Human factors
Investigating the human element’s impact on quality in production systems is another opportunity for future research. First of all, quality is often associated with culture. Culture impacts execution and decision making and undoubtedly impacts quality. However, since culture is difficult to define and model, there remains a considerable opportunity for future research in understanding the relationship between culture and quality. Another human factor that impacts quality is ergonomics. Ergonomics is an element of production system design and its role in productivity and worker health and safety is widely studied. However, there is an opportunity to further investigate the impact of a production system’s ergonomics on quality. A related production system design decision is whether or not to automate an operation. This issue is especially important in developing counties where the labor cost relative to automation is low and the decision is typically made by balancing throughput and cost. However, the quality impact of this decision is not well understood and is an opportunity for future research.

Propagation of quality metrics through the production system
As discussed in Section 2, there is a substantial literature on how dimensional quality propagates through the production system. Still, there are opportunities for future research, including investigating the propagation of other quality metrics (i.e., other than dimensional variation) through the production system and integrating that knowledge of quality propagation with production system design.

Supply chain
Another opportunity for future research is supply chain design for quality. For example, the quality implications of the supply chain design decision to single-, dual-, or multi-source is a possible research area. While multi-sourcing is more resilient to production disruptions, it makes quality control more challenging because the components sourced from different plants will invariably differ. As many production systems involve worldwide operations, another area for future research would be to explore the effects of global sourcing and supply chain flexibility on system design objectives. In global networks, complex routing and long lead times may result in special issues that need to be addressed with regard to production system design and quality. Additionally, extended global supply chains may increase supply chain supply risk and make it more difficult to maintain quality. Future work could extend the research more broadly to logistics networks in order to ensure that quality standards carry throughout an entire supply chain. Some of the topics mentioned in Section 2.1.1 may serve as building blocks for extensions to large complex supply chain networks.

Competing objectives
Another broad area of opportunity is to address the problem of competing objectives (such as cost, safety, throughput, flexibility, and quality) in production system design. A major challenge is to establish basic design principles that ensure top quality while accounting for these competing objectives. Finally, looking into the future, production systems may change drastically. Trends such as globalization, increasing fuel cost, technological advances, and environmental initiatives could certainly reshape production enterprises. The future research challenge will be to understand how to maintain and improve quality in the design of the production systems of the future.
4.2.2. New applications

Energy efficiency

One competing objective seldom considered in the design of production systems for quality is energy efficiency. Instead of focusing solely on productivity and quality, there is an opportunity for integrated models of productivity, quality, and energy efficiency. The goal is for production systems to be productive, ensure quality, and be energy efficient as well.

Digital manufacturing

Digital manufacturing can refer narrowly to a process of additive manufacturing or three-dimensional (3D) printing where a part is made directly from a digital file by laying successive layers of material or, more generally, to the use of a computer-based system of analytics, simulation, and 3D visualization to create product and manufacturing process definitions simultaneously. Sometimes referred to as the third industrial revolution, the digitization of manufacturing will drastically affect how things are made. The accelerating use of digital manufacturing opens new opportunities for better understanding how to design production and quality control systems for new digital manufacturing processes.

New product launches

New product launches often suffer quality lapses, yet there is little research regarding designing the production and quality control systems for product launches. Should the new product production start in multiple manufacturing sites simultaneously or sequentially? Should new products be launched from plants building similar products or have their own plant?

Product usage

QFD incorporates customer requirements in product design, process planning, and process control. However, this unidirectional process can benefit from adding a feedback loop from actual customer usage. Hence, another research opportunity is to understand the relationship between product usage and the production and quality control systems. For example, if the product’s usage varies even slightly from the original customer requirements, it may be possible to improve customer satisfaction and excitement by modifying manufacturing tolerances, routings, and inspection policies.

4.3. Research challenge

Research in these areas is challenging because of the confounding effects. The impacts on quality of the various stages of production system design and quality control system design confound each other and often can only be measured at the end of all these interacting processes. Despite its challenging nature, research in this area has substantial leverage. Once a production system design is in place, it becomes difficult and expensive to modify to improve quality and productivity. By considering quality during production system design, expensive renovation and remediation can be avoided. Furthering our understanding of the interface between production system design and quality will enable higher quality products as well as cost-efficient production.

Acknowledgement

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References


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### Table A1. Examples of the impact of the production system on quality by industry category

<table>
<thead>
<tr>
<th>Industry category (NAICS US Code)</th>
<th>Evidence of production system impact on quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Manufacturing (311)</td>
<td>Daily The Pak Banker (2009) reports that a manufacturer used tainted fish when producing fish crackers, leading to a cholera outbreak in Malaysia</td>
</tr>
<tr>
<td>Beverage and Tobacco Product Manufacturing (312)</td>
<td>The Associated Press (2001) reports that a major international soft drink company recalled thousands of bottles of beverage because of a manufacturing defect caused by broken glass in the bottling process</td>
</tr>
<tr>
<td>Textile Mills (313)</td>
<td>Market News Publishing (2008) reports that a textile manufacturer adopted new thermal insulation and corrosion protection for its dyeing machines which increased product quality</td>
</tr>
<tr>
<td>Textile Product Mills (314)</td>
<td>The Economic Times (2005) reports that the Indian textile industry is working on reducing its manufacturing defect rate from thousands per million to four per million</td>
</tr>
<tr>
<td>Apparel Manufacturing (315)</td>
<td>Business Wire (1995) reports that a major sport shoe company identified a manufacturing defect and offered replacements for defective shoes</td>
</tr>
<tr>
<td>Leather and Allied Product Manufacturing (316)</td>
<td>Science Letter (2009) reports that leather quality can be improved by using experimental design of the fatliquoring stage of the production process</td>
</tr>
<tr>
<td>Wood Product Manufacturing (321)</td>
<td>Lloyd (2004) reports that a major furniture manufacturer identified a manufacturing defect in one of its wood furniture product lines that led to a significant decline in its operating margin</td>
</tr>
<tr>
<td>Printing and Related Support Activities (323)</td>
<td>Transportation and Distribution (1998) reports that a book printer improved quality by reducing the handling damage to paper rolls and by providing computer-aided inspection</td>
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<tr>
<td>Petroleum and Coal Products Manufacturing (324)</td>
<td>Yang (2010) reports that a major gasoline refiner apologized for defective gasoline resulting from lax supervision and ineffective quality control</td>
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<tr>
<td>Chemical Manufacturing (325)</td>
<td>Chase (2004) reports of flu vaccine being contaminated with dangerous bacteria during production</td>
</tr>
<tr>
<td>Plastics and Rubber Products Manufacturing (326)</td>
<td>Reed and Whitmire (2000) report that a major automotive tire manufacturer recalled thousands of tires due to a manufacturing defect</td>
</tr>
<tr>
<td>Nonmetallic Mineral Product Manufacturing (327)</td>
<td>Rogers (2007) reports a faulty concrete mixture used in a highway bridge</td>
</tr>
<tr>
<td>Primary Metal Manufacturing (331)</td>
<td>Modern Casting (2009) observes that new cleaning and degassing techniques can reduce the manufacturing defects in metal castings</td>
</tr>
<tr>
<td>Fabricated Metal Product Manufacturing (332)</td>
<td>Calcott (2000) reports that faulty heat treatment caused tie-rod end and steering joint assemblies to fail prematurely</td>
</tr>
<tr>
<td>Machinery Manufacturing (333)</td>
<td>The Esmerk Danish News (2008) reports that a wind turbine lost one of its blades due to a manufacturing defect</td>
</tr>
<tr>
<td>Computer and Electronic Product Manufacturing (334)</td>
<td>Clark (2004) reports that a major semiconductor producer recalled computer chips because of a manufacturing defect</td>
</tr>
<tr>
<td>Electrical Equipment, Appliance, and Component Manufacturing (335)</td>
<td>The Desert News (2002) reports that a major camera maker recalled 75 000 cameras because of a manufacturing defect</td>
</tr>
<tr>
<td>Transportation Equipment Manufacturing (336)</td>
<td>Koenig and Freed (2011) report that a major aircraft maker identified misaligned rivets due to poor workmanship as the cause of a hole being created in an airplane</td>
</tr>
<tr>
<td>Furniture and Related Product Manufacturing (337)</td>
<td>Paradis (2005) reports that a manufacturing defect can cause swing seats to fall</td>
</tr>
<tr>
<td>Miscellaneous Manufacturing (339)</td>
<td>The Drug Industry Daily (2011) reports a medical device maker recalling surgical sutures because the packaging may not have been properly sealed, allowing some sutures to become non-sterile</td>
</tr>
</tbody>
</table>
Biographies

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