# POLITECNICO DI MILANO

## Master of Science in Management Engineering

FINAL WORK: LITERATURE REVIEW

# Optimization of Inspection Process in a Production Line

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# OPTIMIZATION OF QUALITY INSPECTION PROCESS IN A PRODUCTION LINE

## Abstract

**Purpose:** The paper is intended to classify research on **Optimization of Quality inspection process in a Production line** on the basis of the main research themes, methods and proposes directions for future research.

**Methodology/Approach**: The review is based on36 papers published from 1964 to 2013 in international peer-reviewed journals. The academic papers are analyzed and classified according to the research methodology adopted and the themes addressed.

**Findings:** Future areas of research identified in the field optimal inspection policies for a production line. General trend is seen towards creating integrated models for production to create more realistic models utilizing heuristic and simulation methodologies. Huge research possibility available towards diagnosis-oriented strategies which is in its early stages. Other broad venues of research possibilities highlighted.

**Originality/Value:** The paper intends to be an overall study of the main themes and functional parameters addressed in previous research on the topic of improving inspection strategies in a production line based on optimization. The paper on its course will also be touching upon important issues that need to be addressed in future research.

*Keywords:* Optimization models, Inspection strategy, production line, economic, Quality inspection policies,

*Paper Type:* Literature review

# TABLE OF CONTENTS

# SECTION I: SCOPE AND METHODOLOGY

## 1. Introduction

Managing quality is fundamental to any activity, and having a clear understanding of the main aspects, measuring its performance, and taking action to improve, is essential for any organization to survive and grow in this competitive world. Operations managers tend to view quality as being the fraction of products that are made right the first time in each of the various stages that constitute a manufacturing process. More quantitatively, quality is defined to be inversely proportional to variability, and quality improvement is then equivalent to variation reduction by producing fewer defective parts.

Since almost all manufacturing processes are technologically incapable of delivering perfect quality, establishing an effective quality-assurance program by planning and managing resources dedicated to the inspection, and testing of critical quality characteristics is important. Human inspectors, automated devices, or a combination of both are often used for quality inspection processes. The ‘screening’, or ‘inspection’ or ‘measurement-taking’ may simply be process checks for defects resulting from an individual process that has just been completed, or may be a part of a more comprehensive diagnosis that traces an underlying error that was existing for a number of previous processes.

The cost justification for a quality inspection process is generally considered difficult. Introducing inspection stations or deploying sensing devices in a production process constitutes additional cost, but is expected to be a profitable course of action for the future because it’s assumed at some point the related costs will be recovered from the benefits realized through the detection, restoration and elimination of defective items along with reducing variability and improving processes. This inspection cost associated with adopting a strategy of screening, reworking and scrapping is usually considered as expensive and a non-value adding activity, eventhough its capability for variation-source diagnosis is often considered to be effective, but on the other hand its influence on the final product quality is rather indirect.

Thus, an Inspection Strategy needs the ability to consider the needs of multiple stakeholders and make reasonable trade-off between different objectives. Therefore, when and where in a production process an inspection should be performed or probing devices be distributed is an important and challenging decision in quality control. The various cost and constraint factors as well as operational alternatives interact in an intricate fashion and make the solution seem complicated. Research efforts have been made to address this objective over the past five decades and they are still going on today.

The paper aims to provide a literature review of the contributions on **'Optimization of Inspection Process in a Production Line'** taking the perspective of an Operational Manager who is predisposed to improve quality in his operational production line.

The purpose of the reviewer is to gain an overall knowledge on this topic based on the previous historical research conducted in this area. The work aims for two main objectives:

- classify research on this topic on the basis of the main themes and methods as a guide practitioners and academics;
- Propose directions for future research, mainly for academics.

The paper is organized as follows. The first section sets the scope and methodology of the review presented by identifying the selection process, inclusion criteria, keywords used and the review methodology adopted.

The second section introduces the field of Optimization of Quality applicable to a production line, and what are the fundamental questions answered by an inspection strategy. An overall content review is presented for a general understanding of the concepts behind the review is presented in a systematic way. Also, the classifications of system characterization that shapes the constraints of the model, and the modeling characteristics behind developing an optimization problem is delved in detail.

The third section presents and discusses the review results, and illustrates the identified gaps, as well as, highlights potential directions for future research in this field. In the final section, conclusions are drawn and research limitations are identified.

## 2. Scope of Analysis

The review is conducted to examine literature relating to achieve optimization in a production line with respect to quality inspection process, done in the joint perspective of practitioners and researchers. More specifically we take viewpoints of different managerial roles played by employees in a manufacturing company. Some of these key roles are Operational Managers, Quality Supervisors and Inspectors. This perspective can also be extended to that of a researcher whose aim is to understand the application of inspection process in a production line and the various rules, procedures and managerial decisions that are carried out during quality implementation into a production line.

In context with this viewpoints, this paper aims to capture the main research themes in terms of its key purpose, most important findings and the practicality related with implementing and decision making. The main themes addressed in the papers are identified and the various papers analyzed are grouped according to common characteristics. So in a way, he paper aims to avoid mathematical terms and equations, and instead concentrates on its real world meaning and managerial implications.

The review does not aim to be a comprehensive or a thorough analysis, but rather to for the reviewer to get a start on the topic of Quality Optimization by introducing himself to highly technical concepts utilized in operational research and advanced mathematics but understanding them as an average manager trying to deal with the operational complexity of a production line with respect to a quality inspection procedure. Thus the key aim to understand how to enable the Quality manager to understand essential characteristics and their relation by which he can make decisions to improve the inspection process in his production line and gain direct benefits in terms of cost savings and overall quality improvement.

The reader who is new to the research area, will be able to gain an overall broad view of the field before beginning to work in this area.

# 3. Methodology

## 3.1 Selection Process

A search by keyword was conducted using library databases like Science Direct, Scopus, Opac PoliMi, Springer .etc. This method allowed for scanning major mathematics, industrial, production and operations related journals, as well as management journals. Also benefits from e-journal packages, online databases and multi-disciplinary indexes, such as Google Scholar was utilized for making full text analysis of relevant keywords.

From this base a wide set of papers were selected by analysis from the title, abstract and full text in order. Later the base set was reduced to a proper subset dealing only with topics considered for discussion in this review. From this subset a smaller cluster was identified that only deals with optimization models of inspection and other topics were excluded.

This review primarily focused on journal articles, as referred journals are arguably the major outlet for original technical publications and thus they are expected to reasonably reflect the trends in technology developments. For this reason, articles in those journals are studied, including

- European journal of Operations Research
- IIE Transactions
- Journal of Manufacturing Systems
- Computers and Operations Research
- Optimization and Engineering
- International Journal of Production Economics
- Handbook of Permeability Engineering
- Computers and Industrial Engineering
- Reliability Engineering and Systems Safety
- Applied Mathematical Modeling
- Chinese Journal of Chemical Engineering
- CIRP Conference for Computer Tolerance Testing
- Precision Engineering

## 3.2 Inclusion Criteria

The general keywords used for finding relevant research papers in the above journals are as follows:

Quality Inspection, Quality Control, Quality Improvement, Optimization models, Inspection strategy, Inspection policy, Inspection models, economic order quantity, optimum, on line, off line, simulation, heuristic, cost benefit, Inspection Allocation, Single stage Vs Multi Stage,

Some other terms and considerations utilized to find relevant papers are:

Economic Optimization, Inspection Policies – Sampling Vs 100% Inspection, Minimize Scrap and Rework, Inspection Technologies, Cost to capture a defect – Cost Effectiveness, Mathematical Optimization models, Simulation Software, Machine-Specific; Technology-specific; Product-Specific, Discrete Production Vs Process Production, Queues.

In order to obtain the most comprehensive list of articles which can provide a robust knowledge in Optimization of Quality Inspection Process in a Production Line, a systematic review approach was applied. First of all, a research relevant to the generic concept which is 'Quality Inspection in Discrete Manufacturing Process' was conducted. The reason that the investigation was kept broad is that, not to avoid any relevant work. After producing the primary set of articles which was wide, it was narrowed down to the designated area. In the last iteration of the research, the focus was on the core research field which is Inspection strategies for optimizing inspection processes in a production line.

Finally, 36 papers published in the last twenty years were selected and examined. In general, more papers were found in the areas of Industrial engineering and production while some where concerned to mathematical and operational research in computational field.

### 3.3 Review Method

The papers were examined and a number of review methods were taken into account that were used in previous literature-review papers like (Sampatraj S. Mandroli, 2006), (Qianmei Feng, 2008) and (Fiona Zhao, 2009). For the purposes of the review the contributions were classified using a two-pronged approach. On one hand, the papers were categorized on the basis of the research method adopted. On the other, the papers were examined on the basis of their contents.

As a result of the review process, the relevant articles were identified with systematic examination and categorization. The main information about the listed articles studies is shown in Appendix which includes the following attributes of studied articles': Name of author(s), publishing year, country, Title, journal name, methodology applied, objective, drivers and scope and length of supply chain. Throughout this document, paired terminologies such ''as-good-as new state" and ''in-control state"; are mentioned to be equivalent terms.

# SECTION II: CONTENT REVIEW AND TOPIC ANALYSIS

## 4. Need for Optimizing Quality

The organizations nowadays have to reduce costs through managing different aspects of their business operations to continuously improve products, services, and processes. They must satisfy the customers' needs and expectations to survive in the severe competitive environment. Since quality of services and products is one of critical factors that significantly affects customers’ satisfaction, developing efficient quality systems is then very important for organizations.

The research paper (Chun-Tai Yen, 2013) emphasizes the *need for high quality systems*, applies the scenario for an automotive industry, since it not only forms an economic base but also plays an important role for safety and convenience in the society. In average, a vehicle is composed of more than thousands components, and the quality of each component is very critical. Automotive component manufacturers, as suppliers to automotive manufacturers, are forced to emphasize the quality inspection for their products with specified critical tolerances which if not maintained may risk the life of a customer and will ultimately lead to loss of brand image. A proposed quality system for a vehicle component manufacturing industry, can be validated by its capability to reduce the effort spent on inspection work, the rate of waste, and to improve overall equipment efficiency (OEE).

Implementing a quality system is expensive and requires valuable resources of the organization. Moreover, the products and production systems become more and more complex with a larger set of failure possibilities. As the organizations invest large amounts in such systems, implementing an efficient inspection strategy is of much importance to reduce quality related costs. Therefore, the *quality economics is a major issue for the organizations*. (Sampatraj S. Mandroli, 2006)

Many organizations establish inspection systems as a tool to achieve quality. However inspection is an inferior way of dealing with quality problems, but the benefits of quality improvement are superior to any inspection scheme for many cases. (Ali Azadeh, 2012) Quality Control satisfies both the objectives of high quality and low cost since it brings the effects of fewer rework labor hours, less material wastes and high quality of final goods. To accomplish such quality control, high-performance production lines have quality inspection machines that inspect the quality of parts and then reject defective parts. (Man-Soo Han, 2002)

Identifying an efficient inspection policy has economic relevance, as adopting different inspection policies will result in different costs. The inspection policy may affect the production process in different stages, thus inspection only in the last stage may cause to non-conformance products, waste resources, and incur penalty costs because of customer dissatisfaction, losing market share, etc. On the other hand, subjecting a larger product fraction to inspection, or tightening the acceptance limits, will normally lead to a higher product quality, but will result in higher costs of inspection, scrap, and rework. Establishing an efficient economic inspection policy is desired to balance these effects. Therefore, a **quality Vs cost trade-off** or '**optimization**' is necessary in selecting the best suitable inspection policy. (Ali Azadeh, 2012)

## 5. Inspection Strategy

The struggle for higher quality, lower cost, and shorter response time predominates any competitive industry. Consequently, products and production systems become more complex with a larger set of failure opportunities. In order to get more reliable and less expensive products, in-line and off-line quality control measures are employed. In case of in-line systems, firms invest large amounts in sophisticated flexible inspection systems, and inspection management problems become more significant. Inspection capacity, allocation, and scheduling decisions are actually made by quality managers, but they lack an overall framework for their decisions. (Hamilton Emmons, 2002)

The question of whether or not to inspect a final or semi-finished product can be asked after every manufacturing operation (Sampatraj S. Mandroli, 2006). To determine if the answer is yes or no, we need to raise a lot of questions. Here are some examples:

- How much time is available to perform inspection?
- What are the defects and what are the quality levels that customer demand for them?
- What should be done with the defective items?
- What is the inspection threshold or specific region for conforming items?
- Whether inspection should be performed on a batch of items or just a single unit?
- Whether the inspection location should be fixed or flexible?
- Where the inspection should be performed?
- How many times the inspection should be repeated?
- Should the quality characteristic be monitored and how frequently?

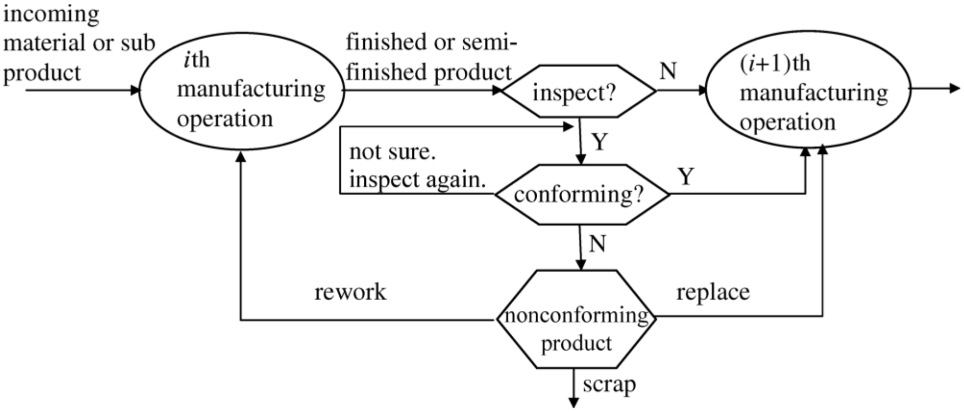

*Figure 1. The inspection process (Sampatraj S. Mandroli, 2006)*

The questions posed above are just some of many posed in different literature and its effects were studied. An Inspection strategy answers the above questions. They can be combined to be called as **Inspection capacity, allocation, and scheduling decisions.** Some of these decisions tend to be short term decisions like inspection schedule and subset of tasks, and others are long term decisions like determining the inspection rate capacity. (Hamilton Emmons, 2002)

# 6. Quality Management - On-Line Vs Off-Line

It can be seen that relevant research efforts can be classified according to two broad categories: (i) on line inspection models and (ii) off-line inspection models

## 6.1 On-Line Inspection Model

On-line quality engineering methods are used for monitoring process and inspecting products in order to further reduce variation and improve quality. Since no process is free of variation, on-line process control techniques are always required to prevent, detect and reduce variations. Since the publication of the book ''Quality Engineering in Production in Systems'', by Taguchi (1989), which introduced on-line process control designs applied to a production line, there have been many developments related to on-line process control. The first contributions related to on-line process control originated from Taguchi. (Linda Lee Ho 2012)

Such techniques can be broadly elaborated into the following: (Qianmei Feng, 2008)

- Acceptance sampling,
- Statistical process control,
- Process adjustment using feedback control, and
- Inspection strategies.

It should be noted that the above techniques are not mutually exclusive and they are used accordingly based on the specific application, objective and availability.

### 6.1.1 Acceptance Sampling

(Qianmei Feng, 2008) Acceptance sampling is defined as the inspection and classification of samples from a lot and decision about disposition of the lot. At the beginning of the concept of quality conformance back in the 1930s, the acceptance sample was taking the whole of the quality improvement effort. The most widely used plans are given by the Military Standard tables (MIL STD 105A), which were developed during World War II. The last revision (MIL STD 105E) was issued in 1989, but canceled in 1991. The American Society adopted the standard for Quality as ANSI/ASQ A1.4.

It is one of the earliest methods of quality control, but due to its less proactive nature in terms of quality improvement, acceptance sampling is less emphasized in current quality control systems. Usually, methods of lot sentencing include no inspection, 100% inspection, and acceptance sampling. In addition, acceptance sampling has several disadvantages compared to 100% inspection:

- There are risks of accepting “bad” lots and rejecting “good” lots.
- Less information is usually generated about the product or process.
- Acceptance sampling requires planning and documentation of the sampling procedure.

Some other problems with acceptance sampling, is that while minimizing the inspection cost, it does not minimize the total cost to the producer. In order to minimize the total cost to the producer, Deming indicated that inspection should be performed either 100% or not at all, which is called Deming’s “all or none rule”.

### 6.1.2 Statistical Process Control

As traditional approaches of on-line quality engineering, acceptance sampling and inspection strategies control the final product and screen out items that do not meet the requirements of the next customer. This detection strategy related to after-the-fact inspection is mostly uneconomical, as the wasteful production has already been produced. A better strategy is to avoid waste by not producing the unacceptable output at the first place and focus more on prevention. Statistical process control (SPC) is an effective prevention strategy for monitoring the manufacturing process or any other process with key quality characteristics of interests. (Qianmei Feng, 2008)

**Control charts** are implemented to monitor the stability of a production process. (Abdur Rahim, 2004) Implementing control charts for monitoring the process dispersion allows possible shifts to be quickly detected, thus limiting the amount of produced non-conforming parts. (E. Trovato, 2010) Generally, production quality is not always perfect. It is usually depend on the operating state of a production process which may shift from an in-control state to an out-of-control state due to occurrence of some assignable causes.

Some of the charting schemes proposed in literature to control the process dispersion within a manufacturing process which operates continuously and indefinitely. Some of them are listed below:

- Traditional X -chart is used to control process mean and an R chart to control process variance. Considerable attention has also been devoted to the study of the joint economic design of X and R control charts in recent years. This growing interest is due to the greater power of joint X and R charts for catching the shifts in the process parameters compared to that of the X or R chart used separately. (Abdur Rahim 2004)
- The Shewhart $S^2$ control chart monitors dispersion by plotting the sample variance $S^2$
- More recently, EWMA (Exponentially weighted moving average) charts for monitoring process dispersion and variability statistics.
- Another recent charting takes the logarithmic transformation of the sample variance $S^2$ as the monitored statistic of a CUSUM (Cumulative Sum).

The comparison among the control strategies is performed usually by evaluating their optimal economic design constrained by the inspection activities configuration. In the economic design of control chart, the objective is to determine the optimal design parameter values of the sample size n, the sampling interval h, and the control limit coefficient k for the chart so as to minimize the expected cost per unit time of operation. (E. Trovato, 2010)

## CONTROL LIMITS, WARNING LIMITS AND CONTROL ZONES

Control limits are quality control specifications set for a particular quality characteristic outside which if points fall (which is found through inspection), will lead to stoppage for finding the cause and eventual process recovery. Some analysts suggest two sets of limits in which the outer limits are the typical action limits and the inner limits are called the warning limits. Points falling outside the control limits lead to a stoppage for an assignable cause, and after the process is recovered, it may wait a long time for an inspection. Therefore, a longer sampling interval may be used. Points falling inside the inner limits may indicate that the process operates adequately. Therefore, a longer sampling interval for the next inspection can also be applied. In other cases, a shorter sampling interval is used. (E. Trovato, 2010)

In recent research, the system of control is extended by implementing control zones. In (E. Trovato, 2010) for designing economic inspection strategies for shorter production runs, three zones are defined: the green zone, the yellow and the red zone. An observed value in the green zone indicates that the process is in control and that the production should continue. However, a decision in favor of an adjustment of the process is made if the observed value falls within the red zone. Moreover, a sequential verification occurs if an observed value is within in the yellow zone. If a sequence of h values in the yellow zone is observed, then an adjustment is decided upon which may present increased performances.

## BENEFITS OF USING CONTROL CHART IN TERMS OF OPTIMIZATION

Statistical process control plays a very important role during the effort for process improvement and subsequently optimization. Some of the important benefits that come from using control charts AS LISTED (Qianmei Feng, 2008) include:

- Control charts are simple, reliable and effective tools to achieve statistical control. When a process is in statistical control, its performance to specification will be predictable. Hence reliable and consistent quality levels with stable costs can be achieved.
- Process improvements can be applied and anticipated. Cost benefits are received through increasing yield, increasing quality, decrease rework or scrap.

- Control charts provide a common language for communications between different actors: operators, supervisors, support personnel, producer and suppliers thus, minimizes the confusion, frustration, and excessive cost of misdirected problem solving efforts.

### 6.1.3 On-Machine Inspection

In automated production systems and flexible manufacturing systems, On-Machine Inspection (OMI) or On-Machine Measurement (OMM) has been widely used as the preferred measuring equipment for the purpose of direct inspections in manufacturing and quality control. OMI is a process that integrates the design, machining, and inspection aspects of manufacturing to allow a product to be inspected and accepted directly on a machine tool. This process is accomplished by using the machine tool as the inspection device while the part is secured on the machining center with its coordinate system intact. Thus, using the machine tool as an inspection device eliminates the need for expensive inspection equipment, allowing the manufacturer to divert resources to other uses. As the component gets more complicated, the role of OMI becomes more significant as efficient dimensional measuring equipment. (Fiona Zhao, 2009) Sensors providing accurate feedback but they are often limited in just performing these functionalities and not geared toward supporting any inspection tasks. A common disadvantage is that it increases machine time but it is seen to have the potential to replace end-of-line inspection.

#### ECONOMIC BENEFITS OF OMI

The benefits of OMI in terms of economization can be summarized from the paper – Computer aided inspection planning by (Fiona Zhao, 2009).

- **Cost and time saving** through decreasing lead-time required for inspection, minimizing need for inspection equipment reducing inspection queue time and inspection time, reducing rework and eliminating of non-value added operations.
- Changing from ‘‘**reactive**’’ inspection to ‘‘**proactive**’’ control through agile machining by integrating quality control and focusing resources on prevention of defects instead of detection by utilizing real-time process knowledge and control of part acceptance/disposition.
- Elimination of **non-value** added operations such as lot inspection, sampling plans, receiving inspection, design, fabrication and maintenance of hard gages, and reworking nonconforming parts;

Successful implementation of OMI however requires robust and reliable hardware and software. A multi-tool capacity machine tool is often used. An open architecture controller is also seen essential for inclusion of any additional probing software that may be needed. The probing system comprised of different probes, sensors and electronic elements, is needed for implementing the OMI process on the machine tool. The feedback mechanism needs to be in place and in real time.

The optimization variable considered for an on-machine inspection procedure is usually the accuracy and precision with which the process characteristic being measured is identified by the inspection system. Such a system assumes that the accuracy of the measurement directly relates to effectiveness. The efficiency in terms of cost savings is realized through having lesser inspection time and frequency, usage of less resources and reducing defective percentage in the line.

In the future, the trend towards literature is seen to move towards OMI. As inspection technologies mature and product quality requirements become more stringent, on-machine inspection will take the center-stage of quality assurance.

## 6.2 Off-Line Inspection Model

On-line process control is widely accepted as a more effective and economic quality assurance policy than product inspection. However, taking corrective action in an on-line mode in certain situations may be infeasible. (Tzvi Raz, 2000)

Some case where this can happen are: (Illana Bendavid, 2009), (Chih-Hsuing Wang, 2007)

- Any process in which the inspection time is higher than the process time. For example, consider machine embroidery production where the time to embroider a cloth is very short compared to the time required to inspect the embroidery. In this case the results of the inspection, if carried out in an on-line mode, may come after the entire batch is completed. Or the food industry where laboratory analysis takes more time than making the product. Or where the products needed to be inspected on a coordinate measuring machine. (See section --)
- Processes where the delay costs of a setup adjustment in mid-batch is very high.
- In some situations the physical environment of the production process may not allow the implementation of on-line inspection. For example, food processing industry where it is impossible to inspect a part without damaging the parts in production.
- Any production environments in which non-conforming items can be economically salvaged rather than scrapped. For example, the pasteurized food industry where sample containers after stored till the inspection tests are done, and if the specified fat level deviates from the specification, then all of the containers filled after the sample are disposed of as non-conforming product.

In such cases, an effective approach is to carry out off-line inspection after preserving the processing order of the product. Then, by inspecting the batch it is possible to identify at which product unit, if at all, the process deviated from its intended setup and to act accordingly.

Off-line inspection is conducted after all the units of the batch have been produced and their production order is preserved. It consists of inspecting units according to a specific inspection/disposition (i/d) policy. An inspection policy specifies the first unit to be inspected. After each inspection, considering the results of this and all previous inspections, which are assumed to be error-free, it is to be decided which unit to inspect next. When inspection is deemed completed, usually before all units have been inspected, all the uninspected units has to be classified in the batch as conforming or nonconforming and be disposed of accordingly.

### 6.2.1 Coordinate Measuring Machines

An often adopted measurement system for geometric error evaluation is a Coordinate Measuring Machine (CMM), which is a very flexible instrument, being able to sample discrete points on a large class of surfaces. Previous research focused upon Computer Aided Inspection Planning (CAIP) had concentrated mostly on CMMs. Contrary to CMMs, On-Machine Inspection (OMI) systems provide direct inspection in manufacturing and quality control. (Fiona Zhao, 2009)

In a conventional quality control systems, a component machined requires being moved to a CMM to check its dimensional accuracy. Some disadvantages of moving the component is that the manual job set-up and inspection of machined parts are usually time consuming, subject to human errors, and often lead to longer lead times and the need to rework. This bottleneck problem is further compounded with the difficulty of capital investment for purchasing CMMs and time delay of material flow. (Giovanni Moroni, 2013)

CMM used for checking geometric tolerances and they come with wide range of distinguishing features such as accuracy, working principle, sampling and volume. Most coordinate measure system are flexible, this flexibility makes evaluation of measurement uncertainty difficult since different measurement tasks are characterized by different uncertainties; hence, a “task specific uncertainty” is always associated. There are several identified several sources of measurement uncertainty such as hardware, work piece geometry, sampling strategy, fitting and evaluation algorithms, and extrinsic uncertainty sources noted in previous literature. (Giovanni Moroni, 2014) So many recent literature are dedicated towards evaluating the uncertainty involved with the sampling strategy selection, concerning inspection planning for CMMs.

## 6.3 Variations in usage of the term ‘Off-Line’

Here a peculiar variation of the term ‘Off Line’ utilized in research journals is discussed so that the difference will be understood by the reader. Research terminologies often use inter-related words that can be interpreted differently based on different applications where it is used. It is to be noted that quality engineering approaches towards a product during its product life cycle phase can also be differentiated into two major areas: (Qianmei Feng, 2008)

(i) On-line quality engineering that is typically applied during production.
(ii) Off-line quality engineering that is implemented as part of the research, design and development phases.

The original principles developed by Taguchi states Off-line quality engineering is employed to make product or process performance insensitive to uncontrollable noise factors. The optimal values of the mean and standard deviation are determined by minimizing the variability of the quality characteristic through experimental design and process adjustment techniques. It has three design phases: system design, parameter design and tolerance design. It was introduced to American industries in the 1980s and since then, lot of research has improved the related statistical techniques clarifying many underlying assumptions and principles. In this kind of research, on-line quality engineering is referred (as discussed before) to as techniques employed to maintain quality during the manufacturing process.

Off-line and on-line quality engineering provides the technical basis for problem solving in quality improvement, while quality management ensures the effective implementation of such techniques within an organization.

For our research, we do not consider this kind of off-line quality measures for any further discussion in this paper. From here on, off line quality will only be related to quality inspection process that is carried out after the end of production run. Another equivalent term used is **end-of-line** (EOL) inspection performed on the final product, and in-line (IL) inspection performed on partially processed items throughout the production line. (Israel Tirkel, 2013)

# 7. System Characterization

Literature survey conducted by (Sampatraj S. Mandroli, 2006) classified the systems in existing literature. The survey categorized the characteristics of a manufacturing process into six major aspects (i) production configuration; (ii) item flow; (iii) Inspection type; (iv) Inspection capability; (v) defect rate; and (vi) defect reparability.

These individual characteristics takes on different assumptions that shapes the Optimization model that is being built. The more realistic and practical the assumptions are, the more complicated the model will be. But this makes the model more close to real world solutions. Thus in managerial perspective, those inspection models proposed that are most effective are the ones that has considered the most realistic assumptions as possible.

In this review, we classify the systems mentioned in the selected papers according to the above and also touch upon other variations developed during recent studies. Also we delve deeper into realistic assumptions that are conveyed in the papers and those that have not been addressed in order to identify venues of future research.

## 7.1 Production Configuration

The survey (Sampatraj S. Mandroli, 2006) identifies the major process configurations seen in literature based on the flow of conforming items:

- Serial or sequential systems where the raw material passes through successive workstations and get processed in a sequential way.
    - Single-stage or Single-station manufacturing process is seen as one special case of a serial system. Significant mathematical models have been developed for a single station or a multi stage process considered to have an inspection only at the end stage. This form of process model has been identified in many papers and seems to be the most concentrated upon early literatures owing to its simplicity in mathematical modeling and application into many realistic assumptions that may prove an insight before delving into more complicated models.
- Non-serial systems where the raw material can turn into finished products by taking one of several paths through the system. It can also be in a way where certain combination of sequential stations exist that joins together in multiple ways to push the required output.
    - Assembly or convergent systems are seen as one special case of a non-serial system where one workstation has one successor but may have several predecessor workstations. The combination of one workstation with two predecessor workstation is seen in literature as one of the simplest form that can be relatively easy to solve mathematically.
    - Systems which are neither serial nor assembly falls into general category of non-serial systems.

### 7.1.1 Single Stage Vs Multi Stage Inspection

Generally a manufacturing process goes through several stages or machines where the raw material are machined and eventually transformed into finished products. At each stage, a number of items which were good in pervious stages may become defective as a result of subsequent processing. A preliminary idea to maintain the quality level is providing an inspection station after the last stage. This is generally referred to as outgoing inspection. So in a way it is convenient to consider the process operations in the final stage to be packaging and delivery, so that a potential inspection point at the last stage represents final inspection, and the quality of product which leaves this stage is that which reaches the customer. So in this scenario a **single stage i**nspection strategy is applicable.

However, with outgoing inspection, all efforts and costs invested in producing defective items are wasted. In order to reduce the wasted efforts and costs, inspection stations should be placed immediately after each major manufacturing process. In this case, accepted items are sent forward to next stages, whereas rejected items can be either reworked at the stage or scrapped out of the process. Such a scenario is where a Multi Stage Inspection strategy is applied. (A. Vaghefi, 2009)

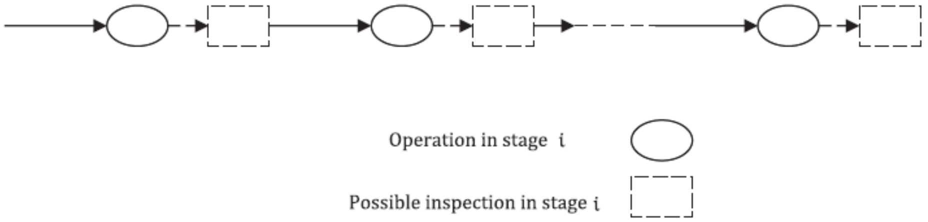

Fig. 1: Serial multi stage processes (A. Vaghefi, 2009)

For a single stage production process, usually the extent of inspection refers to the number of inspections executed (sample size and sampling frequency) and to the tolerance of the inspections (acceptance limits). Thus, the objective of the inspection strategy would be finding the combination of these inspection parameters that minimizes the total expected inspection cost

For multi-stage production processes, since products travel sequentially, the output of each process stage is the input for the next one. Thus, the last stage is dependent on the outputs of all former stages. **The main benefit of inspection** is that the downstream operations are not applied to already defective products, resulted in saving cost and preventing a congestion of the production flow.

Hence, additional decision variables are added to the problem for multi stage inspection strategies addressing the following: (A. Vaghefi, 2009) (Ali Azadeh, 2012)

- The number and location of inspection stations. So it paves to decide whether inspection is needed at a particular stage or not.
- The number of inspections executed given by the sample size and sampling frequency, for each inspection station; (degree of inspection)

- The rigor of the inspections (acceptance limits) for each inspection station. Usually a 0% or 100% inspection or acceptance sampling is used.
    - If the costs for inspection and scrapping are assumed to be linear and the fraction of defective units for each stage is assumed to be fixed, then 100% inspection will be more efficient than sampling.
    - Presented several situations in which sampling is most likely to be useful. For example, when the cost of 100% inspection is high and/or inspections typically need destructive testing, acceptance sampling is preferred.

It is to be noted that, the optimum inspection plan for each stage does not necessarily guarantee the global optimum inspection plan for the multistage manufacturing system.

### 7.1.2 Deteriorating Production Systems

In this part, the two operating state of a production line and its impact is elaborated based on literature study. A production cycle is assumed initially to be in the 'in-control' or IN state when the machine is producing items of perfect quality. But in reality, a production system is generally considered to be imperfect. So after a particular time period of operation, that machine will transit to the 'out-of-control' or OUT state where it is assumed that some percentage of the items produced are defective. (Chih-Hsiung Wang, 2001), or the items are produced at a sub-standard quality but may still be acceptable. (Kit-Nam Francis Leung, 2009)

The above phenomenon can be expressed as production quality not always being perfect but is usually dependent on the machine's state. The time period before which this transition occurs is generally considered to follow a random variable with exponential distribution. This kind of restrictive assumption was commonly found in many literature related to economic production quantity. This is because it is seen historically that many components and systems follow exponential failures. And this failure law characterizes a wide variety of mechanical devices like ball bearings, bus engines and electronic systems. (Chih-Hsuing Wang, 2007)

When this transition happens, in many cases defects can be identified only through an inspection process which carries an inspection cost. Alternatively the machine stays in out-of-control unless found by inspection and is followed by restorative work. In some cases, the defective items found are reworked at some cost before delivery. If the defective items are not inspected, it will be passed to the customer, incurring a much larger warranty cost. Hence inspection plays two major roles in detecting defects and identifying machine state. Also continuous monitoring of operating state is also not economically justifiable for some machines.

Frequent inspection increases inspection costs while infrequent inspection leads to reducing profits. This can be attributed to the triple effect that an out-of-control state could correspond to an increased production cost per unit time, reduced selling prices of inferior items (or warranty cost); and cost-time for restoring machine. In order to operate such a system economically, tradeoffs among production setup, inventory, inspection and defective cost must be analyzed and an economic inspection interval should be highlighted.

Deterioration of the production system is an inherent process in all manufacturing industries. A general research tendency is to understanding the relationship among production, inventory and inspection that will help managers to maintain efficient and economic control of operations.

#### TRANSITION POINT

The transition point is when a production process transitions from IN state to OUT state (Tzvi Raz, 2000). Information regarding **the transition point** can be obtained by inspecting the units in the batch until a non-conforming unit preceded by a conforming unit is found. It is not economically justifiable to find the actual transition unit, as it may be possible to accept the first part of the batch and discard the rest, knowingly accepting the risk of committing one of two possible types of errors: rejecting some conforming units or accepting some non-conforming ones. This leads to the question of how much inspection, if any at all, is economically justified. Moreover, if we decide to inspect, then the question is which unit or units should be inspected.

Literature has considered different transition points as a means of studying economic feasibility considering the various cost parameters involved. Many research paper consider to find the economics of the search for the transition unit in the production batch.

### 7.1.3 Real world Applications

The papers studied in this literature review considered production configurations that imitate real world applications. The earlier papers concentrated on single stage manufacturing with only one machine and one inspection stage that can be mimicked in any manufacturing setting. Thus even multi stage processes with an inspection policy that only considers screening after the end of production process, was a universally applicable policy for most type of production systems including serial, assembly and non-serial. The assumption that made it possible was that inspection policy was independent of the type of defect or the type of process.

As models where were made more realistic and robust, the production setting was considered for specific type of manufacturing settings especially for simulation experiments where the type of plant was very important. A typical setting for a **multi stage deteriorating production system** were: electronic assembly lines, semiconductor fabrication lines that produce printed Integrated Circuit boards, plating of components, TFT and LED Panels manufacturing company.

A typical setting for a non-serial production line was Just-In-Time mixed-model assembly lines, apparel or any industry producing custom designed products.

**Future research trends** show that the optimization problem for a production line is being extended towards non-manufacturing settings like large service-oriented organizations like police and army where attention-management problems exist.

## 7.2 Item Flow

The system characteristic that represents item flow refers to the type of product that is being manufactured through the production process. The product can be a single type or a multiple type. Also the product can pass as a single product or as part of a batch. These two conditions combine to create four combination of possibilities. However in this review most of the papers fell under single product in a batch category with a single quality characteristic considered.

## 7.3 Inspection Type

The type of inspection that is performed for a product in the production line is one of the most rigorous assumption set for an inspection model as it impacts the inspection cost in a major way. The paper (Sampatraj S. Mandroli, 2006) identifies four inspection types seen in literature based on the fraction of items inspected, repeatability (whether the inspection has to be repeated on the same product) and decision making ability. (i) a simple inspection is to inspect a single item once; (ii) a fractional inspection is to inspect a fixed fraction of items in a batch, where zero and one (full batch) are the two extreme cases; (iii) a repeated inspection is to inspect the same item(s) more than once; and (iv) a dynamic inspection is to inspect items in a batch sequentially and a decision of whether to reject or accept the batch is made dynamically instead of at a fixed fraction.

Early literature considers a simple inspection or a fractional inspection based on integer programming method. However recent literature concentrates on dynamic inspection model where a decision to accept or reject a batch is made in a dynamic way with heuristic rules applied to help identify general rulings for decision making.

## 7.4 Inspection Capability

The capability of the inspection performed on a product refers to the reliability of the inspection process.

### 7.4.1 Misclassification Errors

Inspection process and is generally considered to be of two types – **perfect** inspection where the screening activity performed is 100% capable of indicating whether the item is defective or not, and **imperfect** inspection where the screening activity is considered to have misclassification errors associated with it. The general misclassification error that usually exists when inspecting an item can be of two types.

- Type I error that exist when a conforming unit is rejected. Also referred to as 'False failures'
- Type II error that exist when a defective unit is accepted. Also referred to as 'Missed Faults' (Giovanni Moroni, 2013)

Earlier papers considered inspection to be perfect (error-free) or just considered one of the above errors to simplify the model. Later inspection models proved through analytical and empirical ways that considering a combination of both errors is more realistic and effective, because in real world, inspection is usually considered to be unreliable.

The cost associated with making a misclassification error is generally called as penalty cost. The paper (Chih-Hsuing Wang, 2007) considers expected penalty cost as the cost where a break-even point is reached such that when the inspection is carried out and a unit whose two expected penalty cost for both type of errors are found equal. Thus the optimal inspection policy was to accept the units produced before the breakeven point and reject the rest.

### 7.4.2 Uncertainty

The probability of misclassification errors related to inspection are strictly related to uncertainty (Giovanni Moroni, 2014). The appearance of misclassification errors is considered directly proportional to uncertainty, so "error cost" increases as uncertainty increases.

In terms of accuracy and precision, different technologies implemented for inspection possess different inspection capabilities that possess different measurement costs. But high accuracy measurements are generally more expensive than low accuracy measurements. More the accuracy, less is the uncertainty. So reducing inspection errors by choosing low uncertainty measurements (or accurate measurements) will increase measurement costs. So measurement cost is usually inversely proportional to uncertainty.

Hence in an optimization model, a trade-off between inspection error costs and measurement costs has to be defined by carefully choosing uncertainty. Also a task-specific uncertainty should be considered for inspection models, related to the inspection technology implemented in the system. (Giovanni Moroni, 2013)

### 7.4.3 Compliance to Tolerances

Geometric tolerances are specifications that states how much a manufactured part differs from its ideal geometry set during the design stage. It is important because of the performances the customer requires to ensure functionality, complex fits and well-structured definitions. The checking of a geometric tolerance involves the estimate of the geometric deviation by the act of inspection, and proposing an uncertainty evaluation.

International series of standards are available giving guidelines for this evaluation, like ASME B89.7.3 and ISO 14253 that propose “guidelines for decision rules” for “considering uncertainty in determining conformance to specifications”. A decision rule should essentially identify three regions for the measurement result: (Giovanni Moroni, 2014)

1. Conformance zone where if the inspection and consequent measurement result falls, then the product is said to be conforming and is accepted.
2. Non-conformance zone where if the inspection measurement falls, the product is said to be defective and is rejected
3. Uncertainty range. If the measurement result falls in this zone, it is not possible to state whether the part conforms or not to the tolerance.

The standards available give only guidelines on how to choose these regions, because the selection of a decision rule is considered an **economic decision**, and the flexibility of having different rules ranging from stringent to relaxed acceptance or rejection are needed in order to satisfy a broad range of industries.

It is to be noted that traditional instruments are not suitable to check geometric tolerances. Geometric tolerances verification is usually performed by means of coordinate metrology used in recent on-machine inspections and on the off-line, using a coordinate measuring machine.

### 7.4.4 Sampling Strategies

In the study of computer aided inspection planning for production systems, (Fiona Zhao, 2009) notes that many literature works have pointed out that the sampling strategy for an employed inspection technology can significantly affect measurement uncertainty, in particular when the sample size is small, which is the typical economical solution in case, uncertainty cost has to be optimized. Because sampling strategy is most often determined by the operator in real time, it is the main leverage to control uncertainty as well.

Methodologies for sampling strategy planning may be grouped into three categories:

- Blind sampling strategy are standard sampling strategies, which do not require any knowledge of the product or process.
- Adaptive strategies try to adapt the sampling strategy itself to the actual quality characteristics.
- Manufacturing based sampling strategies are strategies developed for parts manufactured by a specific process. They originate from the observation that sampling strategy uncertainty contribution and the actual deviation tend to be closely interrelated.

## 7.5 Defect Rate

The proportion of defective items among all items manufactured by a process at a stage is termed as the defect rate. It is one of the aspects that provide a characterization of the behavior pattern of quality defects. General assumptions for the defect rate in many literary papers are as follows:

- Known constant defect rate for all operations. This is the simplest assumption possible is considered unrealistic and infeasible. It is usually taken from historical data or determined using expert opinion.
- Possible range of defect rates (from zero to an upper bound) with an assigned occurrence probability for each defect rate. (Researchers have pointed out that many unavoidable factors such as the wear of tools and the fluctuation of power supply may result in different lots with different defect rates).
- Treating the defect rate as a random variable following certain distribution.

Researchers have also considered single defect type, or multiple defect types. (A. Vaghefi, 2009). The general cost term associated with defect rate is termed as Yield Loss Cost. (Israel Tirkel, 2013)

## 7.6 Defect Repairability

After the inspection process detects a defective item, certain actions need to be performed. There are several possible outcomes for nonconforming items: (i) they may be replaced with a conforming item which is then sent for the next processing operation; (ii) they may be sent back for rework/repair; or (iii) they may be simply scrapped. Which of these actions is to be followed will depend upon the cost associated with the subsequent action and also the Repairability of the defect since each defect has its once degree of repair possibility. Indeterminate cases arise due to poor measurement statistics and this problem is alleviated by performing repeated inspections.

In real production systems, a portion of non-conforming items can be changed into conforming items by reworking. This involves three different situations in which all, none, or some of the defects are reparable and the ones that are cannot be reworked are scrapped. Hence the assumption to rework or repair a defective item is usually considered as follows: (Ali Azadeh, 2012)

- Perfect Rework.
- An imperfect rework process assigned with a deterministic degree of reparability which means that for a given type of defect whether or not it is reparable is predetermined.
- A probabilistic approach assumes that a defect is repairable with a given probability.

## 8. Modeling Characteristics

The optimization problem for economizing an inspection process sin a production line is generally solved by creating a production model through analytical ways. The fundamental pieces of an optimization model is generalized by the survey paper (Sampatraj S. Mandroli, 2006) (i) cost components (ii) the objective function; (iii) the constraints; and (iv) The solution approach.

### 8.1 Cost components

The objective of a Management taking care of a production line is to maximize profit by increasing revenue gained by the production throughput and simultaneously reducing the cost of production. The production or manufacturing cost of a component is usually taken into consideration wherein the profit is usually found by subtracting it from the revenue gained. If a product is manufactured with a satisfactory quality, then all manufacturing costs will be recovered by achieving net profit.

The revenue function is considered in only in some literary papers and is usually considered fixed as it depends on the market and not on production or quality management. The overall cost of production, also termed as cost of goods sold if minimized will consequently and equivalently maximize profit.

However when quality failures occur, a number of other cost components like the cost of applying quality inspection and improvement activities get involved. The specific cost of quality is seen to be consisting of two components: the cost of failure (Internal and external) and the cost of inspection.

#### COST OF FAILURE

- An internal failure cost is incurred when defects are detected and handled prior to delivery to the customers. It is equal to the cost associated with reworking, replacing, or scrapping a defective item. Equivalent Terms used: Rework cost, scrap cost, Disposition cost
- External failure costs arise from the repair or replacement of defective products after delivery to the customer. Equivalent terms – Penalty cost, Warranty cost.

## The external failure cost is not considered in every publication. It’s a good area of future research. When the external failure cost is indeed considered, some authors assumed that the external cost may depend on the defect type, whereas others assumed no dependence between the external failure cost and the defect type.

### COST OF INSPECTION

The inspection cost includes two components:

- Fixed Cost which includes the amount of capital invested in inspection equipment, building, machine, and overhead costs. Higher quality investments lead to lower defective rates yet higher production costs. (Chung-Chi Hsieh, 2010)
- Variable cost that depends on how frequently one actually performs the action of inspection. The simple linear function that gives this value is the number of units inspected multiplied by the inspection cost per unit which can consist of costs such as material, machine maintenance, resources and labor.

In some papers the inspection costs is considered as a assumed proportion of machine maintenance and operation costs, considering: facilities (e.g. electric, water, vacuum), consumable materials, and labor. In the paper by (Israel Tirkel, 2013) the maintenance cost is taken in correspondence with machine availability, and operation cost is taken in correspondence with machine utilization.

### OTHER COSTS

In addition to the above-mentioned cost components, some other cost components are also considered throughout literature: like the process setup and inventory holding cost, and the cost for searching, and eventually, eliminating the causes of defects. Considering various type of cost expands the optimal problem into becoming complete and realistic but complicates the analytical solution thus requiring advanced optimization methodologies like heuristics and simulation.

## 8.2 Objective Function

In the optimization of inspection strategy, many variables are considered as the objective function. The most commonly used is the total expected cost. The expected unit cost is also used but there are differences in how the number of units is considered. The units considered can be the input units or the output units which can be just the conforming units or total output considering the reworked units also. (Sampatraj S. Mandroli, 2006)

##However, not all the papers try to minimize the cost. There exist a few papers that choose to maximize the throughput or production capacity. That usually happens when an inspection scheduling problem, in addition to the allocation problem, is being considered.

A typical objective to achieve in inspection routine generation is the minimization of total production costs. However, information on costs is often difficult to obtain in some cases as in on-machine inspection for circuit boards. Thus, alternative objectives are sought where an optimization function is generally seemed to be directly related with cost. For example, the maximization of an information gain factor (G) is proposed as the objective to optimize in the paper (Adan Verduzco, 2001)

Direct Cost Objective Functions:

- Expected total cost per unit time
- Minimum expected profit per unit time
- Minimum total cost per unit time
- Minimizing total cost at each stage (Mukesh Taneja, 1994)
- Minimizing total cost of Inspection policy (Glenn F Lindsay, 1964) (Tzvi Raz, 2000)
- Minimizing loss due to imperfect quality (Hamilton Emmons, 2002)

Indirect Objective Functions

- Information gain
- Throughput (Man-Soo Han, 2002)
- System utilization rate (Jim Lee, 1996)
- Reduced Inventory (Jim Lee, 1996)
- Dimensional Accuracy (Fiona Zhao, 2009)
- Maximizing machine availability (Yan-Chun Chen, 2013)

## 8.3 Constraints

In the problem of optimizing of an inspection strategy arise from the characteristics of the production system as listed in section ##

The constraints mentioned can be summarized as follows:

- Production configuration:
    - On line Vs Off Line
    - Single stage Vs Multi stage
    - On-Machine Vs Screening Vs Burn-in
- Zero Inspection Vs 100% inspection Vs Acceptance Sampling
- the Average Outgoing Quality Limit (AOQL) or total defect coverage
- Inspection time limit comparative to processing/manufacturing time.
- Limitation in the number of inspection stations
- How many times the inspection can be repeated (usually assumed only once)

- A Budget limit on manufacturing and inspection actions;
- Minimum throughput or production capacity.
- Ratio of inspection operation time to the machining operation time,
- Maximum Inspection cost limit
- Perfect restoration of machine after defect with negligible restoration time. (see section ##)
- Perfect maintenance.
- Perfect production or non-deteriorating process
- Perfect inspection
- Single unit Vs Multiple units in a batch
- Single quality characteristic Vs Multiple inspection variables
- Number of Production Buffers
- Limitations on Queuing & Quality Buffers
- Supply Chain considered: Single Production Line Vs Multiple Production line spanning suppliers and customers.
- Cost of Penalty with or without warranty costs
- Allowing for production shortages due to inspection and maintenance actions.

It can be seen that each of the above constraints may represent an unrealistic production scenarios. However these constraints are needed to simplify and make possible construction of foundation models that can further be developed upon for future research. Thus each of these constraints open up a new path to improve upon future research.

## 8.4 Optimization Solution Approaches

A variety of optimization methods have been used to solve the resulting optimization problem that is formulated with the constraints and components. The literature survey by (Sampatraj S. Mandroli, 2006) identifies the many methodologies used but in this review, the three major optimization methodologies are captured.

- Dynamic Programming,
- Heuristics and
- Simulation expert systems.

The survey also notes that the methodologies of analytical solutions utilized are not mutually exclusive as the problem formulation may contain different sections that use the above methodologies together in combinations wherever it is applicable, in order to reinforce the problem solving technique and move closer to more realistic solutions. **Integer Programming, Stochastic programming** and **Non Linear programming** are almost always used in combination with the optimization methodology and with each other.

The capability of nonlinear, integer and dynamic programming in terms of solving a large-scale problem is limited. For actual manufacturing system, the computations required escalates considerably as the number of stations increases, and as the constraints and assumptions are more relaxed to imitate more real world problems. That is when heuristic algorithms are utilized to reach better solutions, even though it may not be the optimal one. Other optimization methods include those using discrete-event simulations and expert systems.

### 8.4.1 Dynamic Programming

The consistently used dynamic programming methodology enables solving the optimization problem by breaking it down into simpler sub-problems, solving different parts of the problem and then combine the solutions of the sub problems to find an overall solution. It is also an efficient way as it takes far less time than earlier methods. The dynamic programming approach seeks to solve each sub-problem only once, thus reducing the number of computations: once the solution to a given sub-problem has been computed, it is memorized": the next time the same solution is needed, it is simply looked up. This approach is especially useful when the number of repeating sub-problems grows exponentially as a function of the size of the input. Thus it’s one of the best algorithm for solving optimization problems as it can examine all possible ways to solve the problem and force us to pick the best solution. Hence if the scope of the problem is such that going through all possible solutions is possible and fast enough, dynamic programming guarantees finding the optimal solution. (Wiki)

### 8.4.2 Heuristic methodology

An alternative method of solving an optimization problem, Heuristic algorithms refers to experience-based techniques for problem solving, learning, and discovery that gives a solution which is not guaranteed to be optimal. Where the exhaustive search (like what is implied in dynamic programming) is impractical, heuristic methods are used to speed up the process of finding a satisfactory solution via mental shortcuts to ease the cognitive load of making a decision. Examples of this method include using a rule of thumb, an educated guess, an intuitive judgment, stereotyping, or common sense.

While a heuristic algorithm does not guarantee the optimal solution, it is faster. Fortunately, many heuristic algorithms are proven to lead to the optimal solution. (Wiki) It is noted that the problem of finding an optimal solution for the inspection routine generation is not only very complex, but its complexity is compounded by inspection time constraints. Thus, generating real-time, optimal solutions even for a small-sized problem is not feasible. Hence, heuristic approaches are most suited to generate inspection routines of meaningful size. (Adan Verduzco, 2001)

Several heuristic rules for solving optimization problem of implementing a quality inspection procedure existed in the literature papers. They were analyzed and some of them were proven to provide optimal solutions analytically and also by combining them with simulation models to see the effectiveness over certain period of time. Here some of the rules used are mentioned, however to be noted that not all rules were proven effective rather the efficiency depended upon how the dynamic program was developed and how each of the solution were proved to be effective through discrete event simulation wherein these rules are applied to real world production lines.

### SELECTION RULES

Part Scheduling Rules for serial production systems. Also called as ‘Selection Rule’. This rule defines the priority which allows an idle machine to select the next part to be processed from those available in the machine input buffer. Scheduling decisions at the shop floor are normally made on a real time basis. Examples:

(Jim Lee, 1996)

- SPT: Part with shortest process time first.
- SRPT: Part with shortest total remaining operation time first.
- LRPT: Part with longest total remaining operation time first.
- SPT. TOT: Part having smallest value of operation time multiplied by total operation time first.
- SPT/TOT: Part with the smallest value of operation time divided by total operation time first. (which yielded the best result in the simulation experiment)
- LPT/TOT: Part having largest value of operation time divided by the total operation time first.
- LPT. TOT: Part having largest value of operation time multiplied by total operation time first.
- PTPR: Part type priority, i.e. part with highest expected profit margin first.

### STOPPING RULES

Inspection Sequencing Rules also referred to as ’Stopping Rule’ refers to whether the part should be inspected or not. Examples:

(Jim Lee, 1996)

- ANO: Sequence the inspection operation after the machining operation that has the highest probability of generating nonconforming units. The purpose of this rule is to ensure that no further work will be done on the nonconforming (scrapped) units. Under this rule, each part will be inspected only once during the manufacturing process, and the inspection sequence is part specific.
- BCO: Sequence the inspection operation before the most costly machining operation. This inspection rule will avoid performing high cost machining operations on parts which are already nonconforming.

- AFO: Sequence the inspection operation after the completion of final machining operation. Inspection only after the final machining operation does not interrupt the normal processing operations. This means that the transportation time between the inspection station and the workstations can be reduced. However, inspection time might increase in proportion to the number of uninspected machining operations. Also, a nonconforming part detected after the final operation will result in a higher scrap cost.
- CFO: Sequence inspection operations before the most costly machining operation and after completion of the final machining operation. This rule is designed to capture the strength of both BCO and AFO rules and is the rule allows two inspection operations per part.
- AEO: Sequence inspection operations after every machining operation. This 'inspect all' policy is considered as a benchmark in the study.

### I/D POLICIES BASED ON THE HEURISTIC RULE

The inspection/disposition policy concerned with a heuristic rule is generally considered easy to apply as they are based on experience and action research. A typical way of implementing a heuristic in the real world would be to find the unit to inspect (in accordance with the associated selection rule) and check the associated stopping rule. If the stopping rule indicates that the inspection should be performed, then inspect the unit. This procedure is repeated until the stopping rule indicates that the inspection should not be performed. In some cases, the remainder of the batch is disposed of or scrapped according to the optimal no-inspection policy.

- The paper (Kit-Nam Francis Leung, 2009) used two interchangeable heuristic algorithms: The general exponential form of approximation, and the general logarithmic form of approximation.
- (Illana Bendavid, 2009) used the two stopping rules and two selection rules to study the efficiency of four heuristic rules:
    - The uncertainty-myopic (UM) heuristic composed of the greedy in uncertainty selection rule and the myopic stopping rule,
    - The cost-myopic (CM) heuristic composed of the greedy in cost selection rule and the myopic stopping rule, (faster to implement than other rules)
    - The uncertainty-look-ahead (UL) heuristic composed of the greedy in uncertainty selection rule and the look-ahead stopping rule, and
    - The cost-look-ahead (CL) heuristic composed of the greedy in cost selection rule and the look-ahead stopping rule. (gave the best results under the given constraints)
- Genetic Algorithms (Mukesh Taneja, 1994) that mimics the process of natural selection.
- Evolutionary algorithms (Sofie Van Volsem, 2007)
- The paper (Ali Azadeh, 2012) tests Particle Swarm algorithm which is a modern evolutionary algorithm comparable with genetic algorithm (GA).

### 8.4.3 Discrete-Event Simulation & Simulation Expert Systems

Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics or behaviors/functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time. (Wiki)

Simulation is used in many contexts, such as simulation of technology for optimization problems, often, by using computer experiments to study simulation models. Simulation is considered as an increasingly important computer aid to the design process, partly because of the growing complexity of manufacturing systems, and partly because of their dynamic and stochastic behavior Key issues in simulation include the acquisition of valid source information about the relevant selection of key characteristics and behaviors, the use of simplifying approximations and assumptions within the simulation, and fidelity and validity of the simulation outcomes.

When considering a production line, a lot of problems could occur which requires a lot of preparation and consideration so that everything will run as it should be. Doing a rigorous on-floor tests combined with mathematical problem solving is costly, unrealistic and time consuming (Umol Syamsyul Bin Rakiman, 2013). They also stipulate many limitations such as requirement of high investment and technology, highly skilled workers, and rigorous training.

Hence computer simulation has become an absolute necessity in the design of practical systems, as a means of overcoming manufacturing problems, and the trend towards broadening its capabilities is becoming a large part of future research to encompass more and more of the factory. The application of simulation has the scope of becoming even broader, relevant and practical with the increasing technological advancements. It is also considered less expensive. (Giovanni Moroni, 2014)

# SECTION III: KEY FINDINGS & FUTURE RESEARCH AREAS

## 9. Optimized Inspection Strategies in a Production Line

In this section we through light on the various findings of our literature review and find a chronological research-based connection between relevant papers in order to analyze the addressed areas of research in terms of its effectiveness and applicability as real world solutions. It is to be noted that the findings are analyzed in the point of view of a manager hence the intricate mathematical details are assumed to make sense based on previous applications. The other focus during the analysis of the key findings will be to address future areas of research that has been proposed in each of the papers.

## 9.1 Inspection Strategy Classifications

An efficient inspection strategy aims to maximize quality and minimize cost associated with inspection. The inspection strategies will therefore answer questions such as the fraction of items to be inspected, the number of repetitions, and how to deal with a nonconforming item. This type of work is usually referred in literature as a **parametric strategy**, whereas research involving the determination of where to allocate inspection capability is referred to as an **allocation strategy**. A typical goal of an allocation strategy is to strike an economic balance between inspection capacity, number of inspection stations allotted, and inspection scheduling.

Early literature concentrated on developing strategies for simplified situation which will enable more practical extensions in the future. Also earlier literature on inspection strategies does not differentiate between inspections conducted by automated devices, human inspectors, or a mix of. This is because the actual inspection actions are usually modeled using a set of parameters that are independent of the actual inspection methods. (Sampatraj S. Mandroli, 2006)

According to the paper by (Israel Tirkel, 2013), Inspection policies can be broadly classified into (a) **Predictive or Static or Fixed** policy, where in-advance schedule of items for inspection is generated, or (b) **Completely-Reactive or Dynamic or Flexible** policy, where no schedule is generated and decisions are made in response to real-time situations or events.

Many variations of what exactly is the objective of an inspection plan in terms of optimization are available throughout literature. These definitions are not mutually exclusive and they encompass all the posed questions. The objective as explained in (Illana Bendavid, 2009) is to find an **economic trade-off** between learning/improving actions (preventive actions) and reactive/corrective actions (after inspection). In another variation, (Jim Lee, 1996) explains that the objective for an effective inspection plan is to find the **optimal balance** between the costs of additional inspections at earlier stages and the costs of forwarding down the production line units that are already defective. The economic comparison is usually performed by implementing a proper cost model for each investigated strategy and running an optimization algorithm specifically developed to cope the constrained problem. A benchmark of process scenarios is generated and the obtained results are observed to point out important findings.

The two policies that are usually set as comparative study for a production system before arriving on an optimal inspection policy are the zero inspection and full (100%) inspection policies. In the development of the optimal inspection policy, the optimal disposition policy if no inspections are performed, should be determined. Such a **zero-inspection policy** must be considered because when inspection costs are relatively high there is the option to produce small batches without performing inspections. After developing the no-inspection policy, the globally optimal inspection/disposition policy can be determined in order to minimize expected costs. (Tzvi Raz, 2000)

Recent development of automated inspection technologies, such as optical sensors, thermal detectors, gas sensors, and CT scanners, makes it feasible to perform full or **100% inspection** on all items with low operating cost. It plays an important role in many processes, such as automobile assembly, semiconductor manufacturing, airport baggage screening or other decision-making processes where the consequences of excessive deviations from target values are very high.

Another approach presented is an inspection policy considering zero-defects where one does not allow non-conforming units to reach the process customer but may allow conforming units to be scrapped. Many models have constantly demonstrated that, under certain realistic cost combinations, the policies of **perfect information** and **zero-defects** cannot be justified economically. (A. Vaghefi, 2009)

## 9.2 Observations about Total Cost Relations

Based on simulation experiments and sensitivity analysis performed in the reviewed papers, the relation of different variables with total cost relations can be generalized. Decision makers can refer to these results to determine how their limited resources can be invested to enhance their decision making process for an integrated model like that proposed in (Yeu-Shiang Huang, 2013).

- **Rate of Production** is inversely correlated to the **reworking time** per product as increase of production rate increases the production lot size, which results in an increase of defective products. Hence to prevent late delivery, the reworking time per product has to be reduced accordingly.
- The **sampling size** increases as the **production rate** increases as an increase in lot size, needs more product inspections to ensure product quality to lower the warranty cost after product sale.
- **Demand rate** is inversely correlated to **reworking time** per product as it has to be reduced to prevent increased demand causing late delivery because of longer reworking time.
- Also as more conforming products are processed, more defective products are detected and reworked, which may result in a long reworking process and an inventory shortage. Therefore, the **sampling size** of conforming products has to decrease as the **demand rate** increases.
- It is also interesting to find that when demand is increased, the reworking time per unit and the sampling number of conforming product have to decrease. This would result in the possible condition in which the reworking cost may increase because extra operation shifts will be

needed, and the warranty cost may increase because more uninspected defective products may be sold in the market. Consequently, the **total cost** would increase as the **demand rate** increases.

- **Sampling size** of conforming products decreases as the **defective rate** increases.
- Since when **defect rate** is relatively high, more conforming products for sampling results are collected resulting in increase of **inspection** and **reworking** costs.
- The **total cost** increases as the **defect rate** increases because a higher defect rate increases costs corresponding to reworking, warranty and brand loss.
- **Sampling size** increases as the **warranty term** increases because then quality has to be higher to ensure that the warranty cost can be met; which can only be achieved using a stricter inspection process.
- The **warranty term** is not significantly correlated to the **sampling size** per unit; however, it increases the **total cost** since the increase of the inspection and reworking cost.
- **Inventory holding cost** is inversely related to reworking time because as holding cost increases, the reworking time reduces to shorten inventory storage period to cut down the total inventory cost.
- Obviously **total cost** increases as the **holding cost** per unit increases.
- The **sampling size** increases as the **brand loss** cost increases as stricter inspection is needed to maintain high quality.
- The brand loss cost is not significantly correlated to the reworking time per unit; however, it affects the total cost. The **total cost** increases as the **image damage cost** increases.
- **Warranty term** plays an important role in determining the sampling size of conforming products and has the greatest impact on the expected cost.

## 9.3 Literature history

(Glenn F Lindsay, 1964) was one of the earliest works to apply Dynamic Programming Approach to an Inspection Allocation problem for **multi stage production systems** thus creating a variation from Non Linear, Integer and Stochastic programming that was previously applied to the optimization problem to overcome the limitation of single stage models. They showed that a dynamic approach was far better to determine minimum total expected cost of manufacturing but as early models work were bound by rigid assumptions for the sake of simplicity.

Later research in inspection allocation extended towards finding the best heuristic rule for managerial decisions. (Mukesh Taneja, 1994) applied a genetic algorithm to the problem of inspection allocation in order to minimize total inspection costs. (Hamilton Emmons, 2002) extended the concept to deal with three interrelated decisions of optimizing the overall inspection capacity, assigning inspection tasks and scheduling to minimize economic loss due to inferior quality in a multi stage deteriorating production systems. (Abdur Rahim, 2004) implemented statistical process control and economic production lot sizing to the above problem by introducing control limits for a more realistic approach. (Sofie Van Volsem, 2007) applied an evolutionary algorithm which was validated though a discrete event simulation that illustrated the potential of applying meta-heuristics rules for solving optimization problem for the first time in literature.

In recent work, (A. Vaghefi, 2009) emphasized the importance of simulation modeling for multi stage manufacturing systems by developing a mathematical model considering the two types of misclassification errors to show their impact on costs. (Kit-Nam Francis Leung, 2009) concentrated on finding out optimal inspection intervals for a deteriorating production system by expanding upon previous research and proving it by applying two specific heuristic algorithms.

(Israel Tirkel, 2013) studied the impact of inspection capacity on quality and its impact on costs also considering the inspection response time. (Umol Syamsyul Bin Rakiman, 2013) used the inspection allocation problem for finding better production layouts for effective production through simulation of different inspection models in an assembly line. The finding of this paper was very important because it contradicted the conventional thought that having fewer workstations means shorter processing time.

The inspection allocation problem focused on early literature was later extended by (Jim Lee, 1996) to **flexible manufacturing systems** for a dynamic inspection policy. In order to solve the complex problem, the paper combined and applied general part scheduling rules and inspection sequencing rules found in literature to create combination of heuristic algorithms. The rules were run through the simulation of real FMS plant and the best heuristic rule was highlighted. Further research for inspection strategies in flexible manufacturing systems was directed towards including newer technologies related to tool loading and material handling shifting focus from inspection to global system optimization.

Research towards **off-line inspection optimization** by (Tzvi Raz, 2000) focused towards finding the optimal inspection/disposition policy for an optimal production batch size where the inspection and penalty cost are too be minimized mostly thorough dynamic programming approach as the complexity is as reduced similar to a single stage process. As an extension (Chih-Hsiung Wang, 2001) implored in detail the relationship between production, inventory and inspection by finding the optimal batch size that minimizes the total cost per unit time based on three inspection policies: zero inspection (used as benchmark), 100% inspection and a special policy that disregards the first s items in a batch. The implied policy was found to perform better (in terms of cost savings) than the previous economic lot size models that considered only 100% inspection. (Chih-Hsuing Wang, 2005) tested an off-line policy that only inspects production only at the end of the complete production run instead of a full inspection, and found that optimal production time is higher when rework cost is more than the scrapping cost due to process deterioration. He extended his work (Chih-Hsuing Wang, 2007) by including the two misclassification errors associated with inspection for a more realistic model with a small batch size, but found that it is infeasible to detect shift in process when inspection errors exist. He also saw the potential to extend the work towards imperfect processes. (Illana Bendavid, 2009) in a similar research included inspection errors and applied four heuristic policies to reduce the computational complexity of solving for a large batch size.

(Wen-Ying Wang, 2008) extended the work of (Chih-Hsuing Wang, 2005) to include rework time and restoration costs as an important consideration and justified the significant effect rework can have on the optimal batch size, thus models more closer to real world applications. In his later work (Chih-Hsiung Wang, 2009) tested an approximate solution by implementing an equally spaced inspection policy and found that significant inspection savings are possible thus emphasizing periodic inspection is economically justifiable. In another extension, (Fei Hu, 2009) considered an extended inspection policy considering optimal production run time to realize more savings than (Chih-Hsuing Wang, 2005). However, in the paper by (W.C. Tsai, 2011), the (Chih-Hsuing Wang, 2005) model of rework and disposition was reformulated for three deficiencies and solution was redeveloped for more realistic results.

(Adan Verduzco, 2001) applied heuristic rules for a simulation based on an electronics assembly industry to find the optimal inspection plan for real time systems. But instead of considering the cost function which is difficult to estimate, he used information gain about misclassifications as a function that directly links with cost benefits, as it enables diagnosability of the system to improve quality in the future.

In terms of **surveys and review-papers** studied, (Sampatraj S. Mandroli, 2006) presented a very comprehensive survey of inspection and diagnosis strategies for discrete-part manufacturing systems capturing the methodologies, modeling approaches and the various interactions between the system elements. (Qianmei Feng, 2008) in his review of quality engineering techniques captured the status and trends of quality control and optimization during the design and operation stages and found that statistical process control tools have become very prevalent with focus towards more advanced quality technologies utilizing integrated and unified quality methods.

(Fiona Zhao, 2009) created a paper that systematically reviewed the recent developments in computer aided inspection planning covering the new standards and technologies that are being implemented touching upon strategies for on-machine inspection and coordinate measuring machines. The paper emphasized the need for integrated solutions rather than one-off piece-meal approaches to inspection process planning. It also focused on trends in quality technologies like feedback loop system, machine error prediction database and mechanism to analyze inspection results to guide subsequent machining operations.

(Wenbin Wang, 2009) developed an inspection model that splits the inspection policy based on two types of machine deterioration to minimize total expected cost of production based on a model applicable in food industry, touching upon **machine maintenance** concept through dynamic optimization approach. (T. Nakagawa, 2010) considered an inspection policy for machine maintenance with a random working time but equally spaced inspection checks in a periodic way and confirmed the existence of a better optimal solution than previous literature models. (Linda Lee Ho, 2012) integrated a variable sampling interval on-line inspection with two types of imperfect corrective maintenance and extending it to include control limits only by using dynamic programming. (Yan-Chun Chen, 2013) also developed a model that integrates the problem of production, maintenance, inspection and inventory. The various relations were studied under strict constraints as it is one of the first models that presented an integrated solution for many production questions.

(E. Trovato, 2010) applied statistical process control techniques to non-serial production systems to develop an optimization model to test several inspection strategies like **preventive maintenance** and control charts to study its efficiency in terms of optimizing total quality costs associated with each strategy. It posted major findings: Inspection rate strongly affects strategy. For slow inspection rates, no inspection and preventive maintenance strategies are suited. For higher rates, control charts are competitive necessity as for moderate to large dispersion shifts, the Shewhart chart is found to be the most appropriate due to its easiness of implementation and less quality control cost.

(Chun-Tai Yen, 2013) considered the simulation for an **automotive component manufacturing** facility that included three subsystem of inspection based on on-machine inspection, supply chain management and production information management. The system proposed on a combined level proved to be effective and promised benefits of quality improvement and optimization.

(Giovanni Moroni, 2013) proposed a methodology for planning sampling strategies for **coordinate measuring machines** employed for off line inspections, for parts with multiple tolerances with the aim to minimize costs by impacting the measurement uncertainty. The paper later evolved itself (Giovanni Moroni, 2014) to test two heuristic methodologies on the proposed mathematical model and optimum sampling strategy was evaluated considering manufacturing signatures.

## 10. Other Broad Categories of Research Venues Identified

The literature review presented in this work aims to understand the optimization problem for justification of an inspection process in a production line which is a form of *maximizing quality* with the main emphasis is on economic benefits by *minimizing costs*. The surveyed papers in this work touch upon different areas of research topics but it can be broadly considered to be part of the overall research concentrating on **Quality Improvement in a Production line**.

So in this broad topic of Quality Improvement, there exists many different venues of research concentrating on various other objectives which are as important to a production line as the cost. In fact these objectives can directly or indirectly impact the cost of quality in a manufacturing line.

Hence this section aims to concentrate on those areas of research that coincided with inspection optimization problems during the review, and provide a little insight to identify future research paths that branch out (by combination or extension) from the concerned topic analyzed in this work.

## 10.1 Inspection oriented Strategy Vs Diagnosis Oriented Strategy

The survey paper by (Sampatraj S. Mandroli, 2006) classifies relevant research efforts into two general broad categories: (i) **inspection-oriented quality-assurance strategies**; and (ii) **diagnosis-oriented sensor-distribution strategies**.

An inspection-oriented quality-assurance strategy are those that attempt to allocate an economically viable level of inspection activity by balancing the various cost components associated with inspection, repair and replacement due to quality failure, and/or the warranty penalty in the case where a nonconforming product has been shipped to customers. Thus an **inspection-oriented strategy focuses on an optimization** that minimizes the total manufacturing costs associated with quality appraisal and failure. This is the focus of this literature paper.

But it should be noticed that although an inspection-oriented strategy potentially improves the quality of products eventually going to customers, it does nothing to alter the overall product quality, since nothing has been done to improve the underlying process. Ideally to ensure satisfactory product quality, the role of measurement-taking should be to diagnose the underlying sources that caused the defect and provide immediate feedback to workers and suppliers so that they can make adjustments to the process as soon as any defects occur. Here it is assumed that another set of underlying yet unknown variables are responsible for the quality defects. These underlying variables are usually not directly observable, and hence, inferences about their status have to be made based on inspection in order to determine which variables are causing the quality problem. Instead of simply minimizing the overall cost, **a diagnosis-oriented strategy** or sensor-distribution strategy imposes estimation accuracy requirements for a particular quality characteristic as a constraint, while finding the optimal way to deploy inspection technology.

The difference between the two approaches is caused by differences in their respective assumptions about the behavior patterns of manufacturing costs. An inspection-oriented strategy emphasizes a cost-effective production and tolerates a nonzero level of defective production. A diagnosis-oriented strategy focuses on the creation of a near-zero level of defective production. It is to be noted that the two types of research have been conducted rather independently without much overlap between them.

It is seen that research into Diagnosis-Oriented strategy is a significantly new research field and has lots of potential to expand by combining optimization objective with that of improving quality by implementing adaptive strategies and realistic quality fault model.

## 10.2 Optimal Production Batch Size for an given Inspection Policy

The main focus of this venue of research work is the economic optimization of the inspection/disposition policy for a batch of given size. This takes into consideration the relationship between the optimization problem and the determination of the production batch size.

The optimal batch size of production is referred to as different literature works in many equivalent terms like Economic Production Quantity (EPQ) or Economic Manufacturing Quantity (EMQ). The traditional economic manufacturing quantity (EMQ) model has been widely used because of its simplicity. In studies of inventory analysis, many of these studies have attempted to apply the EMQ model to different real-world situations, one of which is the case of an imperfect production process (Chih-Hsiung Wang, 2001).

Earlier works found that it is better to produce lots which are smaller in size than is the case for the classical EMQ model because the use of smaller lots produces fewer defective items and that monitoring the process through inspection is cost effective to produce a large size. The EPQ and inspection schedule are dependent on the trade-off among costs like set-up cost, holding cost, inspection cost, and process deterioration.

Thus in EPQ lot-size model, the problem is to find how much to produce and how frequently to produce (the duration of production run) so that the total cost is minimum. In the development of EPQ models, controlling the quality of the product has not been a general consideration. Rather, product quality has been assumed to be perfect. As a result, the effects of a deteriorating process on the EPQ have seen to have been ignored. In many industrial situations, however, the quality and the quantity of the product are equally important (Abdur Rahim, 2004)

Traditionally, quality control and inventory control have been viewed as two separate problems. However, research work has presented a models for integrating the EPQ, inspection schedule, and machine maintenance, and control chart design of an imperfect production process. (Yan-Chun Chen, 2013). Previous studies have also failed to adequately address the relationship between lot sizes and product inspection. (Chih-Hsiung Wang, 2001). Future is towards implementing heuristic and simulation methodologies, and including realistic assumptions for creating integrated models for off-line quality.

## 10.3 Machine Maintenance Policy

Considerable research has concentrated on the question: is a periodic machine maintenance policy better than an inspection policy? Research concentrating on economic optimization of periodic machine maintenance policies have been in abundance and has concentrated on improving quality by improving a machine‘s state of operation. (Chih-Hsiung Wang, 2001) Quality control and maintenance models have been proposed separately, although these two dimensions have many characteristics in common and are equally important. (Linda Lee Ho, 2012)

Earlier constraints for inspection models have been developed based on the assumption that the restoration time of the machine is negligible during a production run and that maintenance of a machine is perfect. These assumptions are unrealistic as it is known that machine restoration can sometimes interrupt production for a finite amount of time that is usually difficult to measure or estimate. Also it is to be noted that in real world there are many production processes where it is either impossible or expensive to interrupt the production process during a production run, or where it is not possible to detect the deterioration of the process. In these cases, economic justification of a maintenance process becomes necessary but increasingly difficult.

Two types of maintenance actions are mentioned in literature:

- Corrective Maintenance or Adjustment where action is performed on the machine after a defective item is found during inspection process or when process failure occurs.
- Preventive Maintenance where a regular or periodic machine inspection policy is introduced with or without a part inspection policy.

The paper (Linda Lee Ho, 2012) combines statistical process control for inspection with corrective maintenance to identify two types of corrective maintenance actions: first type where stoppage occurs due to one observation outside control limits and the second type where stoppage is due to a sequence of observations in the warning limits of the control specifications. Both maintenance type are considered to be imperfect with measured performances assuming a probability based on expert opinion or historical data. It is important to note that maintenance actions can be conducted with different levels of detail. The more detailed the maintenance is, the more efficient and more expensive it will be.

A production system after maintenance is not as efficient as a new system. It becomes “younger” than its actual age, but does not reach age zero (Yan-Chun Chen, 2013). Thus the effects of various preventive maintenance policies on the joint optimization of the EPQ and the economic design of the control chart has been studied in literature. Another consideration is that preventive maintenance can with a given probability, cause process deterioration due to its imperfect nature.(Chih-Hsiung Wang, 2001)

In a variation of imperfect production systems, (Wenbin Wang, 2009) considers two types of deteriorations in a production line by differentiating the inspection done. A minor inspections for product quality related problems that may not cause the breakdown of the line, but influence the product quality or productivity. And a major inspections carried out at a longer interval to check for major mechanical or electrical defects which can lead to the breakdown of the process if not attended.

The benefit of Maintenance action can be of many types: improve the yield performance of the machines to increase throughput, and improve the quality of the products as well as the process technology. (Israel Tirkel, 2013). There are separate research works concentrating just on one part of the benefit achieved through maintenance:

- Improve Production performance by reducing machine deterioration, preventing system failure and improving machine reliability. (Yan-Chun Chen, 2013)
- Improve Product Quality to prevent machine stoppages due to inferior quality of the product manufactured.
- Improve process technology by using the maintenance to provide valuable feedback data that improves quality as well as reduce machine stoppages.

Each of these three benefits if seen clearly are in some ways not mutually exclusive and can be combined into several models of optimization with different objective functions like: cost of maintenance, opportunity cost, inflammatory cost, sensitivity measure, minimizing a deteriorating characteristic, improving one or more process characteristic and reducing operation and repair time. Also the constraints applicable to a quality inspection strategy also is directly applicable to machine maintenance. Thus, each of the above mentioned functions and constraints open up different areas for future research.

## 10.4 Manufacturing Process Signatures

Manufacturing Signatures is the term applied to process-specific error detailing on a produced part (Fiona Zhao, 2009). They arise from the strong inter relation that exist between sampling strategy, quality characteristic (especially surface measurements) and the inspection technology capability (usually for coordinate measuring machines) for identifying non-conforming units. It is noted that quality conformance specification for a produced part for a given manufacturing process tend to be the same throughout production which are captured using the manufacturing signature.

A specific research venue concentrating on the interaction between sampling strategy and manufacturing process error signature exist and they have found effective sampling strategies through heuristic policies to bring down uncertainty related to quality. (Giovanni Moroni, 2013) This kind of research has specifically concentrated on optimization methodologies where more than a single geometric tolerance is involved. The objective function considered usually is a cost function related to the sampling strategy.

It is noted that, even if the optimization of the strategy is based on the presence of a manufacturing signature, explicit knowledge of the signature is not required. Therefore, signature based sampling strategy planning may be time consuming (but easy, because no effort in manufacturing signature modeling is required. Also a main drawback of a signature based sampling strategy is that if the signature itself changes then the measurement uncertainty will probably increase thus worsening product quality and cause undetected failures in the manufacturing process. However, further research has shown to adopt efficient statistical process control techniques to identify signature modifications. Thus future research on what can modification of manufacturing signatures mean for the expected total cost of a manufacturing process can be studied in detail.

## 10.5 Burn-in test

Burn-in is the process by which components (usually for the electronics industry) of a system are exercised prior to being placed in service. The intention is to detect those particular components that would fail as a result of the initial, high-failure rate associated with component reliability. By stressing all devices for a certain burn-in time the devices with the highest failure rate fail first and can be taken out of the system. Thus by applying a burn-in, early in-use system failures can be avoided but at the expense of reduced yield caused by the burn-in process. An alternative to burn-in will be to eliminate possible root cause of early failures. (Wiki)

Burn-in tests are a method of screening or inspection that ensures high outgoing quality to customers. In general, if the burn-in time is long enough, then most of defective items would be screened out. Thus, the outgoing batch of items would satisfy the quality requirements. (Hong-Fwu Yu, 2007)

Unfortunately, compared with the inspection test, burn-in is usually costly. That is, the longer the burn-in is, the higher the manufacturing cost is. Thus, a practical problem is to study the optimal length of the burn-in process for repairable products. Previous research are available to determining the optimal burn-in number for items, maintenance policies and inspection. In (Hong-Fwu Yu, 2007), an optimum model for balancing the trade-off between having both inspection and burn-in as screening procedures was developed. This case is particularly applicable in electronics industry as having a pure inspection policy has the disadvantage of imperfect inspection causing misclassification errors causing reduction in outgoing quality and increasing costs. For the latter, having a pure burn-in policy is time-consuming and, hence, cost-consuming, although it can guarantee that the outgoing batch satisfies the quality requirements if the burn-in time is long enough. Also inspection and burn-in cannot replace each other completely. So an optimal mixed-inspection policy is proposed on a given acceptable quality level.

(Hong-Fwu Yu, 2007) determined an optimal mixed policy that can economically justify a production lot size that is screened both through burn-in and inspection. Future work proposed the inspection of more than one quality characteristic during burn-in owing to the costly nature of burn-in tests and combining economic benefits of multiple quality characteristic inspection during a single burn-in.

The effectiveness of a burn-in test has generally considered questionable and various research is directed towards finding the effectiveness of implementing a burn-in test which can serve as a leverage to justify high costs associated with them. But the employment of burn-in test is wide spread among many industries today and the justification is associated with the alarming possibility of losing quality and brand image due to product failure at the customer end.

## 11.6 Optimum Inspection Policy in a Supplier-Manufacturer Supply Chain

The research paper by (Chung-Chi Hsieh, 2010) concentrated its efforts for finding an optimum inspection policy for a product that enters manufacturing process prior to have been supplied by a supplier. The research thus considers a new variable into the optimization problem, of that of the supplier quality as the quality of a manufacturer’s products sold to its customers depends not only on its process quality but also on the quality of the components supplied by its supplier.

Seen that its essential for both the manufacturer and the supplier to engage in quality-related actions, the paper studies the opposing interests of both parties in terms of efforts made to examine the strategic interaction between the manufacturer and the supplier in a non-cooperative setting, in which quality investment and sampling inspection are taken into account, under different degrees of information available.

The paper examines a simple serial supply chain that consists of one supplier and one manufacturer who make efforts to produce conforming products to customers. Both the parties engage in quality investment in their production processes to reduce defective items being produced. In addition, the supplier engages in outbound inspection before sending the components to the manufacturer, and the manufacturer employs inbound inspection, when receiving the components from the supplier, and outbound inspection, before sending final products to customers.

This research paper seems to be the first attempt in the literature to investigate both chain members’ quality investment and inspection strategies. The paper finds that through optimization of the manufacturer’s inbound inspection information, both their preferences could be aligned and the manufacturer’s inbound inspection policy can be eliminated to improve expected profit per unit. Hence this area of research opens wide range of possibilities for future studies. Issues such as effect of Penalty on Supplier-Manufacturer Relationship, effect on investment costs on both ends with impact on supply chain, and effects of game models for supplier-manufacturer contractual issues based on quality inspection.

## 10.6 Warranty Policy

Considering the broad topic of quality optimization, there may be a situation where a defective product could be shipped to the customer causing an undesirable situation in which unsatisfied customers might take certain actions that would have unfavorable impacts on the future sales of the product. Since selling defective products is unavoidable, warranties thus play a crucial role after a product has been sold. (Yeu-Shiang Huang, 2013)

So the kind of warranty policy chosen for the product is impacted by the inspection strategy chosen for the production line.  Varied literature papers exists that study warranty policies with the objective of reducing warranty cost. So it is imperative for manufacturers to focus on quality management to ensure product quality and to prevent excessive warranty cost. To prevent defective or nonconforming products from being sold to customers, which would increase the warranty cost and damage the company reputation, an appropriate sampling inspection scheme is necessary.

Hence an effective inspection strategy has to consider related costs from three aspects: the production system, the product inspection, and the post-sale warranty. Future research can concentrate on minimizing expected cost by determining optimal plans for a given warranty cost, or study the effect of different warranty policies on the expected cost of inspection through simulation.

## 10.7 Effect of Buffers

The paper (Man-Soo Han, 2002) notes the effect of buffer storages on Machine failures and part defects and presented an approximation method for allocating material buffers to a serial production line considering a given inspection policy with the objective of maximizing throughput to bring down quality inspection costs. It developed an inspection model that captures the effects of failure and part rejection on the throughput of lines that can be reduced by having buffer storages. But however it is seen that this decoupling effect cannot take place when buffers are empty or full. As buffer sizes increase, the probability of buffers being empty or full decreases and thus, the effects of failures on the throughput are reduced. However, installing buffers and buffers themselves require an additional cost and another undesirable consequence of buffers is the work in process. The more the buffer sizes increase, the more WIP the inter-stage buffers can have. Hence, in the design of a production line, the minimum buffer capacity is desired for an aim throughput.

## 11. Research paper Classification Table

| Production Configuration | Application Setting | Optimization Methodology | Papers |
|---|---|---|---|
| Multi Stage – Serial and Assembly/Convergent Systems | Electronics Components Assembly, Semiconductor Fabrication, Flexible manufacturing Systems, Automated Systems, large Organizations with attention-management problems, Supply Chain | Dynamic Programming | (Glenn F Lindsay, 1964), (Hong-Fwu Yu, 2007), |
| | | Heuristic algorithm proved in an analytical way | (Mukesh Taneja, 1994), (Hamilton Emmons, 2002), (Chung-Chi Hsieh, 2010), (Ali Azadeh, 2012), |
| | | Heuristic Algorithm proved through Simulation Experiments | (Jim Lee, 1996), (Adan Verduzco, 2001), (Man-Soo Han, 2002), (Sofie Van Volsem, 2007), (A. Vaghefi, 2009), (Israel Tirkel, 2013), (Chun-Tai Yen, 2013) |
| Non Serial Systems | Just-In-Time mixed-model assembly lines, apparel or any industry producing custom designed products. | Heuristic algorithm proved through analytical simulation/sensitivity analysis | (Mukesh Taneja, 1994), (E. Trovato, 2010) |
| Single Stage (or) Multi-stage modeled as Single stage | General, Wide range of Industries and Management Applications | Dynamic Programming | (Abdur Rahim, 2004), (Wenbin Wang, 2009), (T. Nakagawa, 2010), (Linda Lee Ho, 2012), (Yeu-Shiang Huang, 2013), (Giovanni Moroni, 2013), (Yan-Chun Chen, 2013) |
| | | Heuristic Algorithm proved through Simulation Experiments | (Kit-Nam Francis Leung, 2009), (Umol Syamsyul Bin Rakiman, 2013), (Giovanni Moroni, 2014) |

| | | | |
|---|---|---|---|
| Off-Line Systems (Multi - stage modeled as single stage systems) | Food Industry, Embroidery Industry, | Dynamic Programming | (Tzvi Raz, 2000), (Chih-Hsiung Wang, 2001), (Chih-Hsuing Wang, 2005), (Chih-Hsuing Wang, 2007), (Wen-Ying Wang, 2008), (Chih-Hsiung Wang, 2009), (Fei Hu, 2009), (W.C. Tsai, 2011), |
| | | Heuristic Algorithms | (Illana Bendavid, 2009) |

Table 1: Research classification based on Production Configuration, Optimization methodology and Application

## 12. Future Research

In this section, we summarize the future research possibilities identified in the literature papers.

The general research trends are moving towards **integrated models** that not only consider optimal inspection but combines it with all need of optimization that arises for a production line including: **economic production batch size, preventive maintenance, statistical process control, errors related to inspection and machine restoration, machine availability and utilization** (T. Nakagawa, 2010)**, process intervention, inventory, buffer** (Man-Soo Han, 2002)**, tool loading, information gain, multiple defect characteristics, rework, warranty, brand loss, shortages** (Yeu-Shiang Huang, 2013)**, production rate and demand** (Yan-Chun Chen, 2013), **process characterization**, **setup for multiple products** (E. Trovato, 2010), . These variables make the model as realistic as possible.

Also specific differences concerning the type of assumption taken for a particular variable enhances the model by making it more realistic. Examples: Having **random inspection time**, **random rework times, dissimilar warranty policies, delayed delivery** (Yeu-Shiang Huang, 2013), **more control zones for better action**, including **process-specific failure mechanisms** (Linda Lee Ho, 2012), **multiple failure modes, variable expected time to shift** (Wenbin Wang, 2009)**, multiple quality characteristics** (Hong-Fwu Yu, 2007)**,**

Research trend in utilizing newer optimization methodologies are going towards more and more **application of simulation experiments** to test analytical models to imitate real time. Any proposed model can be extended, proved and disserted using empirical approach. Also applying new heuristic algorithms that proven in other fields into manufacturing like **modern evolutionary algorithms** (Ali

Azadeh, 2012), **meta-heuristic algorithms** (A. Vaghefi, 2009)**, dynamic simulation runs** (Sofie Van Volsem, 2007)**,**

Application of **quality engineering is being expanded to non-manufacturing sectors** (Qianmei Feng, 2008) has seen a trend of **cross adaptation** like application of inspection strategies related to a production line into other field like management areas that are riddled with attention management problems. Examples would be service areas like police stations, voting booths. (Ali Azadeh, 2012)

Optimization of Inspection processes should be enhanced through continuous improvement. **Feedback-loop for quality inspection** are needed that improves quality and simultaneously optimizes it. This narrows down optimization problems to specific quality characteristics and employed technologies, hence can be solved through simulation experiments. Approaches like studying the effect of inspection cost with **accumulated learning over time**. (Israel Tirkel, 2013), **Development of machine error prediction database for monitoring and control of machine accuracy, Mechanism of analyzing and utilizing inspection results to guide subsequent machining operations** (Fiona Zhao, 2009)**.**

Taking the whole **supply chain** into consideration can enable models that **eliminate repeated inspections** and non-value adding activities related to inspection thus creating maximum savings. Thus complete models considering **many suppliers** and integrating them with existing optimal models is a huge possibility (Chung-Chi Hsieh, 2010).

For automated production systems like flexible manufacturing systems, real time monitoring can be improved through empirical experiments. Even though finding direct cost benefits may prove difficult, objective functions that indirectly have a huge impact on cost can be considered. Future models can be more integrated by including efficiency indicators for **agility of newer technologies** that can be implemented like AGV (Automated guided vehicle) and machine tool loading. (Chun-Tai Yen, 2013)

Creating **efficient production and inspection layouts** that optimize inspection allocation problem is a new research area that turns-the-tables on traditional approaches where inspection allocation is considered a post-operation problem. Finding an effective balance between design and operation stages to maintain flexibility and adaptability in designing inspection policies should be the objective target all along concentrating on the cost trade-off necessary. (Umol Syamsyul Bin Rakiman, 2013)

For off-line inspection strategies, research methodology trend is still in nascent stages utilizing dynamic programming. Huge improvements can be made possible by moving towards effective heuristic rules and simulation experiments to include more realistic assumptions like: Finite variable Inspection time (Wen-Ying Wang, 2008) (W.C. Tsai, 2011), process intervention (Fei Hu, 2009), more than one quality characteristic (Illana Bendavid, 2009), optimal production rate (Chih-Hsiung Wang, 2009), and variable shift distribution (Chih-Hsuing Wang, 2007).

In the research towards finding effective sampling strategies for optimal inspection policies for a **Coordinate measuring machine**, employed in off-line inspection, the following research possibilities are available: Finding the specific effect of what can modification of **manufacturing signatures** mean for the expected total cost of a manufacturing process. This section proves as a large area to focus as it can be applied industry-specific and technology-specific. (Giovanni Moroni, 2013), Deep analysis of the effect of correlations between **multiple tolerances** on the inspection cost. (Giovanni Moroni, 2014), and development of flexible and **adaptive sampling strategies**.

## SUMMARY TABLE

| Title | Author, Year, Country | Research Methodology | Addressed Themes | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Type | Objective Function | Cost Components | Production Configuration | Optimization methodology | Application |
| Allocation of Screening Inspection Effort - A Dynamic Programming Approach | Glenn F. Lindsay and Albert B. Bishop , 1964, USA | Analytical | On line | Minimizing Total Cost | Total of the cost of screening inspection,<br>and the cost of returned lots | Serial Multi stage Production System | Dynamic Programming | Electronics Assembly |
| Inspection sequencing and part scheduling for flexible manufacturing systems | Jim Lee, F. Frank Chen, 1996, USA | Analytical & Empirical | On line | Daily Expected Profit | 1) Manufacturing Cost + Inspection Cost + Handling cost<br>2) WIP over simulation time<br>3) ratio of inspection operation time to the machining operation time, | Serial Multi stage Production Systems | Simulation Experiments | Caterpillar East Peoria FMS Plant |
| Inspection Allocation in Manufacturing Systems : A Genetic Algorithm Approach | Mukesh Taneja, N. Viswanadham, 1994, India | Analytical | On line | Minimizing Total Cost at each stage | Inspection cost, manufacturing cost, scrapping cost, penalty cost | (Serial and Non Serial) Multi stage Production System | Heuristic | Semiconductor Fabrication industry |
| Economic optimization of off-line inspection | Tzvi Raz, Yale T. Herer and Avraham Grosfeld-Nir, 2000, Israel | Analytical | Off Line | Cost of optimal inspection/disposition policy | Inspection Cost, Penalty Cost, | Multi Stage modeled as Single Stage | Dynamic Programming | Pasteurized foods industry. |
| Simultaneous determination of the optimal production-inventory and product inspection policies for a deteriorating production system | Chih-Hsiung Wang, Shey-Heui Sheu, 2001, Taiwan | Analytical | Off Line | Minimization of the expected average cost per unit time | Cost of Rework, Production & Inspection costs.<br>Optimal production-inventory lot (economic lot) | Multi Stage modeled as Single Stage | Dynamic Programming | Pasteurized foods industry. |

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| Information-Based Inspection Allocation for Real-Time Inspection Systems | Adan Verduzco, J Rene Villalobos, Benjamin Vega, 2001, USA | Analytical, Simulation | On Line | Expected Information-Gain (assumed to directly link Cost function) | Minimization of inspection errors.<br>Expected cost if an extra inspection is performed.<br>Info gain by generating inspection mix | Serial Multistage Production Systems | Heuristic, Simulation Experiments | Automatic Visual Inspection (AVI) in Elctronics Assembly Industry |
| Optimal buffer allocation of serial production lines with quality inspection machines | Man-Soo Han, Dong-Jo Park, 2002, South Korea | Analytical, Simulation | On Line | Maximizing Throughput | Decrease defective rate of parts.<br>Minimize Buffers | Serial Multistage Production Systems | Heuristic, Simulation Experiments | Serial Production Lines with inspection stations and buffer stations during initial design stage |
| Inspection allocation for multistage deteriorating production systems | Hamilton Emmons, Gad Rabinowitz, 2002, USA, Israel | Analytical | On Line | Minimizing Loss (Economic) | Minimizing number of inspection facilities and Minimizing Inspection time.<br>(Added effects of Number of Production Stages) | Serial Multistage Production Systems | Heuristic | Semiconductor Fabrication process, large organizations (police, army, bank, electric utility, etc.) deals with. |
| An Integrated Optimization Model for Inventory and Quality Control Problems | Abdur Rahim, Hiroshi Ohta, 2004, Canada, Japan, Netherlands | Analytical | On Line | Total expected cost | 1) Quality Control Cost 2) Inventory Control Cost<br>3) Setup Cost | Multi Stage modeled as Single Stage | Dynamic Programming | many industrial applications |
| Integrated production and product inspection policy for a deteriorating production system | Chih-Hsuing Wang, , 2005, Taiwan | Analytical | Off Line | Expected total cost per item under the Production | Expected defective items cost in a production run + Manufacturing cost+ Labor cost+ Setup+ Holding cost+ Process | Multi Stage modeled as Single Stage | Dynamic Programming | Food process industry, glass manufacturing |

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|  |  |  |  | Inspection policy | Inspection cost+ Restoration cost |  |  |  |
| A survey of inspection strategy and sensor distribution studies in discrete-part manufacturing processes | Sampatraj S. Mandroli, Abhishek K. Shrivastava and Yu Ding, 2006, USA | Survey | On Line | Expected Total Cost | 1. Internal Failure Cost<br>2. External Failure Cost<br>3. Inspection Cost<br>4. Manufacturing Cost,<br>5. Setup & Inventory Cost,<br>6. Root-cause searching and elimination cost | Discrete Production Process | 1. Dynamic,<br>2. Integer,<br>3. Non-Linear,<br>4. Heuristic,<br>5. Simulation |  |
| Economic off-line quality control strategy with two types of inspection errors | Chih-Hsuing Wang, , 2007, Taiwan | Analytical | Off Line | Expected total cost per item | Expected inspection cost + Penalty Cost Manufacturing cost+ Labor cost+ Setup+ Holding cost+ Restoration cost | Multi Stage modeled as Single Stage | Dynamic Programming | Industry where stopping Production is costly. Food process industry, glass manufacturing |
| An Evolutionary Algorithm and discrete event simulation for optimizing inspection strategies for multi-stage processes | Sofie Van Volsem, Wout Dullaert, Hendrik Van Landeghem,, 2007, Belgium | Analytical, Simulation | On line | Expected total inspection cost | Inspection Cost,<br>Cost of defective units detected at any stage (Rework cost)<br>Penalty cost | Multi stage Serial Production System | Heuristic, Simulation Experiments | Production of printed circuit boards |
| An optimal mixed policy of inspection and burn-in and the optimal production quantity | Hong-Fwu Yu, Wen-Ching Yu,, 2007, Taiwan | Analytical | On Line | Maximize Expected Profit = Revenue - Total Cost | Manufacturing cost, Inspection cost, Cost of Burin-in and Cost of false rejection of non-defective items. | Multi stage Serial Production System | Dynamic Programming | Semiconductor and IC Industry where inspection and burn-in both are accepted as |

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| | | | | | | | | screening procedure. |
| Economic optimization of off-line inspection with rework consideration | Wen-Ying Wang, Shey-Huei Sheu, Yan-Chun Chen , Der-Juinn Horng, 2008, Taiwan | Analytical | Off Line | Expected Profit | Inspection Cost, Penalty Cost, Rework Cost | Multi Stage modeled as Single Stage | Dynamic Programming | Copper plating of printed circuit boards |
| Quality Engineering: Control, Design and Optimization | Qianmei Feng, Kailash C. Kapur,, 2008, USA | Review | Both (On line & Off Line) | Expected Total Cost | Sum of Expected (Inspection cost + Quality Loss + Scrap Cost ) | Multi stage Serial Production System | NA | General |
| Utilizing an approximative solution to obtain the real optimal solution for a production and inspection model | Chih-Hsiung Wang, Ruey Huei Yeh,, 2009, Taiwan | Analytical | Off Line | Minimize the expected total cost rate | Setup cost, inspection cost, restoration cost, cost incurred by defective items,<br>and the inventory holding cost | Multi Stage modeled as Single Stage | Dynamic Programming | |
| Contribution of simulation to the optimization of inspection plans for multi-stage manufacturing systems | A. Vaghefi, Vahid Sarhangian,, 2009, Iran | Analytical, Simulation | On line | Expected total cost per item | Inspection Cost<br>Rework cost<br>Penalty cost<br>Replacement Cost | Multi stage Serial Production System | Heuristic, Simulation Experiments | |
| Two general forms of approximation for determining near optimal inspection intervals with non-zero inspection and replacement times in a deteriorating production system | Kit-Nam Francis Leung, , 2009, China, Australia | Analytical | On Line | Expected Profit per unit inspection time | Inspection cost<br>Replacement Cost | Multi Stage modeled as Single Stage | Heuristic | |

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| Computer-Aided Inspection Planning (CAIP) - The state of the art | Fiona Zhao, Xun Xu, S.Q. Xie,, 2009, New Zealand | Review | Both (On line & Off Line) | Dimensional Accuracy Requirements | NA | Automated Production Systems | Simulation Experiments | Automated Production Systems |
| Economic optimization of off-line inspection in a process that also produces non-conforming units when in control and conforming units when out of control | Illana Bendavid, Yale T. Herer,, 2009, Israel | Analytical | Off Line | Expected total cost per item | Inspection Cost, Penalty Cost | Multi Stage modeled as Single Stage | Heuristic | |
| Optimal production run time for a deteriorating production system under an extended inspection policy | Fei Hu, Qun Zong,, 2009, China | Analytical | Off Line | Expected total cost per item under the Production Inspection policy | Manufacturing cost, setup cost, inventory holding cost, restoration cost, inspection cost, and post-sale and rework cost | Multi Stage modeled as Single Stage | Dynamic Programming | |
| An inspection model for a process with two types of inspections and repairs | Wenbin Wang, , 2009, UK, China | Analytical | On line | Minimize long-run expected cost per unit time | Expected renewal cycle Cost / Expected renewal cycle length | Multi Stage modeled as Single Stage | Dynamic Programming | Chocolate Cake Prodcution Line |
| Economic design of inspection strategies to monitor dispersion in short production runs | E. Trovato, P. Castagliola, G. Celano, S. Fichera,, 2010, France, Italy | Analytical, Comparison | On line | Expected total quality cost | Cost of defects<br>Inspection cost = Sampling cost + search and elimination cost<br>Restoration cost | Non Serial for many product variants | Heuristic | JIT mixed-model assembly lines, apparel or any industry producing custom designed products |

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| Production, Manufacturing and Logistics: Quality investment and inspection policy in a supplier–manufacturer supply chain | Chung-Chi Hsieh, Yu-Te Liu,, 2010, Taiwan | Analytical, Comparison | Off Line | Supplier's and manufacturer's expected profits per unit | For Supplier: production cost, inspection cost, and penalty cost<br>For Manufacturer: purchase cost, production cost, inspection cost, and post-sale cost | Multi Stage in a Supply Chain | Heuristic | Example: TFT Panel Manufacturing Supplier |
| A summary of periodic and random inspection policies | T. Nakagawa, S.Mizutani, M.Chen,, 2010, Japan, Taiwan | Analytical | On line | Total expected cost until failure detection | cost of periodic check, the cost of random check, and the downtime cost per unit of time for the time elapsed between a failure and its detection at the next check. | NA | Dynamic Programming | Database and Computer Systems |
| Economic optimization for an off-line inspection, disposition and rework model | W.C. Tsai, Chih-Hsiung Wang,, 2011, Taiwan | Analytical | Off Line | Expected Profit | Inspection Cost, Penalty Cost for Type I & II errors, Rework Cost | Multi Stage modeled as Single Stage | Dynamic Programming | Food Industry |
| A particle swarm algorithm for inspection optimization in serial multi-stage processes | Ali Azadeh, Mohamad Sadegh Sangari, Alireza Shamekhi Amiri,, 2012, Iran | Analytical | On line | Total Inspection Cost | Inspection cost at stage<br>Cost of reworking or replacement<br>Penalty cost | Multi stage Serial Production System | Heuristic | Assembly Lines |
| Integrating on-line process control and imperfect corrective maintenance: An economical design | Linda Lee Ho, Roberto C. Quinino,, 2012, Brazil | Analytical | On line | Expected Cost per item | Inspection cost<br>Cost of defects<br>Corrective Maintenance cost<br>Penalty Cost | Multi stage serial Production System | Dynamic Programming | Integrated Circuit Boards |

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| A study on negative binomial inspection for imperfect production systems | Yeu-Shiang Huang Yan-Jun Lin, Jyh-Wen Ho,, 2013, Taiwan | Analytical | On line | Optimal Sampling Number | production cost + holding cost in warehouse + holding cost in buffer area + set-up cost + system inspection cost + cost for restoring the production system to the in-control + product inspection cost + reworking cost + repair cost for each product breakdown + cost of damaging company image | Multi Stage modeled as Single Stage | Dynamic Programming | |
| Modeling cost benefit analysis of inspection in a production line | Israel Tirkel, Gad Rabinowitz,, 2013, Israel | Analytical, Simulation | On line | Expected Total Cost of Inspection | - Processing/Production Cost - Materials, Maintenance, (Fixed and variable)<br>- Inspection cost: Fixed and variable<br>- Yield Loss Cost: Defects | Multi stage Serial Production System | Dynamic Programming | Semiconductor production line - wafer fabrication. |
| An optimal production and inspection strategy with preventive maintenance error and rework | Yan-Chun Chen , 2013, Taiwan | Analytical | On line | Expected Total Profit per unit time. EPQ | setup cost, holding cost, non-conforming item reworking cost, PM cost, inspection cost, cost of defect scrap, and restoration delay cost. | Multi Stage modeled as Single Stage | Dynamic Programming | Production of the copper plating of a printed circuit board |
| Production Line: Effect of Different Inspection Station Allocation | Umol Syamsyul Bin Rakiman Abdul Talib Bon,, 2013, Malaysia | Analytical, Simulation | Both (On line & Off Line) | Production Time | Assuming the decrease in production time will be directly taken as increase in production and thus profit | Multi stage Serial Production System | Simulation Experiments | Assembly Lines |
| On-Line Quality Inspection System for Automotive Component Manufacturing Process | Chun-Tai Yen, Hung-An Kao, Shih-Ming Wang and Wen-Bin Wang., 2013, Taiwan | Empirical | On line | Process Quality Dimension | More than optimization, the link is that increasing quality will result in increased profit | Multi stage Serial Production System | Simulation Experiments | Automotive Industry |

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| Inspection strategies and multiple geometric tolerances | Giovanni Moroni, Stefano Petrò,, 2013, Italy | Analytical | Off Line | Inspection cost | Grouped into: measurement cost and inspection error cost | Multi Stage modeled as Single Stage | Dynamic Programming | |
| Optimal inspection strategy planning for geometric tolerance verification | Giovanni Moroni, Stefano Petrò,, 2014, Italy | Empirical, Simulation, Case Study | Off Line | Inspection cost | Grouped into: measurement cost and inspection error cost | Multi Stage modeled as Single Stage | Heuristic, Simulation Experiments | |

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