MANUFACTURING SYSTEM DESIGN FOR HIGH PRODUCT QUALITY

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Abstract: *In this paper, through empirical and analytical evidences, we show that manufacturing system design does have an impact on product quality. We suggest several research opportunities addressing the quality implications in manufacturing system design from the automotive industry perspective. Finally, we present application studies to model and analyze the impact of manufacturing system design on quality.*

Keywords: *manufacturing system design, production quality, Andon, quality buy rate.*

1 Introduction

Manufacturing system design and quality management are important parts of vehicle production and extensive research and practice have been devoted to them. However, little attention has been paid to the relationship between manufacturing system design and product quality.

To bring a new product from design to the market, the following processes impact product quality from the production system's perspective: product design, manufacturing system design and validation, and finally manufacturing operation (see Figure 1). Below each process, quality improvement techniques and research efforts to support these processes are outlined.

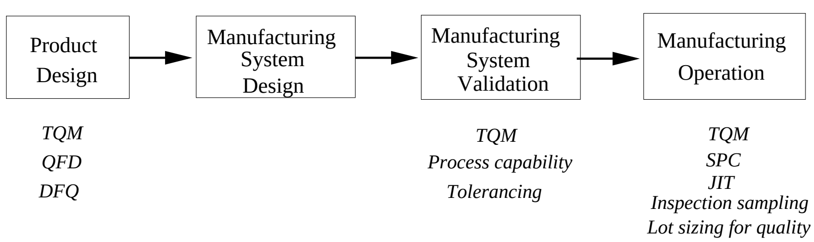

Figure 1: Quality efforts supporting product design, manufacturing system design and validation, and manufacturing operation

As shown in Figure 1, substantial research attention has been paid to product design, manufacturing system validation and manufacturing operation. But what quality techniques are associated with production system design? Although limited related research has been done, it still indicates a scarcity of research on attempting to improve quality in the production system design phase. In other words, the intersection between quality and manufacturing system design is largely unexplored. This gap in quality research presents a promising opportunity.

The goal of this paper is to motivate research on designing manufacturing systems for quality. In subsequent sections, we propose some research topics of interest from an automotive industry perspective. Through application studies, we show that product quality can be improved by designing the manufacturing system more effectively.

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Due to space limitation, we provide here only the outline of the results. Detailed studies and complete list of references and proofs can be found in [1]-[3].

2 Manufacturing System Design Impacts Quality

One could argue that the reason for the lack of research at the intersection of quality and manufacturing system design is that manufacturing system design does not impact quality. To counter that argument, we now provide evidence from the automotive industry that the manufacturing system does impact quality.

- *Observation Exhibit A: The Harbour Report.* Harbour Reports use automotive quality and manufacturing productivity data to show that quality and productivity are positively correlated. It implies that improving the production system can improve quality.

- *Observation Exhibit B: Jaguar.* Jaguar's quality improved rapidly after being acquired by Ford. It is claimed that the quality improvement attributes to Ford's adopting Toyota's production process at the Jaguar plant. These improvements were not due to product design changes, but to production system changes, which indicates that the production system affects quality.

- *Observation Exhibit C: Toyota Motor Company.* Toyota pays particular attention to the production system's impact on quality. Several production system design choices are made to improve quality. For instance, andon, selected stationary assembly stations, additional inspection stations, etc. As a result, Toyota ranks first in initial quality of all the multi-divisional corporations in the JD Power Study.

- *Observation Exhibit D: Ergonomics.* Experiments document that applying ergonomic principles to manufacturing system design can improve quality. For example, poor workstation layout and high line speeds have been shown to hurt the quality performance of manual operations.

- *Analysis Exhibit E: Andon.* Andon is a signaling device enabling an assembly line worker to call for assistance or stop the line. Analytical models of Andon show that stopping the line to fix every problem can improve good job production rate if the average repair time is short (see Application study A).

- *Analysis Exhibit F: Repair and rework system.* Many manufacturing systems have repair or rework areas to fix defects or reprocess jobs. It is shown that with appropriate design of the repair and rework subsystem, the good job ratio can be improved (see Application study B).

The Verdict: The evidence, both empirical and analytical, as well as common sense, convinces us that the production system matters; it does impact quality. Different designs of production systems may result in different quality performance, or, in other words, different designs may require different levels of effort in quality control to meet the same quality standards. Although product design probably plays the largest role in product quality, production system design has a significant impact.

3 Manufacturing System Design for Quality: Research Opportunities

We now present promising research topics, of interest to industry, in designing production systems for quality. Due to space limitation, only a few of them are listed below. More research issues and topics are presented in [1].

- *Assembly Line Balancing.* Traditional assembly line balancing focuses on maximizing worker utilization. As an alternative, engineers could assign large portions of work to sections of the line and allow each section's workers to distribute the tasks among themselves. Another strategy is to identify "quality bottlenecks" in the production system. To enhance the system throughput, we prefer to assign less work to throughput bottleneck stations, and assign more work to faster and more reliable stations. But this ignores the impact on quality. Should we assign more work to a fast and reliable station if it is also a quality bottleneck? Clearly we should consider both competing objectives, productivity and quality, when assigning work to stations.

- *Number, Location, and Size of Rework Loops for Assembly Lines.* Automotive assembly plants typically have a rework loop after body shop and another after paint shop, and a rework area at the end of general assembly. In addition, there could be one or more rework loops inside paint shop with different routing policies. Is this too many, or too few? What should the capacity of each be? It was observed that Japanese manufacturers more willingly stop the line to ensure quality whereas US manufacturers use more rework loops. Which strategy is best?

- *Parallel versus Serial Lines.* Parallel stations or lines offer throughput and flexibility advantages. However, the parallel layout may impair quality. Since no two stations can be truly identical, any two stations (or lines) will produce products with slightly different characteristics. When placed in parallel, this increases the final product's variation. Moreover, when a quality problem is detected in the final product, tracing back to find the cause becomes more difficult if stations or lines are placed in parallel. On the other hand, sometimes parallel layouts can help improve quality. For example, comparing the output from parallel stations or lines can help identify process problems. Understanding parallelism's impact on quality would be valuable and a first step towards the strategic issue of trading off quality and throughput.

- *Centralized versus Decentralized Equipment.* In the past, automakers often had centralized metal stamping and powertrain plants that supplied several assembly plants. However, some new automotive plants have dedicated stamping and powertrain plants nearby. Centralized operations benefit from economies of scale, better utilization, and flexibility. However, decentralized plants may have lower logistics costs, transportation loss and are more responsive to the dedicated assembly plant. Which arrangement is better for quality? Centralized operations make quality control easier by reducing a source of variability, while decentralized operations could have less inventory and quicker feedback from assembly.

- *Batch Size.* Batch size (length of a production run) can have an impact on product quality. Small batch sizes allow quick defect detection, so that problems can be corrected to maintain quality and avoid rework and scrap. However, small batch sizes also mean frequent changeovers that can be disruptive and forfeit "learning curve" benefits. It could be worthwhile to analyze the impact of batching on quality in other production system scenarios.

- *Flexibility.* More work is needed on understanding flexibility's impact on quality. For example, for the body framing process of automotive assembly, two basic fixturing approaches are used to achieve this flexibility. The first is to equip each station with programmable fixtures that will adapt to different models in real time. The second is to include the fixtures as part of the conveyance system (on the product carrier) and process each body without loading and unloading. The latter generally improves throughput while the former reduces the cost if only single product is produced. However, if we want to produce multiple product styles (that require different fixtures), then it is generally cheaper to put the different fixtures on the carriers so simplify the machine. But which produces the best quality? Having a different set of fixtures on every carrier will inevitably lead to more variability and degrade the repeatability and reproducibility. It would be valuable to delineate the tradeoffs between cost, flexibility, throughput, and quality for different fixture locating strategies. This is but one example; the issue of flexibility's impact on quality is very important but largely unexplored.

4 Application Study A: Andon

4.1 Motivation

Considerable study has been done addressing Andon; however, to our best knowledge, no quantitative analysis has been found in the current literature. The goal of this work is to develop a quantitative model to analyze the performance of a transfer production line with Andon and to investigate the tradeoffs between productivity and quality.

In a manufacturing system with Andon, when a defect is discovered (or a problem arises) and can not be fixed by the end of the cycle, the Andon cord is pulled and all machines linked to this cord stop. Extra time is taken to repair the defect. We refer to this case as line with *full Andon* in this paper, denoted as type II system. In some manufacturing plants, Andon is only used for signalling the problem without stopping the line every time. In such systems, the Andon cord is not pulled for every defect, and the line stops for repair only when a severe defect is found. Jobs with minor defects are passed and sent to the next machine. Such systems are characterized as a Type III system, which refers to lines with *partial Andon*. Finally, lines with *no Andon* are referred to as a type I system, where a job is passed to the next machine at the end of the cycle no matter whether it is complete (in good quality) or incomplete (or with defects).

4.2 Problem formulation

An Andon type transfer production line is shown in Figure 2, where the circles represent the machines. Due to page limitation, only the one-machine and multiple machines, one Andon cord cases are outlined here, the case of multiple Andon cords can be found in [2].

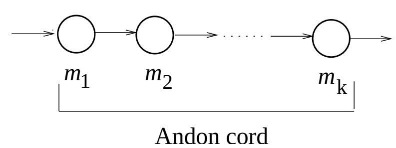

Figure 2: Transfer production line with Andon

(1) A transfer line consists of k machines linked to one Andon cord. Each machine has identical cycle time, c units of time, to process the job. All machines on each Andon cord are synchronized, i.e., jobs are started at the same time. At the end of cycle, there exists a probability λ_i, $i = 1, \ldots, k$, that the job can not be finished with good quality, i.e., has a defect. λ_i is referred to as *quality failure rate.*

(2) For type II or III systems, the extra time needed to repair the defect is described by an exponential distribution with parameters μ_i and ν_i, respectively, $i = 1, \ldots, k$, but constrained by maximum time t_m. When t_m is reached, a job must be sent to next machine no matter whether it is fully repaired or not. In addition, we assume $\nu_i \leq \mu_i$. Parameters μ_i and ν_i are referred to as *quality repair rate* and *quality repair rate for severe defects*, respectively.

(3) For Type III Systems, among all the defective jobs, $\alpha_i \cdot 100\%$, $i = 1, \ldots, k$, of them have severe defects and will be repaired during extra time.

(4) At the end of each cycle, we assume only one worker pulls the Andon cord.

(5) Machine m_1 is never starved and m_k is never blocked.

(6) Independence of quality defects is assumed among all machines.

4.3 One machine case

Let $G_{n,1}$, $G_{f,1}$ and $G_{p,1}$ denote the production rate for good jobs in the one-machine no Andon, full Andon, and partial Andon cases, respectively. The subscript '1' implies the number of machines in the system (subscript 'k' is used to denote k-machine, one Andon cord case). For simplicity, all subscripts of machine parameters are omitted in this subsection. We obtain

Theorem 1 *Under assumptions (1)-(6) with $k = 1$,*

$$G_{n,1} = \frac{1-\lambda}{c}, \tag{1}$$

$$G_{f,1} = \frac{1-\lambda e^{-\mu t_m}}{c+\frac{\lambda}{\mu}(1-e^{-\mu t_m})}, \tag{2}$$

$$G_{p,1} = \frac{1-\lambda+\lambda\alpha(1-e^{-\nu t_m})}{c+\frac{\lambda\alpha}{\nu}(1-e^{-\nu t_m})}. \tag{3}$$

Comparing the good job production rate $G_{f,1}$, $G_{p,1}$ and $G_{n,1}$, we obtain

Corollary 1 *Under assumptions (1)-(6) with $k = 1$,*

$$G_{f,1} > G_{p,1} > G_{n,1}, \quad \text{if} \quad \lambda + c\nu > 1, \tag{4}$$

$$G_{f,1} > G_{n,1} > G_{p,1}, \quad \text{if} \quad \lambda + c\nu < 1, \lambda + c\mu > 1 \tag{5}$$

$$G_{f,1} < G_{n,1}, \ \ G_{p,1} < G_{n,1}, \quad \text{if} \quad \lambda + c\nu < \lambda + c\mu < 1. \tag{6}$$

When the repair rate is high, and the defects can be fixed within a short period of time, then introducing Andon can improve product quality by increasing system throughput of good quality jobs and it is worth to repair all of them. If it takes much longer time to repair the severe defects, but the overall repair rate is still relatively higher, then partial Andon is not as competitive as without Andon, and full Andon is still the best. Moreover, if the failure rate is high, then the line with full Andon is also preferable. If the repair rates for all defects are too low, then no Andon performs better than the other two. To conclude, Andon works well only when the problems can be solved within a short time period.

In addition, the following rule of thumb can be obtained:

Rule of Thumb 1 *If the average time to repair the defect is less than the cycle time, then introducing Andon will improve good job production rate. In addition, if the average time to repair the severe defect is less than the cycle time, then introducing any type of Andon will improve good job production rate and it is worth to repair all the defects rather than the severe ones only.*

4.4 Multiple machines, one Andon cord

Suppose there are k machines on one Andon cord. It implies that if one machine has introduced a quality failure at the end of cycle, and the worker pulls the Andon cord, then all k machines stop and wait either until the problem is fixed or t_m is reached. Then, we obtain

Theorem 2 *Under assumptions (1)-(6),*

$$G_{n,k} = \frac{\prod_{i=1}^{k}(1-\lambda_i)}{c\Big[\prod_{i=1}^{k}(1-\lambda_i)+\sum_{i=1}^{k}\lambda_i\prod_{j=1,j\neq i}^{k}(1-\lambda_j)\Big]}, \tag{7}$$

$$G_{f,k} = \frac{\prod_{i=1}^{k}(1-\lambda_i) + \sum_{i=1}^{k}\lambda_i(1-e^{-\mu_i t_m})\prod_{j=1,j\neq i}^{k}(1-\lambda_j)}{c\prod_{i=1}^{k}(1-\lambda_i) + \sum_{i=1}^{k}\lambda_i\prod_{j=1,j\neq i}(1-\lambda_j)\Big(c+\frac{1-e^{-\mu_i t_m}}{\mu_i}\Big)}, \tag{8}$$

$$G_{p,k} = \frac{\prod_{i=1}^{k}(1-\lambda_i) + \sum_{i=1}^{k}\lambda_i\alpha_i(1-e^{-\nu_i t_m})\prod_{j=1,j\neq i}^{k}(1-\lambda_j)}{c\Big[\prod_{i=1}^{k}(1-\lambda_i) + \sum_{i=1}^{k}\lambda_i\prod_{j=1,j\neq i}^{k}(1-\lambda_j)\Big] + \sum_{i=1}^{k}\lambda_i\alpha_i\prod_{j=1}(1-\lambda_j)\cdot\frac{1-e^{-\nu_i t_m}}{\nu_i(1-\lambda_i)}}. \tag{9}$$

For simplicity, here we concentrate on the identical machine case, i.e., $\lambda_i = \lambda$, $\mu_i = \mu$, $\nu_i = \nu$, $i = 1, \ldots, k$.

Corollary 2 *Under assumptions (1)-(6) with identical machines,*

$$G_{f,k} > G_{p,k} > G_{n,k}, \quad \text{if} \quad (k-1)c\lambda\nu + \lambda + c\nu > 1, \tag{10}$$

$$G_{f,k} > G_{n,k} > G_{p,k}, \quad \text{if} \quad (k-1)c\lambda\mu + \lambda + c\mu > 1 > (k-1)c\lambda\nu + \lambda + c\nu, \tag{11}$$

$$G_{f,k} < G_{n,k}, \;\; G_{p,k} < G_{n,k}, \quad \text{if} \quad (k-1)c\lambda\mu + \lambda + c\mu < 1. \tag{12}$$

Similar to the one-machine case, when the repair times are short, although introducing Andon decreases production capacity, more good jobs are produced due to improvement on product quality and, as before, repairing all the defects is more desirable. When the repair times for severe defects are much longer, it maybe worth to concentrate on repairing all the minor defects. Moreover, longer average repair times can be tolerated to make full Andon system performing better compared to one-machine case. In particular, we can show that $c\lambda$ implies the average time working on the defective jobs (excluding the repair times) for one machine. Then, if we define $kc\lambda$ as the system's average defective working time, we obtain the following rule of thumb:

Rule of Thumb 2 *If the average time to repair the defect is less than the cycle time plus average defective working time, then introducing Andon will improve good job production rate. In addition, if the average time to repair the severe defect is less than the cycle time plus average defective working time, then introducing any type of Andon can improve good job production rate and it gains more benefits to repair all the defects.*

5 Application Study B: Repair and Rework Subsystem

5.1 Motivation

Repair and rework are important parts of production systems in many manufacturing industries. Although substantial effort has been devoted to analyze throughput, the impact of repair and rework subsystem design on product quality has been hardly addressed.

In repair and rework subsystems at automotive assembly plants, product quality typically is characterized by first time quality (FTQ, i.e., the good job ratio of all first time jobs), and quality buy rate (QBR, i.e., good job ratio of all jobs). Both FTQ and QBR are important quality measurements and they have been widely used in many manufacturing facilities. The goal of this study is to address the product quality (in terms of QBR) in repair/rework subsystems by quantifying the relationship between product quality and system design parameters. More specifically, we show that the quality buy rate can be described by a function of repair capacity, and increasing repair capacity can improve the system quality buy rate as well as throughput.

5.2 Problem formulation

A typical structure of a repair/rework subsystem is illustrated in Figure 3. Jobs after the main line processes are inspected and the job flow is then split based on quality measurement. A good quality job is sent to the confirmation station and all defective jobs are routed to either component replacement, minor repair or rework according to the nature and severity of the defects. Jobs undergoing component replacement are routed to the confirmation station if the quality is good, otherwise they are sent either to minor repair or rework. Similarly, jobs exiting minor repair with good quality are transferred to the confirmation station and jobs with unsatisfactory quality are routed either back to minor repair again, or to component replacement or to rework.

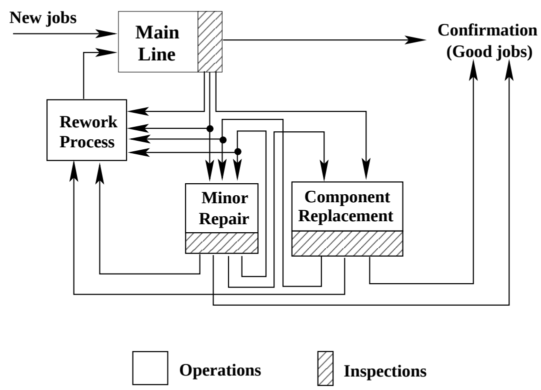

Figure 3: Illustration of job flow in repair/rework subsystems

In addition, since component replacement typically can be finished quickly, its capacity is not a constraint. On the other hand, minor repair often requires more floor space and involves operations that usually take longer time (for instance, involving manual operations). Therefore, its capacity may be limited. When the capacity of minor repair is insufficient, the main line process may be blocked. To avoid this blockage, a typical solution is to reroute those jobs that only need minor repair to the main line for rework.

To analyze this system, the following assumptions are introduced.

(a) A job can be reworked or repaired multiple times. No scrapping of jobs is assumed.

(b) Constant percentages of good quality jobs are assumed in both the main line, and component replacement and minor repair operations.

(c) All rework jobs have the same probability to be good jobs, i.e., the good job ratio of all reprocessed jobs are identical.

(d) All routing probabilities are constant over time. In other words, the probabilities that a defective job should go to component replacement, minor repair and rework are kept unchanged whether the job is a first time processed job or multiple time reprocessed job.

5.3 Model and analysis

Consider the repair/rework subsystem shown in Figure 3. The following notations are used throughout the analysis:

n :	number of first time jobs per day,
q :	first time quality, i.e., ratio of good jobs after first processing at main line operations,
q_r :	rework quality, i.e., ratio of good jobs after rework at main line operations,
$\alpha_x, \alpha_s, \alpha_r$:	probabilities a defective job should go to component replacement, minor repair and rework after main line inspection, respectively,

$\beta_{sx}, \beta_{ss}, \beta_{sr}$ probabilities a job goes to component replacement, minor repair, and rework after minor repair, respectively,

β_{xs}, β_{sr} : probabilities a job should go to minor repair, and rework after component replacement, respectively,

N : minor repair capacity per day,

Q : quality buy rate of all jobs at main line inspection.

The quality buy rate Q of the main line is defined as

$$Q = \frac{nq + n_r q_r}{n + n_r}. \tag{13}$$

From equation (13), a closed formula can be derived for the quality buy rate in terms of the basic design parameters based on conservation of flow.

Theorem 3 *Under assumptions (a)-(d), the quality buy rate Q can be calculated as:*

$$Q = \begin{cases} \frac{q-(q-q_r)\alpha'_r}{1-(q-q_r)\alpha'_r}, & \text{if } N \geq \frac{\alpha'_s n(1-q)}{1-(1-q_r)\alpha'_r}, \\ \frac{nq-n(q-q_r)[1-\alpha_x(1-\beta_{xs}-\beta_{xr})]-Nq_r[1-\beta_{ss}-\beta_{sr}-\beta_{sx}(\beta_{xr}+\beta_{xr})]}{n-n(q-q_r)[1-\alpha_x(1-\beta_{xr}-\beta_{xs})]-N[1-\beta_{sr}-\beta_{ss}-\beta_{sx}(\beta_{xr}+\beta_{xs})]}, & \text{if } N < \frac{\alpha'_s n(1-q)}{1-(1-q_r)\alpha'_r}, \end{cases} \tag{14}$$

where

$$\alpha'_s = \frac{\alpha_s + \alpha_x\beta_{xs}}{1-\beta_{ss}-\beta_{sx}\beta_{xs}}, \quad \alpha'_r = \alpha_r + \frac{\alpha_s(\beta_{sr}+\beta_{sx}\beta_{xr}) + \alpha_x(\beta_{xr}+\beta_{xs}\beta_{sr}-\beta_{ss}\beta_{xr})}{1-\beta_{ss}-\beta_{sx}\beta_{xs}}. \tag{15}$$

In many plants the good job ratio of the reworked jobs is frequently lower than that of the first time jobs. When $q_r < q$, it is easy to show that $Q < q$, which implies that rerouting the jobs needing minor repair to rework, when the capacity of minor repair is not enough, reduces the quality buy rate of the main line. In addition, more materials and resources are consumed during the unnecessary rework and the production rate of the main line is also reduced. Therefore, to ensure a good quality buy rate, minor repair be allocated sufficient capacity.

Consistent with intuition, increasing first time quality, rework quality and minor repair capacity lead to improvement in product quality.

Corollary 3 *Under assumptions (a)-(d), the quality buy rate Q is monotonically increasing with respect to q, q_r and N (if $N < \frac{\alpha_s n(1-q)}{1-(1-q_r)\alpha_r}$).*

This shows that quality buy rate changes is monotonically increasing with respect to minor repair capacity if it does not have enough capacity. It indicates that manufacturing system design does impact product quality.

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