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Computer Manufacturing Management Integrating Lean Six Sigma and Prognostic Health Management

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Abstract: Computer manufacturers have been applying Six Sigma for continuous quality improvement and Lean Manufacturing for reducing process waste in order to maximally meet customer requirements. However, top computer manufacturers are now realizing the design and production with advanced capability for early failure detection, fault diagnostic and prediction will significantly improve product life cycle performance and increase competitive advantages. In this paper, prognostic health management is proposed as a predictive management strategy centered by technological approach. Through integration with Lean Six Sigma, a raised computer manufacturing management performance can be achieved.

Keywords: *Computer manufacturing, lean six sigma, prognostic health management*

1. Introduction

Technological breakthroughs in the computer industry have been dramatic. This industry differs somewhat from other manufacturing industries in that production workers make up a relatively small proportion of the workforce. Technological innovation characterizes this industry more than most others and, in fact, drives much of the industry's production. This unusually rapid pace of innovation and technological advancement requires a high proportion of engineers, engineering technicians, and other technical workers who carry out extensive research and development. Likewise, the importance of promoting and selling the products manufactured by the various segments of the industry requires knowledgeable marketing and sales workers [1]. Computer products contain many intermediate components that are purchased from other manufacturers. Companies producing intermediate components and finished goods regularly choose to locate near each other, because doing so allows companies to receive new products more quickly and lower their inventory costs. Computer companies today are under extreme pressure from shrinking profit margins, fierce competition, short product life cycles, advancing technology, and the emergence of new markets. How to carry on flexible, effective and cost-saving management becomes increasing important for keeping computer enterprises predominant in the world market. Six-sigma has been characterized as the latest management fad to repackage old quality management principles, practices, and tools/techniques [2].

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The Six Sigma method is introduced by Motorola in the late 1980s, which is a project-driven management approach to improve the organization's products, services, and processes by continually reducing defects in the organization [3]. From the statistical point of view, the term Six Sigma is defined as having less than 3.4 defects per million opportunities or a success rate of 99.997% where sigma is a term used to represent the variation about the process average [4]. In the business world, Six Sigma is defined as a "business strategy" used to improve business profitability, to improve the effectiveness and efficiency of all operations to meet or exceed customer's need and expectations [5]. Nearly the same period, Lean manufacturing received an increasing amount of attention as one source for productivity improvements and cost reductions in manufacturing, which was originally developed by Toyota and is now used by many manufacturers throughout the world. At Toyota the system is referred to as the Toyota Production System (TPS) [6]. Lean and Six Sigma are process based improvement methodologies. Both were developed in manufacturing environments. A combination of both can provide the philosophy and the effective tools to solve problems and create rapid transformational improvement at lower cost [7]. Six Sigma, Lean manufacturing or Lean Six Sigma managements have been successfully applied in many manufacturing organizations such as General Electric, Boeing, DuPont, Kodak, Honeywell, Texas Instruments, *etc.,* [3]. In computer manufacturing field, the main computer and components companies like Toshiba, Seagate, HP, Dell, Lenovo, Sony, IBM also carried out many related programs and obviously improved their management performance.

Though many benefits are received and reported by lots of manufacturing companies, the success of Lean Six Sigma management strongly depend on the deep analysis in production problems. In computer manufacturing, for instance, unexpected intermittent failures of components often are serious problems, which reduce products reliability and limit successful management improvement by Lean Six Sigma. As a result, an automotive management strategy is needed to assist Lean Six Sigma implementation, especially in computer manufacturing.

In this paper, prognostic health management (PHM) is proposed which can be regarded as a *technology centered predictive management* strategy and is becoming increasing important in industry areas. PHM, in its low-level is also called prognostics and health monitoring. Here, the term monitoring is used to define the engineering-related functionalities, while management refers to the high-level, business-related functions. Therefore, health monitoring defines the systematic collection and analysis of parametric data from sensors distributed over systems in order to provide advanced failure diagnostics and prediction. Health management is the use of such fault diagnostics and prediction functionalities to implement condition based management concepts, and thus produce economical benefits on engineering, management, logistics and operations [8]. PHM is not only the way of technological solution, but also product life cycle management strategy and parts supply chain optimization approach.

As a result, this paper proposes an integrated management strategy for computer manufacturing as shown in Fig. 1, which combines PHM and Lean Six Sigma for optimal management of manufacturing process. The combination of both can enhance management performance of computer manufacturing and continuously raise the efficiency and effectiveness of enterprise management and improve computer products qualify and reliability. The rests of this paper are organized as follows. Section 2 briefly describes basic knowledge and principle of Lean Six Sigma. Section 3 introduces the novel management strategy – PHM, its current development and methods are summarized. In section 4, the idea of integrating PHM and Lean Six Sigma is proposed, the relation of them are discussed. In the end, conclusions are summarized in section 6.

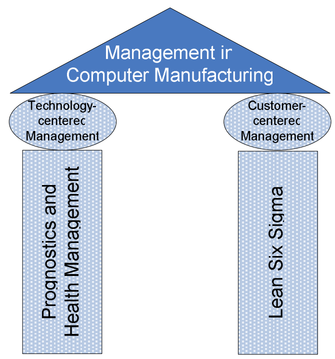

Figure 1: A proposed integration management strategy in computer manufacturing

2. Six Sigma and Lean manufacturing

2.1 Six Sigma

Six Sigma is considered to be a new strategy initiatively introduced by Motorola in the late 1980s, hence several papers from the early 1990's concentrate on explaining the development of Six Sigma using the Motorola case [9]. These authors discuss the new Motorola quality improvement program, namely Six Sigma, which has led to improvements in their quality performance and consequently propose Six Sigma as a new opportunity for any organization that wants to improve quality.

Six Sigma differs from other quality programs in its 'top-down' drive in its rigorous methodology that demands detailed analysis, fact-based decisions, and a control plan to ensure ongoing quality control of a process. Since its initiation at Motorola in the 1980s, many companies including GE, Honeywell, Sony, Caterpillar, and Johnson Controls have adopted Six Sigma and obtained substantial benefits. Six Sigma has been defined as the statistical unit of measurement, a sigma that measures the capability of the process to achieve a defect free performance. Six Sigma has the ability to produce products and services with only 3.4 defects per million, which is a world-class performance. Six Sigma has also been described as a high performance project-driven approach in analyzing the root causes of business problems and solving them.

As a systematic approach, Six Sigma implements the DMAIC process, *i.e.,* define, measure, analysis, improve, and control and utilizes design for Six Sigma method (DFSS) [10]. The fundamental principle of Six Sigma is to 'take an organization to an improved level of sigma capability through the rigorous application of statistical tools and techniques' [11]. It generally applies to problems common to production. Table 1 summarizes Six Sigma business strategies, tools, techniques, and principles.

Table 1: Six Sigma strategies, principles tools, and techniques [11]

Business strategies and principles	Tools and techniques
Project management	Statistical process control
Data-based decision making	Process capability analysis
Knowledge discovery	Measurement system analysis
Process control planning	Design of experiments
Data collection tools and techniques	Robust design
Variability reduction	Quality function deployment
Belt system	Failure mode and effects analysis
DMAIC process	Regression analysis
Change management tools	Analysis of means and variances Hypothesis testing Root cause analysis Process mapping

2.1.1 DMAIC process

DMAIC is a closed-loop process that eliminates unproductive steps, often focuses on new measurements, and applies technology for continuous improvement. Table 2 presents the key steps of Six Sigma using DMAIC process.

Table 2: Key steps of Six Sigma using DMAIC process [12]

Six Sigma steps	Key processes
Define	Define the requirements and expectations of the customer Define the project boundaries Define the process by mapping the business flow
Measure	Measure the process to satisfy customer's needs Develop a data collection plan Collect and compare data to determine issues and shortfalls
Analyze	Analyze the causes of defects and sources of variation Determine the variations in the process Prioritize opportunities for future improvement
Improve	Improve the process to eliminate variations Develop creative alternatives and implement enhanced plan
Control	Control process variations to meet customer requirements Develop a strategy to monitor and control the improved process Implement the improvements of systems and structures

2.1.2 DFSS methodology

DFSS is a systematic methodology utilizing tools, training and measurements to enable the organization to design products and processes that meet customer expectations and can be produced at Six Sigma quality levels [13]. The goal of DFSS is to achieve minimum defect rates, Six Sigma level, and maximize positive impact during the development stage of the products. It is used to develop new products or services with a Six Sigma criteria, capability, and performance [14]. It utilizes variety of quality oriented tools and techniques to meet customer requirements and has shown an increase in life cycle profits. The essence of DFSS is predicting design quality up front and driving quality measurement and predictability improvement during the early design phases [15]. Essentially, the DFSS process is focused on new or innovative designs that yield a higher level of performance. The DFSS has seven elements that can be summarized as follows [16]:

- Drives the customer-oriented design process with Six Sigma capability
- Predicts design quality at the outset
- Matches top-down requirements flow down with capability flow up
- Integrates cross-functional design involvement
- Drives quality measurement and predictability improvement in early design phases
- Uses process capabilities in making final decisions
- Monitors process variances to verify that customer requirements are met.

The common tools that can be used for DFSS process are listed in Table 3.

Table 3: Tools for DFSS process [16]

• Management leadership	• Failure mode and effect analysis (FMEA)
• Project management	• Business process simulation
• Customer research	• Quality function deployment
• Design scorecards	• Rapid product prototyping
• Benchmarking	• ….

2.2 Lean manufacturing

Lean manufacturing or lean production, which is often known simply as "Lean", is a production practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination. In future, Ref. [17] accurately defined Lean manufacturing as “an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability.”

Basically, lean is centered around creating more value with less work. Lean manufacturing is a generic process management philosophy derived mostly from the Toyota Production System (TPS) and identified as "Lean" only in the 1990s [18].

It is renowned for its focus on reduction of the original Toyota seven wastes in order to improve overall customer value, but there are varying perspectives on how this is best achieved. Lean implementation is focused on getting the right things to the right place at the right time in the right quantity to achieve perfect work flow, while minimizing waste and being flexible and able to change. These concepts of flexibility and change are principally required to allow production leveling. Lean manufacturing focuses on reducing seven types of wasteful activities in processes shown in Table. 4. in order to improve overall customer value, but there are varying perspectives on how this is best achieved.

Table 4: Seven types of wasteful activities in processes

Wasteful types	Contents
Overproduction	Producing product in excessive quantities or much earlier that needed;
Waiting	Failure to deliver product when needed by downstream processes;
Transportation	Unnecessary movement of materials;
Excessive processing	Unnecessary activities or features that don’t benefit the customer;
Inventory	Extra production that is not needed by a customer;
Motion	Unnecessary movement by employees;
Defects	Failure to conform to specification or to customers’ needs and expectations.

3. Prognostic Health Management (PHM)

Prognostic health management (PHM) is a method that permits the evaluation of system reliability in its actual life-cycle conditions, to determine the advent of failure, and mitigate the system risks [19]. PHM implementation involves techniques that combine sensing, recording, and interpretation of environmental, operational, and performance-related parameters that are indicative of system health [20]. Prognostics can be implemented using one of three approaches, the physics-of-failure (PoF) approach, the data-driven approach, and fusion approaches as shown in Fig. 2.

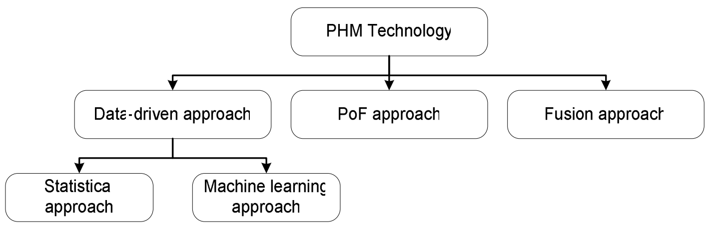

Figure 2: Technology approaches of PHM

3.1 Physics-of-Failure Approach

The physics of failure (PoF) approach to prognostics utilizes knowledge of a product's material properties within its life cycle loading conditions to identify relevant failure mechanisms and estimate its remaining useful life. A PoF-based prognostic permits the assessment and prediction of system reliability under its actual application conditions and also based on expected future use conditions [21]. The flowchart of PoF approach is shown in Fig. 3. In the PoF approach, the knowledge of the life cycle loading conditions, materials property and maintenance records on the system is used to identify the relevant failure modes, mechanisms and effects analysis (FMMEA). Failure models are used to calculate the damage accumulated in the system and the remaining useful life based on the monitored life cycle data obtained using sensor systems. Therefore, the PoF approach integrates sensor data with models that enable in-situ identification of the deviation or degradation of a system from an expected normal operating condition to predict reliability.

Degradation occurs even during periods when systems are not operational. The degradation in such conditions is due to the effect of the environment on the materials that make up the system. Since the PoF approach provides a remaining useful life (RUL) estimate taking into account degradation caused by environmental conditions, it is well suited for applications where the systems may remain in storage or in a non-operating state for significant durations.

One of the advantages of the PoF approach is that it provides a direct means to calculate the damage accumulation for a known failure mechanism, provided the historical loading conditions are known (*i.e.*, the system is continuously monitored). The remaining useful life of the system can be estimated based on the damage accumulated under cumulative loading conditions. Using the PoF approach, the component and the failure mechanisms that are the most critical to component or system reliability can be found. An understanding of the critical components and failure mechanisms can help in improving system design for reliability.

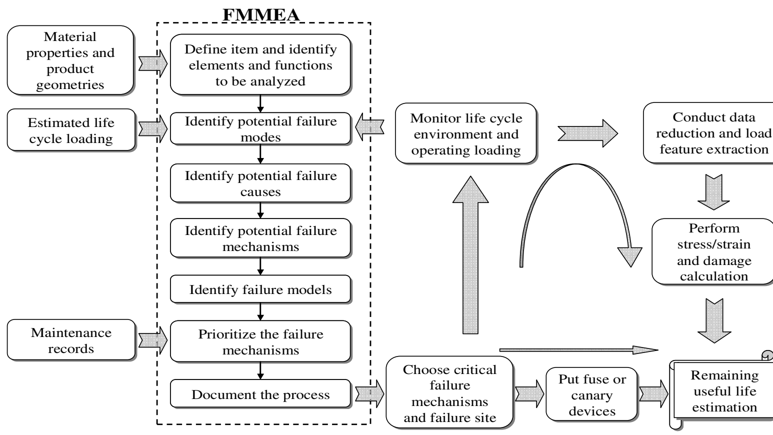

Figure 3: Flowchart of physics of failure (PoF) approach

3.2 Data-driven Approach

Data-driven approaches derive measures from system performance data using statistical and machine learning techniques to estimate the current and future state of health of a system [21]. In this approach, anomalies and trends or patterns are detected in data collected by continuous monitoring of the system. Environmental and operational loads are monitored along with the system parameters. The data collected can be analyzed using a variety of techniques depending on the type of data available. In further, fault prediction and remain useful life estimation can be carried on by feature trending and regression as shown in Fig. 4.

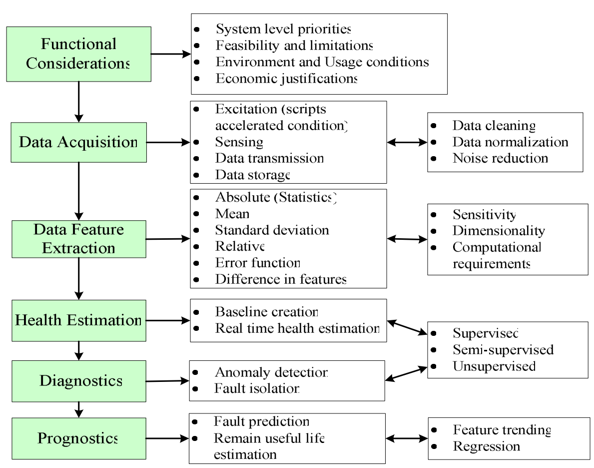

Figure 4: Diagram of Data-driven approach

The data-driven approach can be used in complex systems where PoF models are not available or when system specific knowledge is limited. The data-driven approach is advantageous as it does not require knowledge of the physics of the system. Therefore, this approach can be used to detect degradation in systems for which PoF models do not exist.

Data-driven approaches are capable of using parameter data collected around the time of occurrence of intermittent faults towards the prediction and assessment of system health. The data-driven techniques are hence used in critical applications where marginal deviations from expected behavior or intermittent behavior of the system are of concern and needs to be detected. The data-driven approach integrates information from separate sources for example, the hardware and software components of a system to improve the overall health assessment.

3.3 Fusion Prognostics Approach

Although the data-driven approach is useful for the analysis of complex systems, obtaining an accurate damage assessment is a challenge. At the same time, using the PoF approach enables damage assessment when the failure mechanisms acting in the system are identified. A fusion approach combining both the data driven and PoF approaches can be used to overcome the disadvantages of using just one technique as shown in Fig. 5. The approach presented enables the use of data-driven methods, for anomaly detection and isolation of the parameters that are significant contributors to the anomaly. The critical parameters identified therein can be used in the relevant PoF models to provide accurate damage assessment and hence provide an effective way of calculating the remaining useful life of the system as well as provide the capability of detecting the failure modes and mechanisms that are affecting the system in consideration.

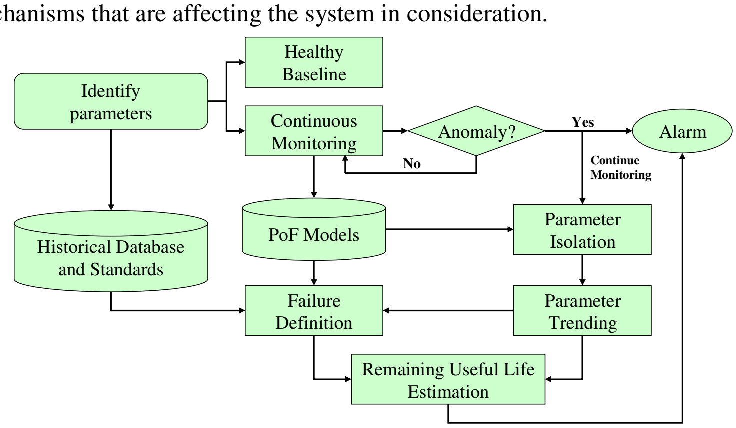

Figure 5: Flowchart of fusion approach

4. Integration of Lean Six Sigma and PHM

Electronic product such as computer is manufactured by putting together a logical combination of sub-assemblies, components, and parts that can fail by various failure mechanisms in the product's life-cycle environment. Though Lean Six Sigma management can identify and solve many manufacturing flow drawbacks, improve process and reduce variation, the anomalous behavior of computer products often prompts customer to return the product to a retailer or a manufacturer. At retailer's facility or at manufacturer's site the product often goes through extensive test. In many cases, these tests fail to regenerate the exact anomalies or faults and hence the discovery of root cause behind the anomalous behavior is difficult [22]. This fault examination process adds expenses to manufacturers in term of research investment, test equipment, personnel together with influence on the product reliability. Furthermore, the low reliability and potential drawbacks often lead to lots of cost on computer components stock and frequent complaints from customers, which become big problems for quick-updated computer industry.

In this section, an integration management strategy of Lean Six Sigma and PHM is suggested for computer manufacturing. On the one hand, Lean and Six Sigma are utilized to continuously improve management process, reduce waste and lift-up speed, maximum human subjective initiative; on the other hand, PHM is the implemented, crossing whole manufacturing processes to solve practical products design and qualification problems by advanced technology and methodology in detection, diagnostics and prognostics, the relations between each other and their integration advantages are introduced below.

4.1 Integration of Lean and Six Sigma

The lean approach is designed to improve the speed and efficiency of an organization by eliminating waste [23]. Six Sigma, on the other hand, is a continuous improvement plan that is intended to reduce variability. Both Lean manufacturing and Six Sigma require a process focus, and both include customer drivers, either to define what needs to be improved (Six Sigma) or to define value (which then drive process improvement).

However, Six Sigma focuses primarily on reducing variation, while Lean focuses on improving flow in the value stream and eliminating waste. Lean focuses on speed and flow, while Six Sigma focuses on quality (defects and process variation). Lean does not make a process stable or under statistical control. Six Sigma does not improve the flow of information and material through a process. Nor does Six Sigma reduce non-value-added time, movement, effort, inventory, and invested capital. Though Six Sigma is adept at identifying and eliminating defects, it does not address how to optimize the system by improving process flow. Lean methodologies, on the other hand, lack the statistical analysis required to achieve a truly “lean” system.

Lean Six Sigma (LSS) is a combination of two methodologies, lean and Six Sigma. LSS focus on continuous process improvement as shown in Fig. 6, which can result in better quality and the reduction in cost and complexity. The techniques and tools of lean manufacturing emphasize eliminating unneeded activity, to reduce lead time and lower total costs. Six Sigma techniques and tools focus on reducing variation in process and product, thereby eliminating rework, which allows faster delivery time and lower total costs. [24].

The combination aims to achieve total customer satisfaction and improved operational effectiveness and efficiency by removing waste and non-value added activities, decreasing defects, decreasing cycle time and increasing first pass yields, all resulting in a significant cost savings. An effective combination of lean and Six Sigma approaches includes the value-maximizing philosophy of Lean, underpinned by data-driven methods in decision making (from Six Sigma) focused on the customer (from Lean). All incentives and measures are reviewed (using Lean) to ensure global optimization and minimization of variation (from Six Sigma) would be a part of this.

The full benefits of Lean Six Sigma will only be realized when applied at both strategic and operational levels, with universal application only at the strategic level. Application at the operational level results only in cost reduction, whereas application at the strategic level results in wider benefits for the organization.

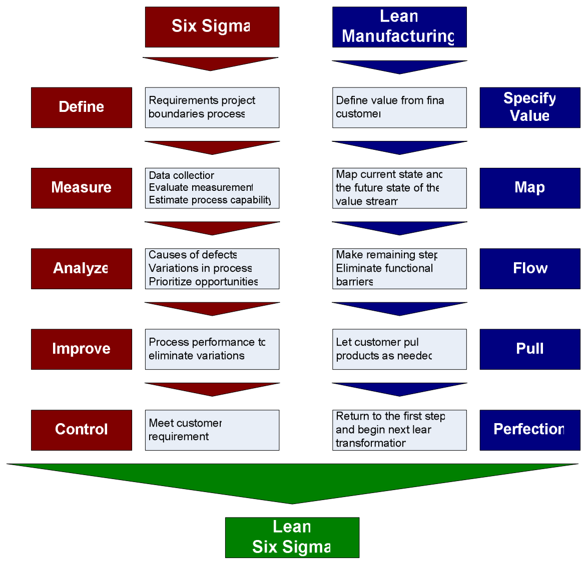

Figure 6: Flowchart of Lean Six Sigma

4.2 Integration of PHM and Lean Six Sigma

Comparing with Lean Six Sigma, PHM focuses on 'automatic' and 'predictive' management by employing advanced techniques of anomaly detection, fault diagnostics and prognostics. The relations between PHM and LSS are shown in Fig. 7. In addition, the benefits of LSS and PHM can be summarized in Table 5. The details are described following the computer manufacturing flow from design to production and qualification until warranty.

- Design stage

Improve products design: The use of PHM promises to enable significant and effective logistical support system infrastructure. Through investigation of failure modes, mechanisms and effects of designed samples, potential design drawbacks can be found prior to production in initial design stage, which will best help computer manufacturers optimize design with low cost and time. In addition, support engineers can get detailed data from health monitoring to uncover design mistakes and products improvements. By carrying PHM, such data base can be built up for future analysis and design improvement [25].

- Production and qualification stage

Discover intermittent failures and root cause analysis: During production and application, some failures are intermittent and difficult to predict using traditional prediction methods. They occur under specific environmental conditions and cure themselves under other conditions. This results in the supply and maintenance chains suffering "Cannot Duplicate" (CND) and "Retest OK" (RTOK) problems. CND and RTOK are problems that have persisted despite advances in built-in test and automatic test equipment. PHM can help with addressing these problems through accurate prognostics models and then reduce the false alarm rates. PHM permits the in-situ monitoring and collection of environmental and usage loads of computer systems by sensors during actual application conditions. The data collected in this way reflects the actual condition of the product. The technology and methodology of PHM can isolate critical parameters related with specific fault model, in further, can trace back to the root cause and make effective decision.

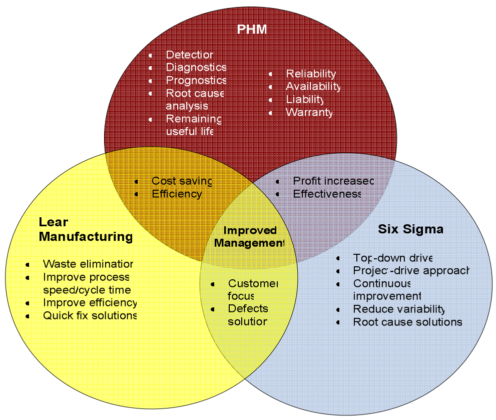

Figure 7: PHM and Lean Six Sigma: Integration, Relation and Benefits

Table 5: Benefits of Lean Six Sigma and PHM in Manufacturing

Lean Six Sigma	PHM
• Process flows improved	• Design
• Improved quality and reduced defects	• Redundancy
• Reduced waste	• Screening (burn-in)
• Improved productivity	• Qualification
• Reduced inventory	• Reliability
• Flexibility	• Intermittent Failures and Root Cause Analysis
• Safe work environment	
• Customer satisfaction improved	• Remaining Useful Life
• Employee satisfaction improved	• Inspection
• Defects reduced	• Spare Components
• Increased productivity	• Warranty
• Improved design	• Logistic Supply Chain
• ROI	• Return-on-Investment

Improve operation reliability: PHM uses sensors to conduct in-suit monitoring of environmental and usage loads, such as temperature, vibration, voltage and current. The loads in nature affect the actual life consumption and operational reliability. So the monitoring capability makes it possible to take active control actions regarding environmental and operational conditions to decrease life consumption and increase the service lifetime [26].

Increase screening accuracy: In testing flow, how to pick out defective samples from huge of products accurately and quickly is a facing challenge in mass computer manufacturing. PHM technology provides effective methodology by in-suit monitoring and early fault detection with clearly-know their products so that good product quality can be assured.

Improve qualification: With the rapid update of electronic and computer products, many of the traditional test and qualification standards are not working. Over the past 10 years, there have been an increasingly large number of products that have passed qualification tests but have failed in the field. The resulting costs of these failures have been in the hundreds of millions of dollars for many companies. PHM utilizes in-suit monitoring and parameters analysis methods effectively overcome errors of traditional handbook. Through carrying out failure models mechanisms and effects analysis (FMMEA) analysis, potential failure reasons are discovered. In addition, risk priority number (RPN) is calculated to represents the criticality of each failure mechanisms. Then specific accelerating lifecycle test can be conducted, which will reduce the traditional qualification time so as to catch up with the step of new computer products renovation.

- Warranty stage

Assess remaining useful life (RUL): PHM can promote the development of condition based maintenance (CBM) for important computer server or telecom systems, which provides benefits including minimizing unscheduled maintenance, eliminating redundant inspections and scheduled regular maintenance, improving maintenance effectiveness and reducing maintenance costs. PHM enable CBM realize the health degradation monitoring. Once an anomaly is detected, the fault will be isolated and assessment of the remaining useful life of the system can be carried out, which maximum extend normal operation cycle.

Enhancement of warranty confidence and improvement of service: A health management solution, when successfully implemented to computer manufacturing, may contribute for creating a positive image of reliability for the products due to the reduced maintenance costs and the other cited benefits. This is a potentially competitive differential that may lead to more computer product sales. As results, customers can get improved service, good warranty and availability from implement of PHM.

Reduction in cost of spare components: One of the most important aims of Lean Manufacturing is to realize "zero-spare" and "zero-defects". By the implement of PHM, the replacement of parts to be scheduled can be depended on the actual health of the computer systems, thus reducing the amount of spare parts required in stock. In addition, advance knowledge of the required number of spare parts allows them to be delivered "just in time", thus reducing stockholding/inventory levels. This leads to a substantial simplification of the supply chain for spares [27].

Optimize logistic supply chain: The role of PHM is to use a priori information about a system along with dynamic sensor measurements and to fuse these into a single estimate of the current damage state, and the future remaining lifetime of the system [28]. PHM can integrate reliable real time information in the decision making of the logistic model. PHM logistics is expected to optimize the performance measures and to improve the planning, scheduling and control of activities in the supply chain. The result can increase efficiency of Lean manufacturing and effectiveness of Six Sigma.

As final result, the PHM benefits listed above can effectively improve management performance in computer manufacturing. Furthermore, the generated economic merits of adopting PHM and Lean Six Sigma can be evaluated by Return on investment (ROI).

ROI measures the "return," the cost savings, profit, or cost avoidance that result from a given use of money. Types of ROI include investment return, cost savings (or cost avoidance), and profit growth [29]. The value obtained by integrating PHM and Lean Six Sigma can take the form of advanced warning of failures; increased availability through an extension of maintenance cycles and/or timely repair actions; lower life-cycle costs of equipment from reductions in inspection costs, downtime, inventory, and no-fault-founds; or improved system qualification, design, and logistical support of fielded and future systems.

5. Conclusions

This paper introduces an integrated management strategy for improving computer manufacturing efficiency, effectiveness and product reliability, which combines the advantages of PHM and Lean Six Sigma approaches to raise management performance and increase enterprise profits. The design process, common tool, available technology approaches and relation of PHM and Lean Six Sigma are explained; and integration benefits are discussed. The suggested management strategy can provide an opportunity for lowering computer manufacturing costs, improving products design and reliability, enhance qualification capability, maintenance decision making, and providing product usage feedback. As a result, better return on investment can be achieved.

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