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Quality Prediction and Mistake Proofing

An LDRD Final Report

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Abstract

Sandia National Laboratories is responsible for assuring that our nuclear deterrent remains credible and that the one in a billion disaster of unintended nuclear detonation never occurs. Letting mistake-generated defects into the stockpile would undermine its mission.

The current era of shrinking stockpiles is shrinking Sandia's opportunities to discover and correct mistakes and fine-tune processes over long production runs. In response, Sandia has chosen to develop and use a science-based, life cycle systems engineering practices that, in part, require understanding the design to manufacturing issues in enough detail to tune processes and eliminate mistakes before ever making a part. Defect prevention is a key area of concern that currently lacks sufficient theoretical understanding.

This report is the result of a scoping study in the application of best-practice quality techniques that could address Sandia's stockpile mission. The study provides detail on sources and control of mistakes, poka-yoke or mistake-proofing techniques, the Toyota Production system, and design theory in relation to manufacturing quality prediction. Scoping experiments are described and areas for future research are identified.

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- Raymond W. Harrigan for helping move the issues discovered in this study forward into other areas at Sandia.

Contents

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1 Introduction

Try inserting a 3 $^{1}/_{2}$ inch floppy disk the wrong way. Put it in sideways, it won't fit. Put it in backwards, it won't lock in. Upside down, twisted, or turned, you can't do it wrong. It's mistake-proof. (Note, idiot and fool-proofing has gone out of favor because many people dislike being called idiots and fools that need proofing.)

Mistake-proofing has become a hallmark of good commercial design. A ring prevents you from pumping leaded gas when unleaded is required. Lawn mowers turn off when you let go. Cars buzz when you leave their lights on. Some cars won't shift out of park until you step on their brake. The list goes on. The possibilities are endless.

Preventing day-to-day consumer mistakes is important. To Sandia, preventing mistakes in building military critical weapons components is much more so. Sandia is responsible for assuring that our nuclear deterrent remains credible and that the one in a billion disaster never occurs. Letting mistake-generated defects into the stockpile would undo its work.

Sandia's mission is getting harder. Shrinking stockpiles are shrinking Sandia's opportunities to discover and correct mistakes and fine-tune process the good old-fashioned way. The National goals of retaining a weapons capability, without further production, further complicates Sandia's job. In response, Sandia has chosen to develop and use a science-based, life cycle systems engineering (LCSE) practices. In part, LCSE requires understanding design to manufacturing in enough detail to tune processes and eliminate mistakes before making the first part.

While it's easy to think of mistake-proofing in terms of the devices used to prevent mistakes, mistake-proofing is much more complex. To use mistake-proofing, requires first understanding mistakes within the context of their environments. This includes understanding why people make mistakes and which mistakes are likely to cause problems. That is, understanding the psychology of mistakes. The second is an understanding of how design relates to production or how design features can lead to production mistakes. Understanding enables control. The final part of mistake proofing is to understand the manufacturing design principles and devices that can be employed to minimize or eliminate mistakes.

The remainder of this report provides further detail on the sources and control of mistakes. Section two describes the scope of a study done to prepare this report. Section three describes findings from the cognitive science fields. Section four describes poka-yoke, the Toyota Production System and related Japanese-developed methods for controlling mistakes. Section five briefly reviews design theory in relation to linking design to production. Section six briefly describes two sets of scoping experiments used to test ideas in automating various quality improvement techniques. The conclusion, or section seven, brings these ideas back together and identifies research areas that could improve Sandia's choice for achieving long-term LCSE goals.

2 Background

The LDRD on Automatic Generation of Foolproof Manufacturing Plans was a focusing study on the application of mistake-proofing and related techniques in low-volume DP critical environments. The study investigated new manufacturing quality techniques from inside and outside Sandia that could be successfully and economically employed to ensure mistake-free manufacturing of DOE mission-critical devices and components.

Areas of investigation included cognitive science studies in human error, Shigeo Shingo's experimentally supported concepts in source inspection, Taiichi Ohno's extension and application of the Shingo's concepts in the Toyota Production System (TPS), and key related design theories. Sandia-developed assembly planning technologies were also investigated for applicability in this area.

The study found that while low defect manufacturing approaches, such as mistake-proofing, are often applied in an ad hoc, problem-specific, experiential fashion, there exists underlying manufacturing principals that can significantly aid in appropriate application of the mistake-proofing principals.

While mistake-proofing draws on many techniques, the study found that some techniques could be computationally automated. Sandia's assembly planning tools were extended to support constraints including those needed to optimize assembly order to either minimize part confusion or to maximize self-inspection (e.g., poka-yoke) opportunities. In addition, Sandia process planning tools were modified to represent process to inspection links necessary for modeling source inspection.

While neither the mistake-proofing nor Shingo or Ohno's principals are currently well suited to rigorous engineering, the researchers felt that development of the necessary

Table 1: Hirano's Manufacturing Errors and Safeguards

Type of Error	Clarification	Safeguards
Forgetfulness	*Missing step*	*Alerting operator in advance. Checking at regular intervals*
Misunderstanding	*Inappropriate action*	*Training, checking in advance, standardized work procedures*
Misidentification		*Training, attentiveness, vigilance*
Immature or Inability	*Lack of experience or training.*	*Skill-building, work standardization*
Willful Errors	*Knowingly ignoring rules*	*Basic education and experience*
Inadvertent Errors	*Absentmindedness*	*Attentiveness, discipline, work standardization*
Slowness	*Inability to control dynamic system*	*Skill building, Work standardization*
Lack of Standards	*Standards left to operator's discretion. Operator fails to use "appropriate discretion.*	*Work standardization, work instructions*
Surprise Errors	*Equipment runs differently than normal*	*Total productive maintenance, Work standardization*
Intentional Errors	*Crimes and sabotage*	*Fundamental education and discipline.*

LCSE theories appears feasible. In particular, Nam Suh's axiomatic design theories appear to be extensible to support the critical time-ordering issues needed to model and predict quality. Proposals for necessary follow-on research were developed.

3 Sources of Mistakes

A significant amount of quality research is focused on the issue of where mistakes originate. In design, the focus has been on identifying the effects that various mistakes or failures would produce. In quality control research, this work has focused on practical ways to identify mistake sources. In addition, a great deal of work has been done in the fields of cognitive science and psychology to better understand the root causes of mistakes. This later information adds a great deal of useful depth to our understanding of mistakes.

Without attempting to understand why mistakes would occur, product designers often analyze designs to determine the impact that various failures (due both to manufacturing defects and usage) would have in the product's functioning. The classic approach to this type of analysis is called Failure Mode Effects Analysis or FMEA. Here, the product is analyzed in terms of its functions and features. All product features are then accessed for potential failure modes. For each failure mode, a list of potential effects of and causes for failure are generated. Finally, for each of these effects, methods for controlling the effects and causes are determined and implemented. At the design stage, FMEA helps bound the controllability of failures and can be used to evaluate competing designs against one another. At the production phase, FMEA helps the process engineer focus and martial resources to prevent predictable defects.

Quality control practitioners have identified and categorized the kinds of manufacturing mistakes that occur most often. This understanding allows building safeguards to prevent those mistakes. For example, Hiroyuki Hirano[1] provides a categorical list of 10 types of mistakes with associated safeguards (see table 1). Similarly, William Binroth[2] lists omitted processing, processing errors, errors in setting up workpieces, missing parts, wrong parts, processing wrong work pieces, misoperation, adjustment error, equipment setup errors, and improper preparation of tools and jigs as the most frequent types of production problems.

From these lists, several dominant safeguards appear. These safeguards are broadly grouped into training, standardization, discipline, human factors, alerts and standardized checking. While it is true that such discipline is an underlying requirement for high quality, the difficulty is in applying these safeguards in a cost-effective and efficient manner. By using techniques like FMEA, mentioned above, along with process control methods including poka-yoke, described below, the quality control engineer attempts to control the effects of the mistakes.

The causes and effects of mistakes have been rigorously studied in the cognitive and psychological sciences. James Reason[3] provides a narrow but relatively deep coverage on the great deal of research on this topic as a way of describing the general principles of error production. Aspects that strongly relate to manufacturing-related errors are described below.

Reason lists several groupings of sources of error according to the cognitive skill levels that people were using when the mistakes occurred. The kinds of mistakes that a skilled person makes are very different than those made by somebody first learning the skill. For example, the mistakes in finding one's way in a new neighborhood are very different than the auto-pilot mistake of forgetting to turn off at the appropriate exit in order to grab some groceries on the way home from work. Both of these mistakes are very different from the conceptual mistakes one might make in developing a new way of navigation.

Table 2: Summary of skill-based, rule-based, and knowledge-based errors

Dimension / Error type	Skill-based	Rule-based	Knowledge-based
Type of activity	*Routine actions*	*Problem-solving*	
Focus of attention	*On something other than the task in hand*	*Directed at problem-related issues*	
Control Mode	*Mainly by automatic processors* *(schemata)*	*(stored rules)*	*Limited conscious processes*
Predictability of error types	*Largely predictable "Strong but wrong" errors* *(actions)*	*(mistakes)*	*Variable*
Ratio of error to opportunity for error	*Though absolute numbers may be high, these constitute a small proportion of the total number of opportunities for error*		*Absolute numbers small but opportunity ratio high.*
Influence of situational factors	*Low to moderate; intrinsic factors (frequency of prior use) likely to exert the dominant influence*		*Extrinsic factors likely to dominate*
Ease of detection	*Detection usually fairly rapid and effective*		*Difficult and often only achieved through external intervention.*
Relationship to change	*Knowledge of change not accessed at proper time*	*When and how anticipated change will occur unknown*	*Changes not prepared for or anticipated.*

Generally, cognitive activities can be grouped according skill-based, rule-based, and knowledge-based performance levels. These levels relate to slips and lapses, rule-based mistakes, and knowledge-based mistakes and errors. (Table 2 helps explain the distinctions.)

According to the research, both error types and the likelihood of self-correction can also be predicted from cognitive levels associated with the activities. Skill and rule-based activities are the primary activity levels related to manufacturing operations. (Generally, workers are given task instruction and do not, therefore, need to develop entirely new processes. This may not, however, be the case in prototyping work.)

During skill-based activities, similarity and frequency information appear to be processed automatically without conscious effort, or perhaps even without awareness, regardless of age, ability, cultural background, motivation or task instructions. Another way to think of these skill-based activities is as being run according to a psychologically programmed flow-chart or roadmap. For example, driving home from work combines driving and executing known routes. Both are typically performed at a skill-based activity level.

During rule-based activities, basic skills are drawn upon but conscious activity is made part of the control loop. This conscious activity slows processing and can result in missed cues. For example, people learning to drive miss turns because they are busy concentrating on basic navigation activities and with dealing with the confusion of traffic around them. People learning to navigate in a new town miss turns due to the difficulty of processing the hundreds of unfamiliar road signs while at the same time trying to remember complicated maps and instructions.

The automatic processing in skill-based activities can, when situations change slightly, be responsible for a large portion of mistakes. This automatic processing can take the form of perfectly carrying out undesired tasks and can also be responsible for performing work sequences inappropriately.

Take, for example, a commuter who plans a side-task of stopping for gas during their drive home. Further, assume the commuter is a good driver who knows the way home. Now imagine that just at the point that the driver should deviate from the normal route home, a traffic condition arises that requires close attention to the driving skills. At this point, according to research, it is very likely that the driver will forget the special task, and miss the planned exit. Furthermore, the research says that if the driver intentionally performed an attentional check at the intersection where the choice needed to occur, the probability of mistakes would be drastically reduced. Finally, the research says that a completely different set of mistakes would be more likely were the driver using rule-based skills to set the driving course.

Manufacturing presents routine opportunities for skill-based and rule-based errors. Hirano’s errors of forgetfulness, misunderstanding, misidentification, inadvertent errors, and surprise errors can all be traced to roots in automatic processing. Conversely, immaturity or inability and slowness relate to a lack of automatic processing skills. Thus, the same research that helps us understand why people forget to stop for gas on the way home tells us why workers make simple mistakes. For example, workers are expected to notice defects while performing other tasks. They are supposed to remember to apply special, easily remembered but uniquely different operations to a family of parts. When they are learning to produce a particular assembly, they are unlikely to make the mistake of using two washers when one is required. Once they are skilled, however, a design change from two washers to one is very likely to generate mistakes. Furthermore, this same research clearly predicts that performing attentional checks just before performing special operations is the best way to eliminate these errors.

Correct performance in any sphere of mental activity is achieved by activating the right schemata in the right order at the right time. Cognitive processes receive their guidance from the conscious workspace and the schematic knowledge base. Schemata require a certain threshold level of activation to call them into operation. Both specific (current intention, present context, and related schemata) and general (recency, frequency and shared or similar elements) activator's work can cause specific schema's to be activated.

The more frequently a particular set of actions is performed, the less detailed are the descriptions (or specific activators) that need to be provided. But this steady devolution of control to schemata carries a penalty. To change an established routine of action or thought requires a positive intervention by the attentional control mode. The omission of this intervention in moments of preoccupation or distraction is the most common cause of absent-minded slips of actions. The more a schema or skill is put to work, the less it requires in the way of intentional activation. Quite often, contextual cueing (via general activators) is all that is needed to trigger an inappropriate schema, particularly in familiar environments. Together, breaking out of schemas and activating inappropriate schemas can result in a broad range of errors.

In order to ensure that skill-based actions are carried out as planned, attentional checks should occur in the region of choice points, particularly when the current intention is not to take the most 'popular' post-nodal route. Well-practiced work activities, typical in manufacturing, should comprise segments of preprogrammed behavioral sequences interspersed with attentional checks upon progress. These checks involve bringing the higher levels of the cognitive system (the 'workspace') momentarily into the worker's cognitive control loop in order to establish (a) whether the actions are running according to plan and (b) whether the plan is still adequate to achieve the desired outcome. The former kind of deviation, as has been shown, is detected far more readily than the latter kind.

As we shall see, the successive check system, source inspection and Poka-yoke provide ways to establish whether actions are running according to plan. Conversely, advances in design theory appear to be sufficiently extensible to provide ways of evaluating designs, in relation to production, to establish whether they are truly realizable.

4 Japanese Quality Control Concepts

The discussion on mistakes showed that mistake frequency is related to appropriate timing of action checking. For example, consider floppy disk insertion as a manufacturing assembly step. If a computer user cannot discover whether they've properly used a floppy until another person tries to use the data, then mistakes will be difficult to control. If the computer were to obviously destroy the disk immediately after any insertion mistake (providing a post-nodal check), users would only make the mistake a few times (or quit using the product). In modern computers, floppy disks are measured before inserting, users cannot make disk insertion mistakes and they quickly adapt to not attempting to make these mistakes. Thus, feedback timeliness and quality are critical aspects of defect control. Japanese quality control concepts derive their power from their successful exploitation of this concept.

Poka-yoke, or mistake-proofing devices have been used for many years. The idea of mistake-proofing manufacturing processes, however, is largely a Japanese invention first studied formally by Shigeo Shingo[4] and first put in wide-scale practice at Toyota.[5] Prior to Shingo's studies, poka-yoke was utilized to prevent very specific, typically high consequence mistakes. Shingo's studies and experiments brought structure and context to poka-yoke through the concept of Source Inspection. In addition to developing the poka-yoke idea, Shingo also developed new methods to organize production systems and new ways to rapidly change workcell setups to allow very frequent product mix changes.

Many of Shingo's ideas are analogous to those well known in control systems. In control systems, maximum control requires minimum feedback delay. In manufacturing, a key source of feedback is inspection. Minimizing its delay maximizes manufacturing control. Feedback systems are best controlled when measurement and control points are placed at the earliest possible points in the plant. Shingo found that in manufacturing, this earliest control point is the control of processing related mistakes rather than measuring process outputs and adjusting for the next part.

Recognizing the high impact that the manufacturing environment has on quality, Toyota focused its quality improvement efforts on optimizing the entire manufacturing enterprise. Rather than treating each process step as an isolated problem that would be engineered and operated, Toyota developed a systems approach to address processes, practices, and factory management in relation to one another. The result was Ohno's Toyota Production System.

4.1 Judgment, Informative, Successive and Source Inspection

Early quality control systems relied heavily on **judgment inspections** that were performed after the final step of manufacturing. These inspections provide a good/bad judgment of a product's quality. Bad parts are rejected. The first problem with judgment inspections is that they are error-prone. Incorrectly performing an inspection can allow bad parts to pass. The second problem with judgment inspections is that their results are not quantified, and the information is not fed back in an effective way to improve future production quality.

Sample-based forms of judgment inspections are currently used for some batch-manufactured products. For example, a batch of detonators might be produced and a sample pulled from the batch. The batch is accepted or rejected based on the performance of the sample. If the batch fails, and no mechanisms are provided to identify and correct the root causes of the failure, then the inspection process cannot provide the needed information

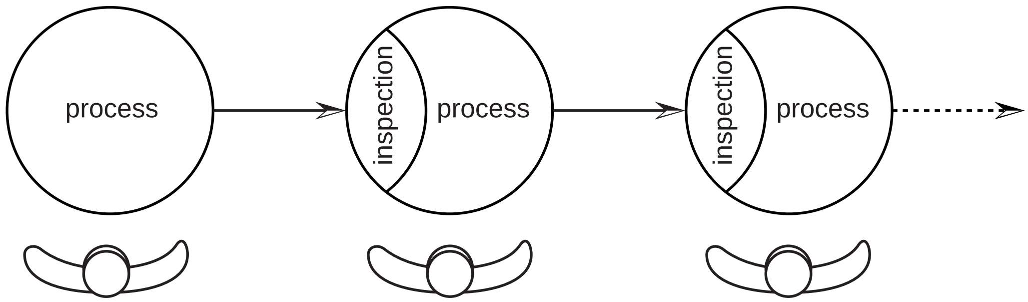

Figure 1: The Successive Check System (as drawn by Shingo)

to avoid similar future defects. Without process improvement feedback, the strongest supportable presumption is that the statistical distribution of quality does not vary from batch to batch, while a weaker assumption is that an unexplainable special condition occurred during the processing of the failed batch. If the stronger assumption is true, then the only justifiable conclusion is that the statistics must be tracked in a cumulative manner and the entire production must be rejected when the cumulative production statistics warrant.

Quality control experts have recognized this fundamental limitation of judgment inspections for over fifty years. In about 1950, **Statistical Process Control** (SPC) was developed to provide process feedback through informative inspections. This feedback helps bring manufacturing quality into control.

In SPC, statistically based control charts are established. The results of actual operations are measured and their values are recorded. If an abnormality is observed in those values, the information is fed back to the process where the abnormality occurred. A check of actual results is then carried out by means of sampling techniques based on statistical theory.

The use of inspection for information contrasts with the use of inspections to sort good from bad. SPC makes it possible to keep defect rates from rising, and, because action is taken when abnormal values show up, the causes of defects can be corrected. Unfortunately, SPC is fundamentally limited by its reliance on statistical sampling. The statistical basis of all SPC control charts requires establishing an acceptable defect level, be it one in ten or one in a million. At best, SPC bounds defect rates for continuously variable process variables. While limited, SPC is important in that it provided the first example of informative inspection for process control.

Shingo, who was studying statistical process control along with ways to combine inspection with processing, first found that using 100% informative inspection close to corresponding manufacturing tasks or operations and sources of quality problems causes dramatic increases in quality. Shingo's implementation of this idea is called the successive check system.

Like SPC, the **successive check system** uses informative inspection for process control. Unlike SPC, the successive check system uses 100% inspection. Unlike judgment inspections, informative inspections typically require quantitative measures. These measures typically take time and effort to perform. In addition, processes must be specifically designed to allow defect information to be fed back to offending processes and work must be performed to provide the feedback. Thus, the practical implication of inspecting 100% of the parts for informative purposes is that inspection must be designed into the manufacturing operation and inspection processes must be automated. The successive check system provides the process design rules for establishing such a system.

Successive check systems are designed according to figure 1. Each work function is designed to automatically inspect the work of the preceding station as its first operation. The successive check system has the following features:

- Each inspection is performed by an independent second person. This retains objectivity.
- Equal level workers perform inspections. This increases the socialization of mistake detection and correction.
- Inspection is performed throughout processing (as opposed to after processing). This improves response time and the ability of the worker to rapidly determine the defect's cause.

The end result is improved root-cause correction. This correction brings the processes into control. Thus, with successive checks, feedback is provided through worker-to-worker interactions. When, for example, one worker discovers a defect, the problem is immediately brought to the attention of the worker who produced the part. This immediate attention allows that worker to identify the cause of the mistake and work toward overcoming the problems.

Through experiments and implementations, Shingo found that many successive checks could be automated through the use of automatic devices. In the beginning, the devices were used for successive check at the successive operation. For some operations, it was found to be more economical to use self-checking. That is, to perform the inspection as a last step in the processing station. Automation of self and successive checks reduced the implementation cost of the successive check system.

Following the success of the successive check system experiments, Shingo reasoned that mistakes are the result of some condition or action, and that it is possible to eliminate the defects by perusing the cause. That is, by automatically inspecting process inputs instead of inspecting process outputs. This concept was termed **source inspection**. That is, inspecting for mistake sources, as opposed to mistake results. Devices that automated the source inspection were true mistake *proofing* devices. In general, however, poka-yoke devices also often describe devices that proof either making or passing on mistakes.

Source inspection moves the inspection point to the sources of defects. Source inspection has its basis in the idea that mistakes will not turn into defects if worker errors are discov-

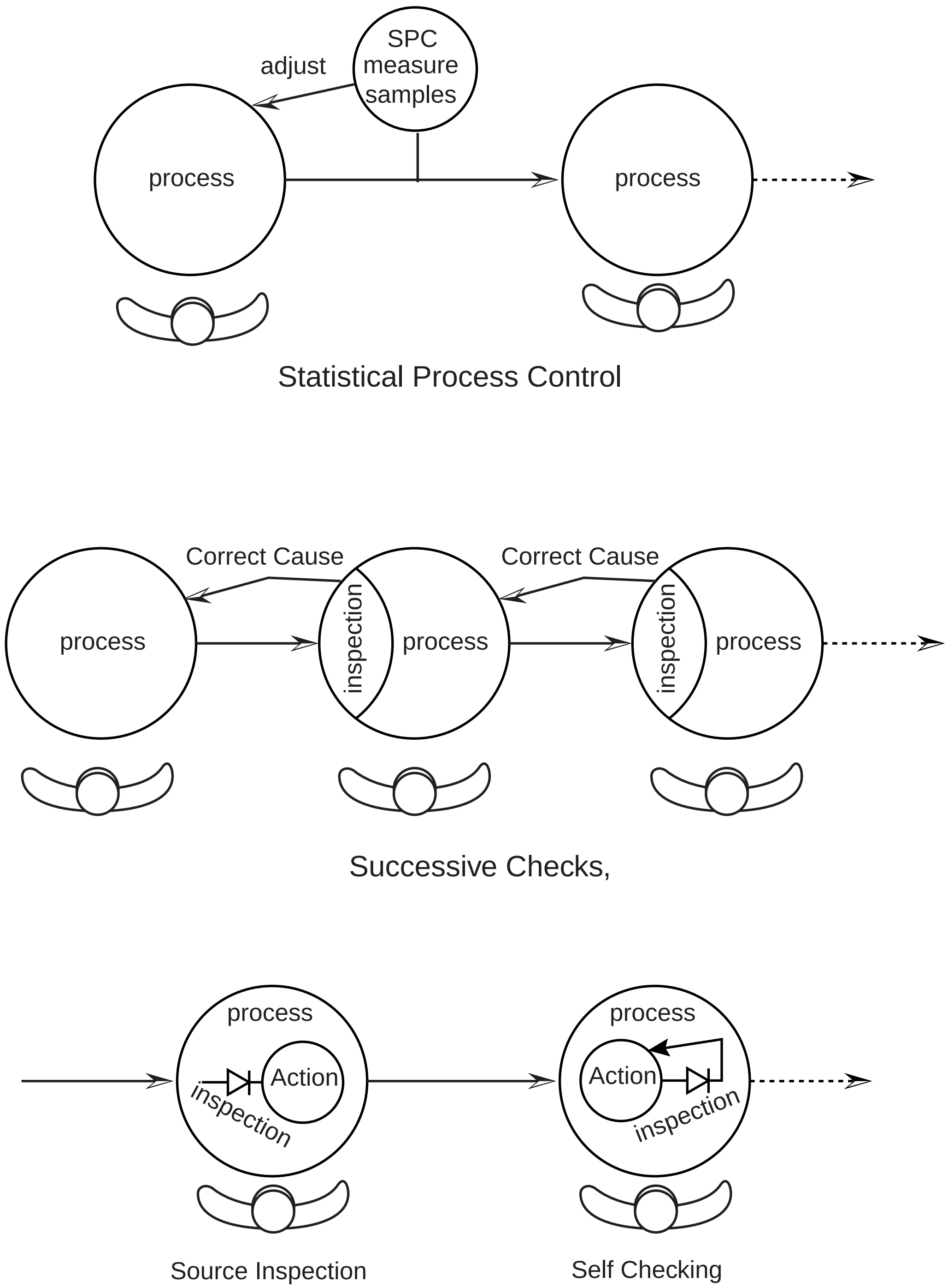

Figure 2: Statistical Process Control, Successive Checks, and Source Inspection drawn with arrows indicating information feedback flows.

ered and eliminated before processing. Use of poka-yoke devices is an absolute requirement for source inspection. Successive checks are then required only when automatic process prevention techniques are not deployed.

Figure 2 shows the information and product flows in statistical process control, the successive check system, self-checking, and source inspection. As can be seen, all three have the feature of rapid process feedback. It should be noted that feedback efficiency is slowed in statistical process control when it is performed as a management (i.e., non-worker) function. In the other three cases, feedback efficiency is improved through worker-to-worker interactions.

4.2 The Toyota Production System

Shingo's work in the successive check system, source inspection and poka-yoke demonstrate the importance of time on manufacturing quality. In this sense, manufacturing processes can be modeled as control systems. Like any other control system, it is impossible to determine or control any parameter, like quality, without understanding the temporal distances between actuation and measurement or, in the case of manufacturing, between production and inspection.

The Toyota Production System (TPS), developed by Ohno, provides such an integrated system approach to achieving quality. TPS integrates the parallel disciplines of autonomation (Jidoka), which includes Shingo's process and quality control techniques, with just in time (JIT). These two disciplines rely on production leveling (Heijunka), worker instruction, and continuous improvement (Kaizen). In TPS, as diagramed in Figure 3, Jidoka and JIT have equally important roles. Here, Jidoka provides techniques for automatic inspection, while JIT provides a system driver for making the autonomation

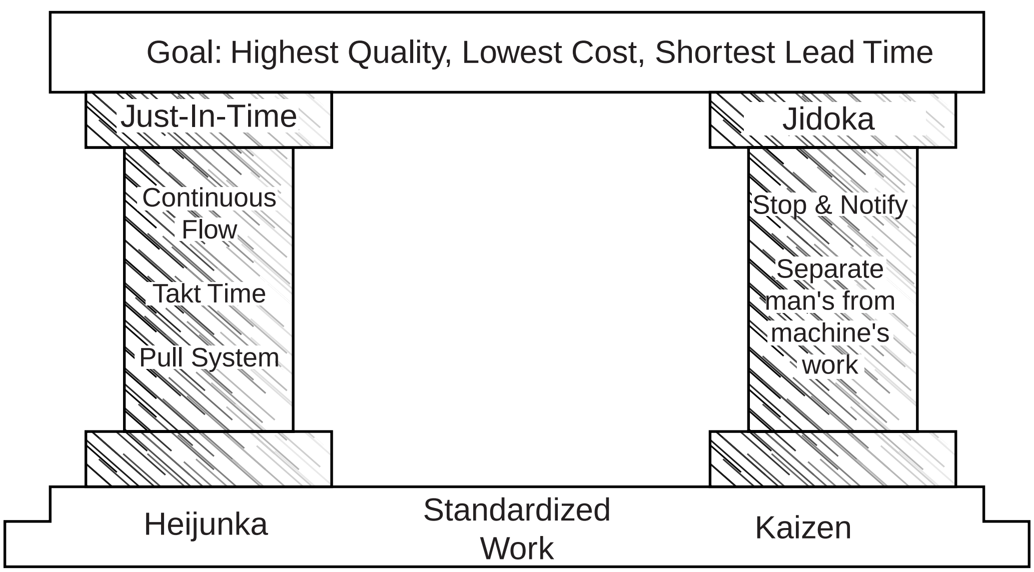

Figure 3: The Toyota Production System Concept of Stability or Stable Manufacturing Processes. Also called Pillars Of Stability

work.

JIT is often misunderstood. As Schronberger[6] observed, "… the prevailing view of JIT is as an inventory control system. In fact it is not uncommon to find just-in-time used synonymously with kanban, which is the name for a specific Japanese inventory replenishment system developed by Toyota. Stockless production is another term that is sometime used. Kanban is indeed one device for moving toward JIT production and "stockless production" captures the inventory control flavor of JIT." In TPS, JIT is much more than an inventory system. "It is used for quality and scrap control, to streamline plant configurations for yield improvements, as a production line balancing approach, and an employee involvement and motivational mechanism."

The JIT concept is to produce and deliver finished goods just in time to be sold, subassemblies just in time to be assembled into finished goods, fabricated parts just in time to go into subassemblies, and purchased materials just in time to be transformed into fabricated parts.

According to Toyota folklore, the Toyota's concept of JIT was developed by Taiichi Ohno's observations of 1950's era American supermarkets. Here, simple and efficient supply mechanisms allow customers to chose exactly when, what, and how much wanted of any item. Ohno arranged production lines along this theme and had workcells produce output for successive workcells as a supermarket system would produce goods for customers. Successive workcells chose exactly what they want when they want it. Cells only produce replacement parts after earlier-produced parts are used. This format is formally called a pull system.

Pull systems contrast with push systems, which are driven by output from preceding lines. In push systems, each manufacturing cell produces parts according to its most optimal rate of production in quantities consistent with its supply. For example, if you provided 100 blanks to a machining workcell that had a cycle time of 1 minute, 100 minutes later, you would expect to produce 100 parts. The machine's capability and its supply of raw materials would set the rate of production. In a JIT pull system, you might setup the machining cell to fill two bins of 10 parts each. When the bins were full, the workcell would be stopped, possibly to be used for another task. When one of the bins were taken away (for use in the next process), the machine would be restarted and another bin filled.[7] The production rate would be set by the actual rate of withdrawal.

From a quality perspective, a key difference between push and pull is in the conditions that cause the machine to stop. In the push system, machines stop when they run out of parts. In the pull system, machines stop when "customers" stop taking or using parts.

A related key difference between push and pull manufacturing is in setting appropriate buffer (i.e., output bin) sizes. In push, buffer sizes are set according to the economic order quantities (EOQ).[8] In pull, the goal buffer size is always one part. Larger buffers indicate process variability. Variability is viewed as the root cause of low quality. As a result, buffers kept are high enough to prevent factory-wide sweeping disruptions but low enough to provide opportunity to reveal and correct variability. Shingo's Single Minute Exchange of Dies (SMED)[9] method is used to reduce the EOQ to make such goals economically feasible.

Along with JIT pull, TPS adds the discipline of jidoka. Among other things, jidoka requires that operators stop machines when they encounter a bad part. Stopping work is intimidating to many workers. This is especially true in push systems when only downstream operations are affected by the stopping while the errant process remains unaffected by the work stoppage. In pull, work stoppage puts pressure on process "suppliers." The result is that the pressure to "do better" gets properly placed on the offending process.

JIT works in close concert with several additional concepts, briefly noted here. These are standardized work, kaizen, kanban, and heijunka.

Standardized work has a much stronger implication than simply prescribing work processes. "Once the standard operations were set by the supervisor (foreman), he must be able to perform these operations perfectly, and then instruct his workers to do so. The supervisor should not only teach the operations, but also explain the reasons the standards must be kept (i.e., the goals of standard operations). This provides the workers with the incentive to take responsibility for product quality." [10]

Kaizen, the discipline of continuous improvement, works in close concert with jidoka to provide a discipline that results in self-correcting processes. Kaizen practices call for both rapidly identifying and correcting root causes of observed defects as well as identifying and eliminating basic conditions that generally lead to defects. For example, poka-yoke devices are often implemented as the result of kaizen activities that follow defect observances. Red tagging, another kaizen activity, is part of regular and biannual cleaning to reduce mess by getting rid of unnecessary items.

Most plants make a variety of parts. As a result, production scheduling is a critical issue. TPS was developed specifically for plants that have high variability in product mixes and as a result, it has developed a very adaptive scheduling mechanism, called heijunka or process leveling. Rather than arranging production exactly according to product orders, the heijunka process distributes production of the various items throughout the day. Shingo's corresponding SMED practice is used to minimize disruption and economic costs from leveling and frequent production changes. As a result, it is typical to see product mixes switch several times per day.

4.3 Summary of Source Inspection and Poka-Yoke

Source inspection and mistake proofing are not isolated practices. Rather they operate in tandem with the underlying manufacturing process in use. As Shingo states:

> … a process is a flow in which raw materials are converted into finished products, and that any errors in process standards would naturally generate defects. That issue, of course, has to be addressed when standards are determined, that is, at the planning stage.
>
> In the course of actual production activities, however, quality is shaped by means of “operations” that fulfill execution functions supplementary to processes. As execution functions, moreover, operations are heavily influenced by the regulatory effects of control functions. It follows from this, surely, that it is correct to say that quality is built into processes.
>
> Furthermore, as the phrase “time is a shadow cast by motion” implies, saying that something takes a long time refers to carrying out motions that require a long time to perform. In the same way, we can say that “quality is a shadow cast by motion.”
>
> What is more, since motions are affected by operating conditions, we can conclude that the fundamental concept of source inspections resides in the absolute need for control functions that – once errors in operating conditions (i.e., in the objects of production, agents of production, methods, space, or time) are discovered – resolve those errors and prevent them from turning into defects.

TPS is one system that incorporates the production practices needed to support source inspection. TPS includes:

- An inspection discipline that causes products to be inspected at the earliest possible time.
- A scheduling process that forces processes to operate in a way that maximizes the chance that errors are exposed,
- A stop on error discipline that causes all defects to be exposed to management and supervision levels where they can be properly addressed,
- A feedback mechanism that causes downstream error discovery to propagate directly to the upstream error sources.
- A continuous improvement discipline that seeks root cause identification and correction as soon as possible to the time problems are first encountered.

5 Design Theories

Applying source inspection in a LCSE environment requires understanding design and manufacturing in relation to the defects and variations that might occur. Source inspection requires knowing what and when to inspect. Both what and when are tied to design and manufacturing. While underlying manufacturing process strongly influence the efficiency of the source inspection, identifying what to inspect and providing allowance to have design features to be inspected at the right time is an issue of design. In this way, it can be said that many manufacturing problems, including mistakes can be eliminated through design. Understanding the design process in relation to manufacturing offers a significant opportunity to reducing manufacturing mistakes.

Within the past two decades, design theory has moved from the obscure to the mainstream. A significant amount of this progress can be traced to Boothroyd and Dewhurst’s and Hauser and Clausing’s practical, as well as Pahl and Beitz’s and Nam Suh’s theoretical work. This section reviews the theoretical work on design as a precursor to understanding design’s impact on manufacturing mistakes.

5.1 Design Processes

Basic design theory focuses on understanding design processes. Different types of design activities are identified and procedures are developed to guide the engineer through the process. Pahl and Beitz[11] break design activities down according to how fundamental of a design effort is being undertaken. They use the terms *original design*, *adaptive design*, and *variant design* to coarsely describe the activities associated with designing a new artifact for a new set of requirements, modifying an artifact to meet a new purpose, or varying the size and or arrangement of an artifact to meet specific requirements.

Pahl and Beitz describe, in great detail, the key processes and activities to accomplish or perform these different types of designs in an effective way. A significant part of the design effort, especially in original and adaptive design, involves describing and understanding the design requirements and solution concepts in terms of their basic functions. For example, the function of a mechanism might be to produce a locking force while the function of a key might be to provide a unique identification. Describing the design in its functional components allows the designer to more easily understand the *essential* functional requirements and simplifies the process of accessing the impact of changing solution elements. For example, the designer might consider electromagnetic means to provide locking forces and electronic means to provide unique identification.

By effectively referencing all work to the functional analysis, the designer can more easily (1) identify new functional arrangements that can fulfill overall functions more effectively or (2) identify alternative solution concepts that achieve or replace functionality in problematic aspects of the design. A significant effort has been made in Europe and the former Soviet Union to catalog solution concepts from functional requirements to speed the second part of this process.

5.2 Axiomatic Design

Nam Suh[12] has formalized many aspects of the functional analysis and developed formalisms for evaluating design qualities. The first aspect of Nam Suh's formalism is the transformations between stages of the design processes. Here, Functional Requirements (FRs) describe the design goals or objectives while Design Parameters (DPs) describe the physicality or physical embodiment of the design. (Please note that these DPs and FRs can be hierarchically defined.) Nam Suh formally defines design as "the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs in the functional domain and the DPs in the physical domain, through the proper selection of DPs that satisfy FRs."

The second aspect of Nam Suh's formalism are the design axioms that provide principles that the mapping technique must satisfy to produce a good design, and offer a basis for comparing and selecting designs. For this, two axioms suffice. (Please note that for these axioms, FRs are defined as the minimum set of independent requirements.)

The first, or the independence axiom, calls for maintaining the independence of functional requirements. This axiom has two alternative statements. (1) An optimal design always maintains the independence of FRs. (2): In an acceptable design, the DPs and the FRs are related in such a way that specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements.

The second, or the Information Axiom, calls for minimizing the information content of the design. This axiom has one alternative form: The best design is a functionally uncoupled design that has the minimum information content.

Nam Suh derives a set of seven key corollaries as direct consequences of the axioms. These are as follows:

(1) Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the designs proposed.
(2) Minimize the number of FRs and constraints.
(3) Integrate design features in a single physical part if FRs can be independently satisfied in the proposed solution.
(4) Use standardized or interchangable parts if the use of these parts is consistent with the FRs and constraints.
(5) Use symmetrical shapes and/or arrangements if they are consistent with the FRs and constraints.
(6) Specify the largest allowable tolerance in stating FRs.
(7) Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.

Mathematically, Nam Suh represents the independence axiom as a design equation.

$$\{ \mathbf{FR} \} = [\mathbf{A}] \{ \mathbf{DP} \}$$

Here, **A** is the design matrix and each element A_{ij} of the matrix relates a component of the **FR** vector to a component of the **DP** vector. (The information in this matrix formulation is similar to that in Japanese Quality Functional Deployment and Hauser and Clausing's House of Quality relationship matricies.) While $A_{ij} = \delta FR_i / \delta DP_j$ for all cases, A_{ij} varies with both FR_i and DP_j in non-linear cases.

Clearly, the simplest design equation occurs when **A** is square and all non-diagonal elements are zero (i.e., $A_{i \neq j} = 0$). A design that can be represented in this way satisfies Axiom 1 since the independence of the FRs is assured when each DP is changed. These are called *uncoupled designs*.

The converse of an uncoupled design is a *coupled design* whose matrix consists mostly of nonzero elements. Here, a change in any FR cannot be accomplished by simply changing a single DP.

Finally, a design is considered *decoupled* when the design matrix is row ordered such that the upper diagonal is zero (i.e. the matrix is triangular $A_{I<j} = 0$). Here, the solution of each design variable cascades from the solution of the first. For example, A_{11} only depends on the relationship between FR_1 to DP_1 while the next two parameters, A_{21} and A_{22} depend on the solution of the first.

These observations lead to the development of 16 theorems. Among these are.

Theorem 1 (coupling due to insufficient number of DPs): When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.

Theorem 2 (decoupling of coupled design): When a design is coupled due to the greater number of FRs than DPs, it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the design matrix containing n x n elements constitutes a triangular matrix.

Theorem 3 (redundant design): When there are more DPs than FRs, the design is either a redundant design or a coupled design.

Theorem 4 (Ideal Design): In an ideal design, the number of DPs is equal to the number of FRs.

The Independence Axiom is based on classical information theory. For design, Nam Suh defines Information as the measure of knowledge required to satisfy a given FR at a given level of the FR hierarchy. This notion of information is very closely related to the probability of achieving the FR. As a result, he defines the information quantitatively as the logarithm of the probability of fulfilling the specified FR. (This is a traditional information theory definition. The result of using the logarithm of the probability is to make the total information additive, rather than multiplicative, across the FRs.)

A few important theorems fall out of the second axiom. Theorem 13 (Information content of the total system) states that if each DP is probabilistically independent of other DPs, the information content of the total system is the sum of the information of all individual events associated with the set of FRs which must be satisfied. The implication is that design complexity in an uncoupled system is additive across functional requirements. Theorem 14 (Information content of coupled versus uncoupled design) states that when the state of FRs is changed from one state to another in the functional domain, the information required for the change is greater for a coupled process than for an uncoupled design.

Recently, software called Invention Machine[13] has been produced that utilizes both principles of functional analysis, axiomatic design, with other principles developed in the Soviet Union. Two aspects of the Invention Machine software are function structure diagrams and catalog-based solution retrieval. This class of software is making design theory application practical for a large segment of the engineering community.

5.3 Theoretical Issues of Design For Manufacturability

It is easy, for most practitioners, to imagine designing products that are difficult or impossible to produce. To a smaller number of practitioners, it is easy to imagine designing products that would be difficult to consistently produce correctly. Low producability results in high production costs and, less obviously, in high defect rates.

Unfortunately, it is difficult, for most, to imagine design processes and metrics that reasonably predict whether given designs would be difficult to produce correctly. Without appropriate processes and metrics, evaluation of producability remains a matter of opinion.

Fortunately, several accepted metrics do exist to predict producability in terms of the cost or difficulty of producing products. Relevant techniques were first developed at the turn of the century when Frederick Taylor developed his principles of scientific management[14] and later refined during world war 2 when Frank and Lillian Gilbreth developed the time motion study techniques, including the Simo, chart for studying and optimizing manufacturing processes. Together these techniques allow determining the manufacturing price of a product in terms of labor content and thereby provide one method for comparing design options. Here, total labor time is predicted as a primary basis for cost.

Boothroyd and Dewhurst[15] have developed Design For Assembly (DFA), a handbook approach to assembly analysis. The DFA approach provides methods and data for estimating the time required for assembling various products and, thereby, ways to redesign the products to reduce assembly time.

Hinckley[16] found that DFA time measures can be used to quantify assembly complexity and that these measures of complexity closely predict defect levels. In essence, Hinckley leveraged the idea of using labor time as a measure of complexity, and demonstrated that defect rates are closely related to this measure of complexity.

In addition, Hinckley developed ways for estimating complexity that do not rely on accurate experimental measures of each production step. Hinckley noticed that the distribution of operation times in any product closely match a Pareto distribution. (i.e., ranking assembly times produces logarithmic relationship.) By ranking operation times according to a Pareto analysis, complexity is characterized by three constants that define a point-slope relationship. These are 1) The number of operations, 2) The minimum assembly time for the parety curve, and 3) The slope of the Pareto distribution.

Hinckley provides the following simple procedure for estimating complexity (in terms of total assembly or touch time):

1) Count the number of assembly operations
2) Sort operations according to difficulty
3) Select two of the operations, A and B (optimally one near the top and the other near the bottom quartile) and identify operation number (N) and time (t).

4) Calculate the Pareto constant $\alpha = [\log(N_a) - \log(N_b)]/[\log(t_b) - \log(t_a)]$
5) Compute total assembly time TM by summing the predicted assembly time for each operation

$$TM = t_{min} * \mathrm{Sum}(N_o/N_i)^{1/\alpha}$$

Hinckley's findings strongly correlate with key aspects of Nam Suh's information theory. Nam Suh design theories extend into the manufacturing or Processing Domains through the concept of process variables. The process domain maps to the physical domain through process variables (**PV**s) through a process design matrix **B** according to the equation:

$$\{ \mathbf{DP} \} = [\mathbf{B}] \{ \mathbf{PV} \}$$

With this extension, Nam Suh proposes additional important theorems. Most importantly for this paper are:

Theorem 9 (Design for manufacturability): For a product to be manufacturable, the design matrix for the product [A] times the design matrix for the manufacturing process [B] must yield either a diagonal or triangular matrix. Consequently, when any one of these design matrices, i.e., either [A] or [B], represents a coupled design, the product cannot be manufactured.

Theorem 16 (Equality of information content)[17] states that all information contents that are relevant to the design task are equally important regardless of their physical origin and no weighting factor should be applied to them. (In a personal email, Nam Suh explained that if one uses a weighting factor, the sum of the information is no longer related to probability. As a result, weighting factors must be taken care of by the choice of the design range.)

While Theorem 9 provides a traditional "can/can't make it" dichotomy, Theorem 16 closely matches Hinckley's findings. For the theorem implies that from a producability point of view, each functional requirement has equal importance. The quality of a design is reduced equally by the difficulty of achieving any functional requirement. (A chain is only as strong as its weakest link.) Or, more simply, complexity, like total labor time, is additive. As such, it appears that combining Hinckley's experimental findings with Nam Suh's theories could yield stronger or more practical design analyses concepts. This combining provides a significant opportunity for further research.

A common weak point of all the research discussed so far lies in the fact that it fails to relate processing history to product quality. Yet Shingo and Ohno's experiences strongly reflect the importance of processing time and process feedback opportunities as key to product quality. It is this final issue that this author believes has the highest potential impact for theoretical and practical progress.

While no such theory exists, it is not unreasonable to use Hinckley's techniques as a model for how the theory might work. In the same way that Hinckley relates total labor time to quality, a theory that included the time element would likely include production to inspection delay time as the second key element for predicting product quality.

An analysis similar to DFA might be used to determine the likely time between performing operations and inspecting their results. For example, features that were physically impossible to inspect until the final assembly would have large delay times. Easy to inspect features would have short associated delay times. When source inspection techniques could be implemented for specific design features, delay time would be zero. Designs with low delay times would likely have the best merits. Pereto-type analysis techniques could possibly be used to extend prototype manufacturing data to full-production defect prediction.

The concept of extending design theory in a way that maps functional requirements all the way through processing histories is a significant opportunity for further research. This author believes that results from such research could have the most significant impact on the LCSE process.

5.4 Summary of Design Theory Issues

In summary, design theory provides methods

- to represent designs in a functional manner,
- to relate design functions to design features to manufacturing steps, and
- to analyze these relationships and compare solutions at their most basic levels.

In addition, key aspects of these theoretically-based methods have been automated and the techniques are gaining acceptance in the design community. Finally, the observation of the importance of time in manufacturing opens new avenues for further extension of the theoretical understanding of design.

6 Experiments

This scoping study included two experiments to determine the possibility of automating the kind of analysis suggested in the prior section. The first set of experiments were performed to determine whether automated assembly analysis software could be extended to allow reordering assembly procedures to either minimize delay time or conversely to minimize DFA measures of part misidentification. Another experiment was used to determine the degree of difficulty in extending manufacturing process design software to capture process to inspection delays.

The first study used automated assembly sequencing software to reduce mistake opportunities in assembly procedures. To reduce assembly mistakes, it's sometimes useful to assemble similar-looking parts at different workstations. This reduces the chance of confusing the parts and, for example, putting a slightly shorter screw into the place that the longer screw belongs. Conversely, it is also sometimes important to make sure that parts get assembled as close as possible to one another. This is important when the later part somehow “inspects” the presence of the earlier part. (For example, if the function of a pin is to keep a slide from traveling too far, installing the pin and slide in close sequence and allows inspecting the pin’s presence by checking the slide’s travel.)

Sandia assembly planning tools were extended to determine the extent to which these techniques could be automated. A prototype of a needed constraint system, called MIN_SIMUL-LIAISON, was developed to penalize any mate that created a significant number of liaisons in a single action. Additional effort will be required to implement further key mistake-proofing constraints. This will include computing cost functions based on overall plans. Such research is recommended for follow-on activities.

A feasibility study investigating the incorporation of poke yoke and source inspection into formal system design theories was performed by extending Sandia process planning tools to model successive checks and source inspection steps. This modeling requires identifying the key features produced in each manufacturing step and then building automatic inspection into that or successive manufacturing steps. Modeling the linkage between production and inspection is key to quantifying mistake-proofing payoffs.

The second study resulted in a proposal to develop the extended theories and incorporate them into conceptual design support tools currently being developed by the Intelligent Systems and Robotics Center. In the assembly example above, assembly plan optimization would require measures or foundations to relate proximity in sequence to expected quality levels. The theoretical work would develop this relationship and the planning tools would allow modeling the quality results.

7 Conclusion

This report summarized a broad cross-section of technologies and approaches for understanding and reducing product defects.

The report reviewed findings in the cognitive sciences field that help identify when and why people make mistakes. From this review, it was shown that the likely kinds of mistakes people make closely relates to training level and that appropriate use of post-nodal checks can significantly reduce mistake levels.

The review of Japanese quality control techniques showed that appropriate use of techniques, such as Poka-Yoke must include a context for adoption. Further, the review showed that the Toyota Production System, which is widely recognized as including the most successful use of poka-yoke, implicitly provides a robust example of the needed system context. Finally, the review showed that time between production and inspection as a key element in determining defect rates and that this element completely parallels findings in the cognitive science field.

The review of design theory showed that an extensive literature exists to support more robust design practices. Furthermore, specific elements of design theory can be used to predict defect rates in production. However, the review also found that these design theories are incomplete in that they neglect the time element in manufacturing processes. Extending the theories has promise for significant improvements in the LCSE process. A brief roadmap for extending theory to address this issue was discussed.

Two sets of experiments were described. The first experiment set showed that advanced assembly planning tools could be adapted to automatically optimize procedures to reduce defect possibilities. The second set showed that process-planning tools could be extended to support time element computations. Both sets of experiments show ways that LCSE design processes can be successfully automated.

It's been said that need is the mother of invention. We need to produce fewer WR products at lower costs. Mistake proofing, when incorporated into the evolving LCSE technologies can allow us to make it right the first time. While so doing, Sandia can lead the way in formalizing this important area of quality manufacturing.

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[7]In practice, the machine groups or workcells are designed to either run at a scheduled time rate of withdrawal (takt time) or designed for multifunction use by means of single minute exchange of dies (SMED) combined with Heijunka-based scheduling schemes.

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