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# Applying the principles of Six sigma to environmental management systems : lessons learned from a case study

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# APPLYING THE PRINCIPLES OF SIX SIGMA TO ENVIRONMENTAL MANAGEMENT SYSTEMS: LESSONS LEARNED FROM A CASE STUDY

by

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**Abstract**

The purpose of this thesis was to explore the potential benefits of applying the key principles of Six Sigma to Environmental Management Systems (EMSs). A survey of peer-reviewed literature on Six Sigma and EMSs was conducted. Based on the literature review, a conceptual framework for the application of Six Sigma to EMSs was developed. The application of the conceptual framework is demonstrated in a case study. The case study focused on a major Middle Eastern manufacturing company. The case study showed that there were numerous benefits to applying the principles of Six Sigma to EMSs. An approach based on the conceptual framework was successful in reducing waste in the case company's paint shop by 80%. Other benefits of applying the conceptual framework included cost reduction, decreased consumption of raw materials, decreased amount of waste water, longer resource life through reduced usage, reduced emissions, reduced energy consumption, and improved employee health and safety due to less exposure to harmful chemicals. The conceptual framework provides a basis for applying the principles of Six Sigma to EMSs. While there is a significant amount of research focusing on the integration of quality and environmental management, the application of Six Sigma in the context of environmental management has not been widely discussed. It is anticipated that the results will be of interest to practitioners and researchers in quality and environmental management.

## Acknowledgement

I would like to thank the case company's paint shop experts. I am greatly indebted to them for their contribution, support and dedication to this project, particularly the paint shop director for allowing me to use their company in order to complete the case study. Gratitude is also expressed to Dr. Searcy for all his support and constructive criticism through my graduate study.

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**List of Abbreviations**

BOM: Bill Of Material

C&E: Cause & Effect

CEN: Comité Européen de Normalisation (European Committee for Standardization)

CEPA: Canadian Environmental Protection Act

CTE: Critical To Environment

CTQ: Critical To Quality

CTS: Critical To Satisfaction

DFSS: Design For Six Sigma

DMAIC: Design, Measure, Analysis, Improve, Control

DMADV: Define, Measure, Analyze, Design, Verify

DOE: Design Of Experiments

EHS: Environment, Health & Safety

EMAS: Eco-Management and Audit Scheme

EMS: Environmental Management Systems

FMEA: Failure mode & Effect Analysis

G Chart: Geometric Chart

IMS: Integrated Management System

MBB: Master Black Belt

MSA: Measurement System Analysis

PDCA: Plan, Do, Check, Act

QC: Quality Control

QFD: Quality Function Deployment

QMS: Quality Management System

RPN: Risk Priority Number

SIPOC: Supplier, Input, Process, Output, Customer

SPC: Statistical Process Control

VOC: Voice Of Customer

WTO: World Trade Organization

# 1. Introduction

## *1.1. Overview*

Environmental health has largely been ignored in favour of economic development since the beginning of the Industrial Revolution (Calia *et al.*, 2009). Such a lack of ecological consciousness has helped contribute to severe pollution around the world. Industrial activity is a primary source of pollution. Many organizations around the world have recognized this and have initiated a number of programs to reduce the environmental impact of their operations. As several authors have noted, the management of environmental impacts at the organizational level requires implementation of a strong environmental management system (EMS) to pursue sustainable production patterns (Hillary, 1997). However, to be successful in the long term, the EMS must provide organizations with economic, as well as environmental, benefits.

The question is whether an EMS could achieve success in solving both environmental issues and cost reduction. However, a limitation of existing EMSs is that they focus on the identification and description of requirements and components, but have not addressed how to put them together to reach a green industry in a cost effective manner (Kirkland & Dixson, 1999). Therefore, there is a need for a systematic, consistent and reliable method to implement an EMS in an organizational context. In order to resolve this challenge, it is proposed that the integration of EMS and quality methods could be effective.

Over the past several decades, the scope of quality management has expanded from a focus on customer satisfaction to comprehensively addressing business excellence. One of the key drivers of this evolution has been the change in how customers are defined (Klefsjo *et al.*, 2008). Juran (1988) defines a customer as anyone who is affected by the product or the production process. Building on this definition, Klefsjo *et al.* (2008) suggested that the natural environment and future generations could be considered as customers. This view is supported by the increasing body of literature that focuses on the relationship between quality, environmental management, and sustainability (Karapetrovic *et al.,* 1998; Mangelsdorf, 1999; Smith, 2001; Karapetrovic, 2002; Leavoy & Phyper, 2010; Leopoulos, 2010; Tari *et al*., 2010).

As the literature highlights, there are many parallels between quality and environmental management systems. For example, both emphasize the implementation of proactive, preventative systems that address key issues at the level of product and process design (Tari & Molina-Azorin, 2010). Both will require the development of a business case, performance measures, and ongoing assessment. As a final illustrative example, both also emphasize the importance of involving the whole organization in addressing key issues. The similarities between quality and environmental management offer many opportunities. For example, as several authors have noted, the similarities between quality and environmental management can help facilitate the integration of management systems established to address these issues (Culley, 1998; Karapetrovic *et al*., 1998; Block *et al.*, 1999; Asif *et al*., 2010; Tari *et al*., 2010). Moreover, the similarities indicate that there are opportunities to explore the application of proven quality management tools in the context of environmental management (Block & Marash, 1999).

### *1.2. Problem statement*

The purpose of this study is to explore the application of the principles of Six Sigma to environmental management systems (EMSs). Six Sigma is a quality management tool that focuses on linking the tactical and strategic levels of a company. An overriding emphasis is on reducing product variation in order to reduce defects (Raisinghani *et al.*, 2005; Klefsjo *et al.,* 2008). While there are many definitions of an EMS, they are fundamentally "a problem identification and problem solving tool that provides organizations with a method to systematically manage their environmental activities, products and services and helps to achieve their environmental obligations and performance goals" (European Commission, 2010). With that in mind, this study aims to answer the core question: "Does Six Sigma provide a systematic and applicable method to implement an EMS?"

In order to answer the core question, a conceptual framework was developed to structure thinking and discussion about the integration of Six Sigma Principles with an EMS. To demonstrate the application of the framework, an in-depth case study was conducted with a major Middle Eastern manufacturing company. An in-depth case study was an appropriate approach to addressing the research question given the exploratory nature of the research. The case study specifically focused on the paint shop of the case company. The case study also provided the basis for reflecting on the implications of the conceptual framework for other companies.

It is important to acknowledge that there were some limitations to the research. As in any single case study, there are questions regarding the generalizability of the research. There were also limitations in the scope of the application of Six Sigma in an EMS context. Six Sigma utilizes many established quality management tools. Many of these tools, such as, QFD (Quality Function Deployment), SPC (Statistical Process Control), MSA (Measuring System Analysis), hypothesis tests, regression analysis, and DOE (Design Of Experiments) are also used outside of Six Sigma projects. It is therefore important to note that the study doesn't cover all of the statistical tools which have been used in Six Sigma. The study also does not address the motivators that encourage staff in an organization to participate in EMS/Six Sigma projects.

### *1.3. Organization of the thesis*

The remainder of the thesis is structured as follows. First, a review of literature on Six Sigma, EMSs and integration strategies is provided. This provides some context for the next section, which focuses on an original conceptual framework that clarifies how Six Sigma can be applied in the context of an EMS. To demonstrate the applicability of the framework, the following section presents an in-depth case study that describes the improvement of environmental efficiency and waste reduction in a manufacturing company through the application of Six Sigma techniques. Finally, the thesis finishes with a conclusion and recommendations for further research.

## 2. Literature review

This section contains a summary of the literature on EMSs and Six Sigma. A brief discussion of other quality methods that may be applied in the design of an EMS is also provided. The potential synergies between Six Sigma and EMSs and the possible applications of an integrated management systems (IMS) approach are then discussed. The section concludes with a brief discussion of the motivations for the research.

### *2.1. Environmental Management Systems*

With the increasing worldwide concern about the environment, international agreements have been reached and national environmental laws have been created to encourage environmental preservation. For example in the Canadian context, key pieces of national legislation include the Canadian Environmental Protection Act (CEPA), the Fisheries Act, and the Canadian Environmental Assessment Act. There are also environmental laws at the provincial level. For instance, selected environmental and related legislation in Ontario includes the Waste Management Act, Green Energy and Economy Act, Environmental Bill of Rights, and Conservation Land Act (Greenbaum & Wellington, 2009). To fulfill mandates of regulations and reach environmental targets, there is pressure on organizations to manage their actual or potential impacts on the environment.

#### *2.1.1. Definition and implementation*

There are many definitions of EMS in the published literature. Table 1 illustrates a sample of the published definitions. The table highlights that each author differs in how they define EMS, but there are some similarities as well. For instance, regardless of the targeted organization, which could be a manufacturing company, government agency, or other organization, EMSs provide a framework for organizations to use in order to determine, monitor and manage the impacts of their activities on the environment and achieve their environmental objectives. As depicted in Table 1, environmental objectives may vary from organization to organization. Depending on the function and/or mission of the organization, the target could be pollution prevention, waste reduction, and/or increasing efficiency, among others. Another key point is the relation between EMS, ISO 14000 and EMAS (Eco-Management and Audit Scheme). EMAS and ISO 14000 are two formal, widely-applicable EMSs. While ISO 14000 is the most widely-applied voluntary EMS standard in the world, EMAS is a voluntary standard that is primarily applied in the European Union. In both systems there is a need for an organization to formalise its policies, procedures and practices that control environmental aspects through a structured management system. However, EMAS goes beyond the requirements in ISO 14000 in several respects, such as in requiring an environmental statement, which publicly reports the environmental performance of a site (Hillary, 2004).

Table 1: EMS definitions

| **Definition** | **Author/ Source** |
| --- | --- |
| An EMS is an institutionalized system designed for the management of people and institutions that impact the environment | Krut & Gleckman (1998) |
| An EMS is a well-defined management structure designed to address the impacts of an organization's activities, products, and services on the environment | Kinsella & McCully (2005) |
| An EMS is a formal set of procedures and policies that define how a business will manage its potential impact on the natural environment and on the health and welfare of the people who depend on it | Darnall *et al*. (2000) |

| **Definition** | **Author/ Source** |
|---|---|
| The purpose of an EMS is to develop, implement, manage, coordinate and monitor corporate environmental activities to achieve two goals: compliance and waste reduction | Sayre (1996) |
| An EMS involves the formal system and database which integrates procedures and processes for the training of personnel, monitoring, summarizing, and reporting of specialized environmental performance information to internal and external stakeholders of the firm | Melnyk *et al*., (2003) |
| An EMS is a set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency | US EPA (2011) |
| An EMS will assist organizations in managing how their activities affect the environment. An EMS enables companies, federal and state agencies, and other organizations to establish and assess the effectiveness of procedures to set environmental policy and objectives, achieve compliance | Schoffman & Tordini (1999) |
| EMSs are the foundation of the ISO 14000 group of international environmental management standards. ISO 14000 is a family of standards intended to support environmental protection and prevention pollution in balance with socioeconomic needs | Federal Facilities Council Report (1999) |
| An EMS is the part of the overall management system that includes organizational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, implementing, achieving, reviewing and maintaining the environmental policy | ISO 14001 (2004) |
| EMAS is a voluntary initiative established by the European Commission and intended to improve companies' environmental performance. Its aim is to recognise and reward those organisations that go beyond minimum legal compliance and continuously improve their environmental performance | Wenk (2008) |

A common approach for implementing EMSs is the Deming Cycle (Schoffman & Tordini, 1999). This cycle is known as PDCA (Plan, Do, Check, Act). The model recognizes that an EMS is a process of continual improvement in which an organization is constantly reviewing and revising the system. This is a model that can be used by a wide range of organizations from manufacturing facilities to service industries and government agencies. Table 2 shows the application of the Deming cycle to EMS implementation based on Maud's (2007) point of view.

Table 2: PDCA cycle in EMS

| Phase | Key Elements | | |
|---|---|---|---|
| **Plan** | Assessment of current situation and interactions with environment | Establishment of environmental policies | Define goals and objectives |
| **Do** | Training should be provided for staff | Implementation of environmental policies via a detailed plan & quick reactivity in critical situations | Documentation of all activities |
| **Check** | Process monitoring of actual performance | Receiving feedback | Comparing achievements with objectives |
| **Act** | Corrective actions for deviations | Management review to analyse the effectiveness of the system | Possible revisions in environmental policies and programs |

*2.1.2. The ISO 14000 standards*

As noted above, one of the most well-known EMS frameworks is the ISO 14000 series of standards. ISO 14000 refers to a family of voluntary standards and guidelines to help organizations address environmental issues and includes standards for environmental management systems, environmental auditing, environmental labelling, performance evaluation and life-cycle assessment. The main document of the ISO 14000 series is ISO 14001, which is an international voluntary standard describing the specific requirements for an EMS. ISO 14001 was originally released in 1996. It was updated in 2004, but the differences between the two versions are minor and do not change how the environmental management system is implemented. Changes in ISO 14001:2004 were made to clarify ambiguities of the old standard. The ISO 14001:2004 has a clearer focus on significant environmental aspects and outcomes rather than the EMS system itself. Since ISO 14001 is auditable, organizations are able to receive certification or registration (Kirkland & Dixson, 1999). However, the standard only provides general requirements for managing environmental performance (Madu, 2007). Table 3 provides a summary of these requirements (Dodds, 1997). As is shown in Table 3, implementation of ISO 14001 may be achieved through the PDCA cycle.

Table 3: ISO 14001 requirements (Dodds, 1997)

| Phase | Requirement | Description |
|---|---|---|
| **Plan** | Environmental Policy | Develop a statement of the organization's commitment to the environment |
| | Environmental Aspects and Impacts | Identify environmental effects of activities |
| | Legal Requirements | Identify and ensure access to relevant laws and regulations |
| | Objectives and Targets and Environmental Management Program | Set environmental goals and prepare proper plans to achieve goals |
| **Do** | Structure and Responsibility | Establish roles and responsibilities |
| | Training, Awareness and Competence | Ensure that employees are aware and capable of their environmental responsibilities |
| | Communication | Develop processes for internal and external communication on environmental management issues |
| | EMS Documentation | Maintain information about the EMS and related documents |
| | Document Control | Effective management of procedures and other documents |
| | Operational Control | Identify, plan and manage the organization's operations and activities according to objectives |
| | Emergency Preparedness and Response | Reactivity procedure for preventing and responding to potential emergencies |
| **Check** | Monitoring and Measuring | Monitor key activities and track performance |
| | Evaluation of Compliance | Develop a procedure to periodically evaluate compliance with requirements |
| **Corrective Action** | Corrective and Preventive Action | Identify and correct problems and prevent recurrences |
| | Records | Keep adequate records of EMS performance |
| | EMS Audit | Periodically verify that the EMS is effective and achieving objectives and targets |
| | Management Review | Review the EMS |

*2.1.3. Benefits and limitations*

Many corporations around the world are adopting EMSs and registering them to an international standard. There are many benefits that motivate organizations to adopt such a system. Several authors have highlighted that these benefits include improving environmental performance, pollution prevention and conserving resources, risk mitigation, attracting new customers and markets, improving employee awareness of environmental issues and responsibilities, improving compliance with legislative requirements, efficiency increase, better image in public, and recognition for incentive programs (Rondinelli & Vastag, 2000; Morrow & Rondinellli, 2002; Roy *et al*., 2001). Although, there are some advantages that motivate organizations to adopt EMS, not all of the expectations in all areas of concern could be met by implementing an EMS.

Further research notes that developing and implementing an EMS may have some challenges, including: an investment of internal resources (staff/employee time), costs associated with training of personnel, hiring consulting assistance, technical resources to analyze environmental impacts and improvement options, and lack of employee motivation and involvement (Darnall *et al*., 2000; Melnyk *et al*., 2003; Nishitani, 2010). These obstacles are more challenging in medium and small sized companies, due to limited available resources (Veldt, 1997; Hillary, 2004).

There are number of broadly applicable limitations associated with the ISO 14000 EMS framework. The general requirements constitute a system which stresses environmental management standards more than performance concerns (Madu, 2007). The wide variation permitted by the standard results in the lack of a common method to implement the EMS and put all elements together. The lack of detailed guidance in the standard on implementation can result in ambiguous procedures that do not clearly help to increase efficiency (Poder, 2006; Pojasj, 2008). Additionally, while there is a strong emphasis in the standard on management commitment, there is relatively little emphasis on employee involvement (Yarnell, 1999). Finally, ISO 14001 is often sold internally on the basis of cost benefits that are difficult to measure and it has been argued that the link between EMS performance and business performance is difficult to make (Petreoni, 2001). Additional discussions on potential improvements to ISO 14001 are provided in Jorgensen (2008).

### *2.2. Six Sigma key principles*

Six Sigma is fundamentally a process improvement methodology. Over a period of time it has evolved into a management strategy which can be used to run an organization in an environmentally friendly manner (Kumar *et al.* 2006). Six Sigma is a customer-focused continuous improvement concept to achieve near perfect processes, products and services. This, in turn, can lead to waste reduction and greener industries. In other words, Six Sigma as a quality improvement approach is aimed at optimising processes while reducing defects and costs as its key principles.

#### *2.2.1. Definition and methodologies*

Six Sigma was developed by Motorola in the 1990s as a set of statistical tools for systematically analyzing processes to reduce process variation. Motorola describes three different concepts for Six Sigma: metric, methodology and management system; the last of which includes all three levels at the same time (Motorola, 2010).

Six Sigma as a metric refers to the statistical understanding of Six Sigma or the number of standard deviations away from the mean. The target of the metric concept is 3.4 measurements outside of six standard deviations from the mean in every one million opportunities (Raisinghani *et al*., 2005). There is a standard conversion table (Appendix 1) which is known as *Z to DPMO* (defects per million opportunities) *conversion table* that translates Sigma level into a corresponding number of defects. Appendix 1 provides detailed insight of the statistical meaning of Six Sigma.

As a Methodology, Six Sigma is a business improvement method that has two common forms inspired by the Deming cycle: DMAIC and DFSS. Define, Measure, Analyse, Improve, Control (DMAIC) is the most well-known Six Sigma methodology. Design for Six Sigma (DFSS), also known as DMADV (Define, Measure, Analyze, Design, and Verify), is used for projects aimed at creating new product or process designs (Williams *et al*., 2001; Cronemyr, 2007; EPA, 2009). Details on the methodologies are presented in Table 4.

Table 4: DMADV & DMAIC key requirements

| **Methodology** | **Phase** | **Activities** |
|---|---|---|
| **DMADV (Cronemyr (2007)** | Define | Defining the design goals based on customer needs and the corporation strategy |
| | Measure | Measurement and identification of critical characteristics, product and production process capability |
| | Analysis | Analysis in order to develop and design alternatives, and evaluate design capability to select the best design |
| | Design | Designing the details, optimize the design, and plan for design verification |
| | Verify | Design verification, arrange pilot models, and implement in the production process |
| **DMAIC (Williams *et al*., 2001)** | Define | Defining the problem or improvement opportunity versus technical and/or business requirements, goal setting and defining the project boundaries |
| | Measure | Measuring the current process or product performance, defining the input/output variables of the process, and validating the measurement system |

| Methodology | Phase | Activities |
|---|---|---|
| | Analysis | Searching for key factors that have the biggest impact on performance and determine the root causes of problems |
| | Improve | The improvement activities should be identified to optimize the outputs and eliminate/ reduce defects and variation |
| | Control | Implementing and monitoring the solution to make sure the achievements are sustained |

The Six Sigma approach as a management system is all about helping managers identify the unknowns in their organization and take action to reduce errors and rework. Six Sigma translates that knowledge into opportunities for business growth (Brue, 2002). To achieve improvements and results that are sustainable over time, Motorola utilized Six Sigma as a management structure. "When Six Sigma is practiced as a management system, it is a high performance system for executing business strategy" (Motorola, 2010). In other words, Six Sigma measures success based on technical requirements established by customer and business targets.

Academicians started showing interest in Six Sigma from about 2000 onwards (Prabhushankar & Devadasan, 2008). There are many discrepancies in the literature on Six Sigma and researchers and practitioners have defined Six Sigma in different ways. Prabhushankar (2008) categorizes these definitions in three groups: statistics-based, management-oriented and holistic (both statistics-based and management-oriented definitions). In statistics-based definitions, the emphasis is more on the application of statistical techniques to reduce the process variation in reaching a performance level of 3.4 DPMO. Prabhushankar (2008) asserts "these definitions approach Six Sigma from statistical, probabilistic and quantitative points of view". He adds "management-oriented definitions view Six Sigma as a philosophy and quality management system (QMS) to reduce variation, drive out wastes and meet the customer expectations through changing the culture of the organisation". Prabhushankar (2008) concludes, holistic definitions describe Six Sigma as a quality management system and philosophy, while also emphasising the use of statistical and other problem-solving approaches. Table 5 summarizes some of the definitions that are available in the literature that fall under these categories:

Table 5: Six Sigma definitions

| Category | Definition | Author/Source |
|---|---|---|
| **Statistics-based** | Six Sigma is a statistical measure of the performance of a process or product which is used as a quality control mechanism, that seeks to reduce defects or variations in a process to 3.4 per million opportunities thereby optimizing output and increasing customer satisfaction | Kumi & Morrow (2006) |
| | Six Sigma is a statistically-based quality improvement program, helps to improve business processes by reducing waste, by reducing costs resulting from poor quality and by improving the levels of efficiency and effectiveness of the processes | Hensley & Dobie (2005) |
| | Six Sigma is a disciplined method of using extremely rigorous data gathering and statistical analysis to pinpoint sources of errors and ways of eliminating them | Harry & Schroeder (2000) |
| **Management-oriented** | Six Sigma is a business improvement strategy that seeks to find and eliminate causes of defects or mistakes in business processes by focusing on outputs that are of critical importance to customers | Snee (2004) |
| | Six Sigma is a break through strategy that combines improved metrics and a new management philosophy to significantly reduce defects, thereby strengthening a firm's market position and improving the profit line | Hensley & Dobie (2005) |
| | Six Sigma is a business improvement strategy that is used to improve profitability, drive out waste, reduce quality costs and improve the effectiveness and efficiency of all operations that meet or even exceed customers' needs and expectations | Bañuelas & Antony (2002) |
| **Holistic** | Six Sigma is an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in the customer defined defect rates | Bhuiyan & Baghel (2005) |

| Category | Definition | Author/Source |
|---|---|---|
| | Six Sigma is a statistical term that roughly translates to only 3.4 defects or failures or mistakes/errors per million opportunities. The Six Sigma approach emphasizes in understanding and documenting the business process, developing metrics and hard data, and reducing process variation | Makrymichalos *et al*. (2005) |
| | Six Sigma is a comprehensive program for managing a business that emphasizes an intelligent blending of the wisdom of the organization with proven statistical techniques to improve both the efficiency and effectiveness of the organization in meeting customer needs | Maleyeff & Krayenvenger (2004) |

### *2.2.2. Benefits and limitations*

Six Sigma has gained attention in the business field due to its potential financial impact and its potential to improve levels of customer satisfaction. Several authors have investigated the key benefits of Six Sigma. Among the benefits cited in the literature are top management support and leadership, focus on a disciplined approach for process improvement, combining human elements and process elements or combining the right projects with the right people and tools, distribution of responsibilities and authorities in a structured way by using the *Belt* system, using several selected efficient tools among quality methods, innovative ideas and solutions from brainstorming sessions, and placing value on decision making based on measurable indicators and data (Antony, 2004; Basu, 2004; Snee, 2004; Jit Singh & Khanduja, 2010).

While some companies have seen tremendous success (Motorola, General Electric, Sony, Honda, Ford, etc.) others, like Clarke American, have abandoned the methodology or found it too overwhelming to support (Szeto & Tsang, 2005). According to the published literature, some of the explanations for unsuccessful results include considerable effort and resources for staff training, difficulties in gathering sufficient data, non-normal situations are not addressed properly, and lack of technical knowledge (Klefsjo *et al*., 2001; Antony, 2004; Raisinghani, *et al*., 2005).

*2.3. Integrated Management Systems*

Asif *et al*. (2010) explained that in recent years the number of management systems and standards have increased to systematically address various stakeholder requirements. The "International Organization for Standardization (ISO) has developed standards for some of the management systems, including quality, environment, customer satisfaction, and auditing, among others" (Asif *et al*., 2010). Quality and environmental aspects are among the most popular standardized functions and the respective function-specific management system standards are quality with ISO 9001: 2000 and environment with ISO 14001: 2004 (Karapetrovic and Casadesu´ s, 2009). Research has shown that maximum benefits from management systems are obtained when they are integrated into one management system (Zutshi and Sohal, 2005; Jorgensen *et al*., 2006; Karapetrovic, 2008). The publication of the ISO 14000 series of standards seeks to strengthen the link between organizations that use these standards; organizations such as the European Committee for Standardization (CEN), World Trade Organization (WTO), and the ISO/TC 176 in quality management systems. Therefore, globalization of trade and harmonization of standards led businesses to identify ways to manage the environmental impacts of their activities. In this competitive market, industry managers have to define environmental targets, develop management systems and monitor their results.  Since, a business wants the most efficient management system possible, integration of its internal systems is essential (Wolfe, 1997).

As Figure 1 demonstrates, an integrated management system (IMS) coordinates an organization's procedures, systems, and processes in the quality, environmental, and health & safety domains within one framework, in a manner consistent with the organization's vision, mission, and objectives (Leavoy & Phyper, 2010; Pojasek, 2006). In particular, both quality and environmental management systems share similar roots (for example, all are rooted in a cycle of continual improvement) and objectives. Many authors have noted that these similarities provide a basis for developing an IMS (Karapetrovic & Willborn, 1998; Leavoy & Phyper, 2010; Tari *et al*. 2010).

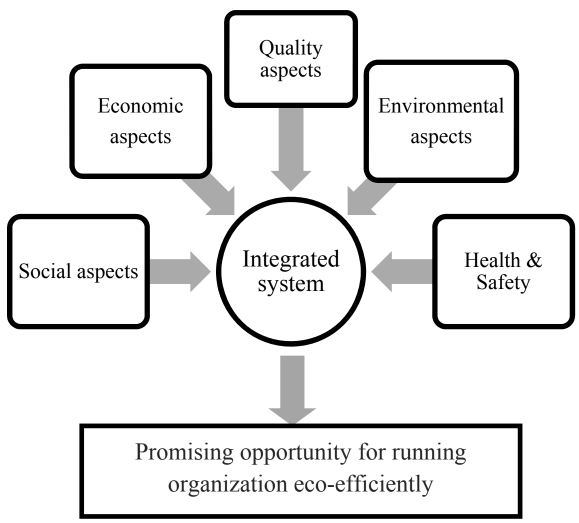



Figure 1: Stakeholder requirements

*2.3.1. Definition*

An integrated system is a full, single system in which quality and environmental issues are taken into account at the same time. In such a system both systems lose their independence (Tari *et al*., 2010). IMS has been discussed by many authors. According to Wilkinson & Dale (1999) the need for clear definitions is always useful in establishing good communications; in particular, when the research area is an emerging one, the need becomes essential. Wilkinson & Dale provided a comprehensive summary of IMS definitions available at the time of their publication. Quoting from Garvin (1991), they noted that "integration refers to the degree of alignment or harmony in an organisation, integration is all about whether different departments and levels speak the same language and are tuned to the same wavelength". The other quoted definition of integration that they provided was given by MacGregor Associates (1996) where integration was seen as "a single top level management core standard with optional modular supporting standards covering specific requirements". MacGregor continues, "Integration is appropriate for parallel management system standards specific to an individual discipline, but with a high degree of commonality of structure and content". According to the British Standards Institution (1998), also quoted in Wilkinson & Dale (1999), "integration means that common elements of the standards can be implemented in a shared manner, in whole or in part, by organisations without unnecessary duplication or the imposition of conflicting requirements". Building on these definitions of integration, one possible definition of an IMS is "set of interconnected processes that share a pool of human, information, material, infrastructure, and financial resources in order to achieve a composite of goals related to the satisfaction of a variety of stakeholders" (Karapetrovic and Willborm, 1998). There is a growing interest in the integration of management systems. The benefits and limitations associated with IMS are discussed in the next sub-section.

### *2.3.2. Benefits and limitations*

There are many benefits of integrating management systems. The published benefits of employing an IMS approach include: cost & waste reduction, time efficiency, improved procedures, integrated audit systems (which could reduce multiple audits), improved community image due to differentiation that arose from improved environmental and quality performance, forming a cross-functional team could potentially decrease inter-functional conflicts and increase staff motivation, joint training, and improvement in communication between all organizational levels (Wilkinson & Dale, 1999; Karapetrovic, 2002; Pojasek, 2008; Tari *et al*., 2010).

However, this path may not be as smooth as expected. While the potential benefits of IMS are substantial, integration is not without its challenges. Some of the key challenges, difficulties and concerns in establishing such a system cited in the literature include: in a diverse business function, sometimes it is challenging to define a common element as an improvement opportunity (system incompatibility); expected loss of unique identities of function, an IMS may face opposition and rejection of integration efforts by quality, environmental and safety personnel due to fear of downsizing; time consuming and high cost audits if audit standards are not integrated; there are different customers and stakeholders for each management system; for example, QMS customers are either internal such as the other departments or external like consumers, while EMS customers are the general public, local communities and government; different operational management methods lead to an intense attempt to harmonize management methods, for instance EMS is based on project management, in contrast to QMS which is process-oriented (Karapetrovic, 2002; Matias & Coelho, 2002; Asif *et al*., 2009; Leavoy & Phyper, 2010). However, integration of EMS and Six Sigma through a project-based methodology could help overcome these shortcomings.

### *2.3.3. Strategies*

Several papers have also focused on different methodological approaches to IMS. These include approaches based on the sequence of integration (Karapetrovic & Willborn, 1998), the systems approach to integration (Block & Marash, 1999; Karapetrovic, 2002), integration at various hierarchical levels (Jorgensen *et al.* 2006; Karapetrovic, 2003), integration through a total quality approach (Wilkinson and Dale, 2001; Andersson *et al.*, 2006), and enhancing the management system standards (Karapetrovic, 2002; Rocha *et al.*, 2007). As underlined in the literature, several levels of integration are possible, ranging from two distinct management systems which are aligned, to a complete integration of systems into a single and comprehensive management system. In this step, each specific system loses its identity and become merged into a common system (Karapetrovic, 1998, 2002, 2003; Tari *et al.*, 2010).

In order to provide a basis for developing a conceptual framework for applying the principles of Six Sigma to EMSs, it is necessary to further explore the two selected integration strategies, i.e. the systems approach to integration and the sequence of integration. The systems approach looks at the problem as a whole, rather than as independent parts. In this method, a system is defined as a composition of interlinked processes that share the same resources and that are all harmonically directed toward reaching targets and objectives (Karapetrovic, 2002). This may lead to a paradigm shift in environmental management as a way of doing business. When systems are integrated based on a systems approach, it is unlikely that an EMS will be viewed as a responsibility of the environmental department from the operational level point of view. Furthermore, an integrated system could create an umbrella that covers all aspects of business, from product quality and customer services to maintenance operations in a safe and environmentally friendly manner (Block & Marash, 1999). These advantages may explain why most of the published work concentrates on the systems approach. Since Six Sigma itself is a systematic approach that emphasizes the support of top managers with the collaboration of the tactical and operational levels, the integration of Six Sigma and EMS strategies based on a systems approach can provide financial, environmental, social benefits and present a promising opportunity for sustainable improvement.

Karapetrovic and Willborn (1998) explain possible sequential strategies for integration, depending on which systems are already in place, and which are required. The first approach is to establish a QMS and subsequently an EMS. Since a large number of companies have a QMS in place, this could be considered the most common approach. This strategy may include integrating environmental records documentation and control with quality control procedures and methods and performing integrated audits. The second strategy is to establish an EMS and subsequently a QMS, particularly for organizations under strong environmental regulations and public pressure. The third strategy is to establish the EMS and QMS simultaneously with an emphasis on a fully integrated system. Integration could begin with common elements such as policy, documentation, design control, management review, internal audits, training, etc. and follow by linking operational/function specific modules which need more specialized and independent treatment for each function which consist of: measurements, testing, corrective and preventive actions, process control, etc. (Karapetrovic and Willborn, 1998).

### *2.4. Quality methods for EMS design*

The world of quality management has been witness to significant changes in the last decade. These changes are mainly due to the expansion of the quality role in achieving business excellence (Karapetrovic & Willborn, 1998). To be competitive, it is not only enough to meet customer needs, but companies must also understand and fulfill economic, quality, health and safety, environmental and social responsibility expectations. In this mix, coordination is a real challenge. Although these expectations belong to different areas of concern, they can be addressed in a similar fashion. In particular, to avoid duplication of effort and to use best practices, integrated systems could be considered as one way to fulfill those demands and coordinate all related areas of concern to take quality and environmental issues into account at the same time (Tari & Molina-Azorin, 2010). To provide a clear picture of the primary quality methods that are used in EMS design and present their advantages and disadvantages, the relevant methods are summarized and compared in Table 6.

Table 6: Quality management system for EMS design

<table>
<tr><th rowspan="2">Method</th><th rowspan="2">Description</th><th colspan="3">Implications in environmental performance</th></tr>
<tr><th colspan="2">Pros</th><th>Cons</th></tr>
<tr><td rowspan="3">Total Production Maintenance (TPM) (EPA, 2010)</td><td rowspan="3">Properly maintaining equipment and systems helps reduce defects</td><td colspan="2">Decrease number of scrapped products</td><td rowspan="3">TPM can result in increased use of cleaning supplies, which may contain solvents or chemicals that can result in air emissions or increased waste generation</td></tr>
<tr><td colspan="2">Decrease the raw materials & energy consumption due to waste and rework</td></tr>
<tr><td colspan="2">Decrease the number and severity of equipment spills and leaks which typically reduces the solid and hazardous wastes</td></tr>
<tr><td>Kaizen (Soltero & Waldrip, 2002)</td><td>Focus on work method simplification to increase work flow</td><td colspan="2">Continual improvement method that uncovers and eliminates hidden wastes by optimizing existing processes</td><td>May ignore environmental risks associated with new processes because of failure to merge environmental considerations into Kaizen</td></tr>
<tr><td rowspan="3">Just In Time (JIT) (EPA, 2010)</td><td rowspan="3">Enable firm to produce products that customer want, when they want in correct amount</td><td>Decrease energy consumption and emission in production process...</td><td rowspan="3">... by eliminating overproduct -ion which affects environmen -t in these three ways</td><td>Increase transport trips to provide parts and materials (traffic congestion, fuel consumption and emissions)</td></tr>
<tr><td>Decreases the number of scrapped or discarded products as waste...</td><td>In market fluctuations, production is unpredictable therefore JIT is not successful in waste reduction</td></tr>
<tr><td>Decrease the amount of raw material...</td><td>If the system is not part of chain management, push inventory carrying activities up to the end</td></tr>
</table>

<table>
<tr><th rowspan="2">Method</th><th rowspan="2">Description</th><th colspan="3">Implications in environmental performance</th></tr>
<tr><th colspan="2">Pros</th><th>Cons</th></tr>
<tr><td rowspan="2">Production Preparation Process (3P) (EPA, 2010)</td><td rowspan="2">Focus on designing processes that require the least time, material, and resources that can improve performance and eliminate waste</td><td colspan="2">Reduce complexity of production processes, especially environmentally sensitive processes</td><td rowspan="2">Failure to consider risk and pollution with new processes which may result in worse environmental impacts</td></tr>
<tr><td colspan="2">Results in correctly sized equipment which take up less space, and reduces the environmental impacts associated with that space (heating, cooling, lighting, cleaning and maintenance materials, building materials, land use)</td></tr>
<tr><td rowspan="4">Six Sigma (EPA, 2010)</td><td rowspan="4">Set of statistical tools which help to reduce process variations and product defects</td><td rowspan="3">Eliminate waste in three ways...</td><td>...decrease the number of scrapped products</td><td>Effectiveness can be decreased due to Lack of technical capacity to implement Six Sigma tools</td></tr>
<tr><td>...reduce consumption of raw material, energy and resources</td><td rowspan="3">Can increase unexpected waste in case of inappropriate application</td></tr>
<tr><td>...decrease Rework</td></tr>
<tr><td colspan="2">Incorporate cost attributes and calculate the amount of cost reduction</td></tr>
</table>

There is one common element among all systems: “commitment”. In other words, one of the keys to success in all of these methods is commitment from top management (Andersson *et al*. 2006). The key difference is that in some methods, commitment is hierarchical, whereas in the other methods, like Six Sigma, everyone has a responsibility for environmental management. Six Sigma has several advantages over the other quality methods. For example, cost attributes are incorporated into the system and eventually all team members could be rewarded with a portion of the saved money. This may encourage them to contribute their efforts in future projects due to new organizational capacity for new projects. This new capacity is the result of the ability to implement an organizational culture for project management by defining an organizational structure with exclusive roles for project members, by training most employees, by annually defining cost reduction goals, by evaluating employee performance in project teams and promoting successful project managers to special career opportunities (Calia *et al*., 2009). Another advantage of Six Sigma compared to other quality systems is its focus on structured problem solving methods and cross functional teamwork. Six Sigma methodology utilises the tools and techniques for fixing problems in business processes in a sequential and disciplined fashion with emphasis on the importance of data and decision making based on facts and data rather than assumption (Antony, 2004).

Six Sigma could help resolve several current challenges in EMSs, particularly converting environmental plans from theory to practice. When comparing the benefits and potential shortcomings associated with all of the aforementioned methods, Six Sigma offers the most interesting contribution to EMSs because it has all the advantages of the other methods but it can also address the drawbacks of them. The package of quality tools, attention to financial results, gains that are sustained, and the focus on the problem solving methods are new approaches in Six Sigma compared to other concepts in quality management (Andersson *et al*., 2006). A primary obstacle in implementing Six Sigma is the lack of technical knowledge which could be resolved by proper training.

### *2.5. Areas of potential synergy*

Six Sigma has proven to be successful in several sectors, including marketing, finance, healthcare, and banking (Antony, 2004). However, although many Six Sigma projects have an environmental aspect to prevent or reduce pollution (Sekhar & Mahanti, 2006), there has been relatively little research of Six Sigma applications in environmental studies. Six Sigma uses statistical and quality management tools to provide a roadmap for continuous improvement in order to eliminate variations from production processes which consequently results in fewer defects, waste reduction and decrease of raw materials and energy consumption (EPA, 2010).

One key reason for applying Six Sigma in an integrated way is to merge environmental and quality concerns within organizations to improve quality levels and meet requirements for different areas of concern (Tari & Molina-Azorin, 2010). For example, research done by Calia *et al.* (2009), which analyzed a company's pollution prevention program from 1995 to 2007, found a 62% improvement in performance of the Pollution Prevention program as a result of implementing Six Sigma. As can be seen in Figure 2, in the six years before the Six Sigma implementation, the Pollution Prevention program prevented a total of 82,769 tons of pollution, while after Six Sigma implementation the amount of pollution prevented was 133,864 tons. The study showed that the Six Sigma organizational structure and methodology increased the organizational capacity for managing Pollution Prevention projects.

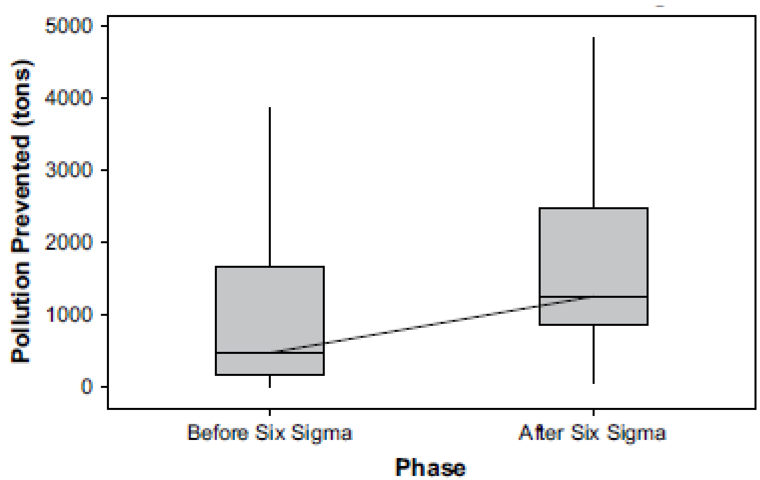



Figure 2: The monthly amount of pollution prevented before and after Six Sigma implementation (Calia *et al*., 2009)

Another study focused on the effective integration of Simulation and Six Sigma in EMSs with the existing manufacturing operation in an Indian foundry to achieve pollution-free ambient air (Sekhar *et al.* 2006). To discover root causes, highlight the problem and prioritize actions, a cause and effect diagram (also known as a fishbone diagram) and Failure Mode and Effect Analysis (FMEA), two tools commonly associated with Six Sigma, were used in this project. The results demonstrated that the integrated application of Six Sigma and simulation has been successful in reducing particulate emissions from 200 milligrams per cubic meter to less than 20 milligrams per cubic meter and sulphur dioxide emissions from 45 milligrams per cubic meter to less than 4.5 milligrams per cubic meter (Sekhar & Mahanti, 2006).

Essentially the keys of Six Sigma are rigorous data collection, analysis and a decrease in deviation, principles which would seem to naturally attract the health care and pharmaceutical industry (International Quality Academy, 2009). Elder (2006) described the basic components of the Six Sigma methodology and applied them to a microbiology process. The study showed that "For this Six Sigma project, the DPMO after intervention was 156,980, corresponding to a sigma of 2.51. While this represents almost a 50% reduction in short-volume collections, the process is clearly still a long way from perfect but on the improvement track" (Elder, 2008). Elder (2008) concluded that "with Six Sigma, clinical microbiology, as well as other sections of the laboratory, has been able to refine the quality of processes already in place and has taken them to the next level through use of this systematic approach to improvement".

Jin *et al*., 2008 provide another example of how Six Sigma may be applied in a healthcare context. Jin *et al*. performed a case study focusing on applying the principles of Six Sigma in designing and operating a healthcare logistics centre. The project resulted in better storage management, better use of space, an improved and cleaner workspace, more timely and efficient delivery of the right items in the right amount to the right patients and tracking and reducing waste. With the same number of staff, the annual cost saving was US$800,000. Another case study focused on implementing Six Sigma in the health care sector was conducted by Heuvel *et al*., 2005. In this article, the results of Six Sigma implementation at the Red Cross Hospital in Beverwijk, the Netherlands, were discussed. The Red Cross Hospital successfully implemented Six Sigma and integrated it within the ISO 9001:2000 quality management system. In doing so, €1.2 million was saved. Even, the quality of healthcare was improved by training employees and having them initiate Six Sigma projects. Heuvel suggests, "the fact that Six Sigma successfully combines quality improvement and cost reduction substantiates that it could be a solution to present day financial problems in healthcare".

There are successful studies in other fields which show the effectiveness of integrating Six Sigma and EMSs. For example, Kaya and Kahraman (2009) present a methodology based on process capability indices (PCIs) in the Six Sigma approach in order to control air pollution. As the authors note, "Process Capability Analysis in Six Sigma approach has the ability of measuring and comparing the degree of air pollution by taking the distribution of related data into account" (Kaya & Kahraman, 2009). This approach can be used for the components of air pollutants to measure and compare with the ideal values. Six Sigma has also been shown to be successful in a number of other areas, including safety (Doble, 2005, Ng *et al*., 2005 and Lok and Rhodes, 2008) and in improving energy efficiency (Kaushik *et al*. 2008), among others.

Other benefits and strengths associated with integrating EMS and Six Sigma can be derived from the literature, including the use of relatively simple quality tools in a structured process to improve the targeted company's EMS without having to recreate what may have already been done (Hillary, 1997), the development of tools and creative solutions (especially during the Improve phase), enabling the company to generate records and improve record management (Sekhar & Mahanti, 2006), and enabling the company to define environmental indicators and implement measurement and tracking tools to monitor the EMS (Sekhar & Mahanti, 2006). The literature on integrated management systems provides further insights about potential integration areas, including policy & objectives, planning & implementation strategies and management structure (Lam, 2008; Karapetrovic *et al.*, 1998 & 2002; Cullay, 1998).

### *2.6. Motivation for research*

As depicted in Table 7, the literature on the integration of management systems can be divided in two categories. The first category consists of theoretical and conceptual models and ideas regarding integration and second one is about how to implement integrated systems, and discuss challenges in implementing an integrated system. Much of the earlier literature focused on the rationale, the motivations & benefits, limitations & challenges, and conceptual ideas for integration.  More recently, empirical & case studies have been conducted that focus on the implementation of IMSs and the impacts of the system. Despite the established need for the integration of management systems, research needs to describe the various strategies of integration of management systems and the comparative effectiveness of such strategies.

Most available literature on the topic discusses the integration of ISO 9001 and ISO 14001; while relatively little research has specifically focused on integrating of Six Sigma within an IMS. These are important contributions; nevertheless there is a need for further research on the applicability, challenges, and opportunities in applying the principles of Six Sigma to EMSs. Relatively few publications have focused on how to apply the principles of Six Sigma to improve an EMS in practice. There is a lack of frameworks to guide the implementation process and in-depth case studies showing the tangible results of applying the principles of Six Sigma to an EMS are scarce. This thesis contributes to the academic knowledge base by seeking to address these gaps.

Table 7: Supporting literature on integrated systems

| **Category** | **Main topics** | **Supporting literature** |
|---|---|---|
| **Foundational Research** | Importance, basic concepts, ideas and conceptual models, pros & cons | Culley, 1998; Karapetrovic, 1998, 2002 & 2003; McDonald *et al*., 2003; Lam,2008; Calia *et al*., 2009; Leopoulos *et al*., 2009; Asif *et al*., 2010; Tari *et al*., 2010; Wilkinson & Dale, 1999 |
| **Implementation Research** | Implementation of integrated strategies, challenges | Block *et al*., 1999; French *et al*., 2006; Elder, 2008; Sekhar *et al*., 2006; Kaya *et al*., 2009; Wilkinson & Dale, 2001, |

## 3. Conceptual Framework

This section provides an original conceptual framework for integrating the key principles of Six Sigma and EMSs. As shown in Table 8, the framework is organized around three fundamental areas. First, the key components of an EMS are organized around the Deming cycle of continual improvement. Second, the key components of Six Sigma are organized around the DMAIC approach to process improvement. Finally, the third area presents a representative illustration of the potential areas for integration of Six Sigma and EMSs. It is important to emphasize that different levels of integration are possible. The spectrum of integration ranges from two independent programs and ends with a single, integrated approach to quality and environmental management.

As Table 8 illustrates, there is significant overlap in the broad approaches to implementing EMSs and Six Sigma. These approaches are mutually reinforcing and provide insight into the many opportunities to pursue integrated approaches to quality and environmental management. For example, the "Plan" phase of EMS development roughly corresponds to the "Define" and "Measure" phases commonly employed in Six Sigma initiatives. Several opportunities for integration of these phases are immediately apparent, particularly with respect to the development of policies, objectives, and targets. Similarly, the "Do" and "Check" phases of PDCA align with the "Analyze" and "Improve" phases of the DMAIC approach. As Table 8 shows, this presents many opportunities for integration, including the use of relatively simple quality tools in a structured process to improve the targeted company's EMS without having to recreate what may have already done, implementing measurements and applying Six Sigma tracking tools to monitor the EMS performance, cross-training, integrated management review meetings, and the development of cross-functional teams. Finally, the "Act" phase of EMS development corresponds with the "Control" phase of DMAIC. Integration in this area enables the company to generate records and improve record management.

The conceptual framework shown in Table 8 provides a basis for structuring thinking and discussion about the integration of EMSs and Six Sigma. It is important to emphasize that the framework will be applied differently in different companies. Companies have different starting and end points and must therefore tailor an application of Six Sigma to their EMS to suit local circumstances. To demonstrate the benefits of this approach, the next section presents a case study of how the key principles of Six Sigma may be applied in the context of an EMS. As the literature emphasizes, integration requires strong leadership. An overriding focus on pollution prevention and waste reduction is necessary in the application of Six Sigma to help achieve environmental goals. Continuous improvement is a hallmark of such an integration which requires a new management paradigm that stimulates innovations, even if there is no external pressure on the organization. In other words, it requires continuous monitoring and corrective actions to reduce waste and achieve sustained results.

Table 8: Conceptual framework

| | EMS | | Six Sigma | | Potential areas of integration | | |
|---|---|---|---|---|---|---|---|
| **Activity** | Plan | Assessment | Define | Identify the improvement activity & project objectives | Initiate the process | Policy & Objectives | Incorporate environmental policies into Six Sigma projects |
| | | Define environmental policies | | Define customer needs and translate them to technical language | | | |
| | | Define objectives | Measure | Information & data collection | | | Link function specific objectives |
| | | | | Sigma level calculation | | | |
| | Do | Training | Analyze | Identify root causes | Develop the integrated system | Planning & Implementation | Cross-training |
| | | Implementation | | Confirm root causes | | | Involvement of EMS personnel in Six Sigma projects |
| | | Documentation | | | | | Involvement of Six Sigma team leader in management review meetings |
| | | | | | | | Using Six Sigma tools to meet EMS requirements |
| | | | | | | | Use shared resources (human, financial and material) |
| | Check | Monitoring | Improve | Creative solutions & corrective action | | | Tracking the environmental performance of Six Sigma projects |
| | | Feedback | | | | | |
| | | Comparison | | Sigma level recalculation | | | |
| | Act | Corrective action | Control | Monitoring | Implement the integrated system | Documentation | Improvement of record management by Six Sigma systematic methodology |
| | | Management review | | | | | Integrate documentation, creating a single comprehensive procedure, work instruction and records for quality and environment |
| | | Revision | | Modification | Maintain the integrated system | Monitor environmental performance of Six Sigma project | Define integrated indicator for both process and environment performance |
| | | | | | | | Create a master system |

## 4. Case study

This section contains a case study of a major Middle Eastern manufacturer. First, a brief review of case study research is provided. An overview of the case company and the selected process is also provided. A brief discussion of the approach employed in the case study is then presented. The four key stages of applying the principles of Six Sigma to an EMS (as indicated by the conceptual framework) are then reviewed and discussed. The section concludes with a summary of results and challenges of the research.

### *4.1. Introduction to case study research*

In explaining what a case study is Yin (2009) suggests that "it is an empirical inquiry that investigates a contemporary phenomenon within its real-life context in which multiple sources of evidence are used". It is particularly useful when the boundaries between phenomenon and context are not clearly evident. Anderson (1993) defines case studies as "being concerned with how and why things happen, allowing the investigation of contextual realities and the differences between what was planned and what actually occurred". Noor (2008) asserts case studies are not intended to study the entire organization, but rather to focus on a particular issue, feature or unit of analysis.

Similar to other research methods, there are number of strengths and weaknesses associated with using a case study. Critics of the case study method believe that the study of a small number of cases can offer no grounds for establishing reliability or generalizability of findings; some believe that case study research is useful only as an exploratory tool (Jonson, 1994; Soy, 1997). Despite these criticisms, reports on case studies from many disciplines are widely available in the literature. These reports provide an indication of the strengths of the case study research methodology. For example, some of the strengths cited in the literature include that: case study research excels at bringing researchers to an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research, case studies emphasize detailed contextual analysis of a limited number of events or conditions and their relationships, case studies can build on the results and findings of multiple cases (Gummesson, 1991; Noor, 2008; Yin, 2009).

The case study method was employed in this thesis for several reasons. This method enabled the author to develop an in-depth understanding of the complexities of real production process activities in which multiple sources for the problem existed. As Patton (1987) explained, "case studies become specifically useful where there is a need for lots of information to understand a particular problem in depth". This was particularly important given that there have been few studies that explore the application of the principles of Six Sigma to an EMS.

The role of the case study in this thesis is illustrated in Figure 3. As Figure 3 highlights, the first stage of the research was completing an extensive literature survey of issues related to the integration of Six Sigma and EMS. This was followed by formulation of a conceptual framework (Table 8) which formed a structure (Table 9) for the study. The four stages of the conceptual framework were applied to the paint shop process in the case company. The case study was aimed at identifying the applicability, strengths and weaknesses associated with applying key components of Six Sigma to an EMS that was already in place. This provided the basis for the development of conclusions and recommendations for further research.

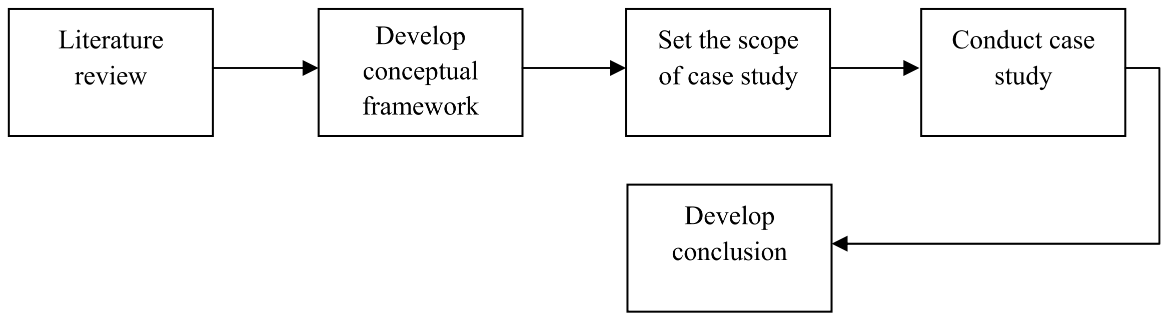



Figure 3: Stages of conducting the research

*4.2. Overview of the case company*

The case company was a major Middle Eastern manufacturer with over 50,000 employees. The company was chosen because it is a pioneer in adopting Six Sigma in the Middle East and it currently has an EMS in the form of an ISO 14001 certificate. Moreover, there is a strong desire at the top managerial level to integrate management systems. In 2000, the case company proceeded to design and deploy its EMS (ISO 14001) in order to align its industrial processes and activities with environmental regulations and standards, to control the environmental impacts resulting from its activities, and to be a world-class manufacturing operation. In 2002 the case company obtained an ISO 14001:1996 certificate.

The case study focused specifically on the case company’s paint shop. The paint shop was selected due to consumption of raw materials which are extremely harmful to the environment and may compromise the health or directly endanger the lives of employees in the plant. There are also internal and external pressures on the paint shop to reduce waste and cost, while complying with customer and regulatory requirements. In any case, waste management activities do not add value; but rather they add costs of handling, transportation and disposal.

As is shown in Figure 4, the paint process at the case company consists of five modules: PT/ED (Pre Treatment/Electro Decomposition), Sealer & PVC, Primer coat, Top coat and Touch up & Circulation or PMR (Paint Mixing Room). The paint process starts with PT/ED to cover a white-body with a protection layer and a substrate surface to increase adhesion of subsequent coats. This is followed by the sealing process. In this stage all gaps fill with sealer to avoid water penetration inside the product. As the last step of this module, part of the product is covered with PVC to prevent corrosion. The next step is applying a primer coat on to the body concordant with the shade of final coat. The final step is a top coat module with three main steps: sanding and dusting which prepares the product for a base coat, paint booth and polishing line. In paint booths, the products are spray-painted by robots. Once the product has been fully covered with a base coat of color paint and a clear top coat, the conveyor transfers the products through baking ovens where the paint is cured at a specific temperature. The third step is post paint or polishing line. In this step, the painted product is sent to a touch up module for further rework in off-line stations if necessary. The paint-mixing room consists of a controlled paint circulation system in order to supply a fixed rate of paint fluidity and viscosity with no sedimentation of solids and stabilized pressure and temperature.

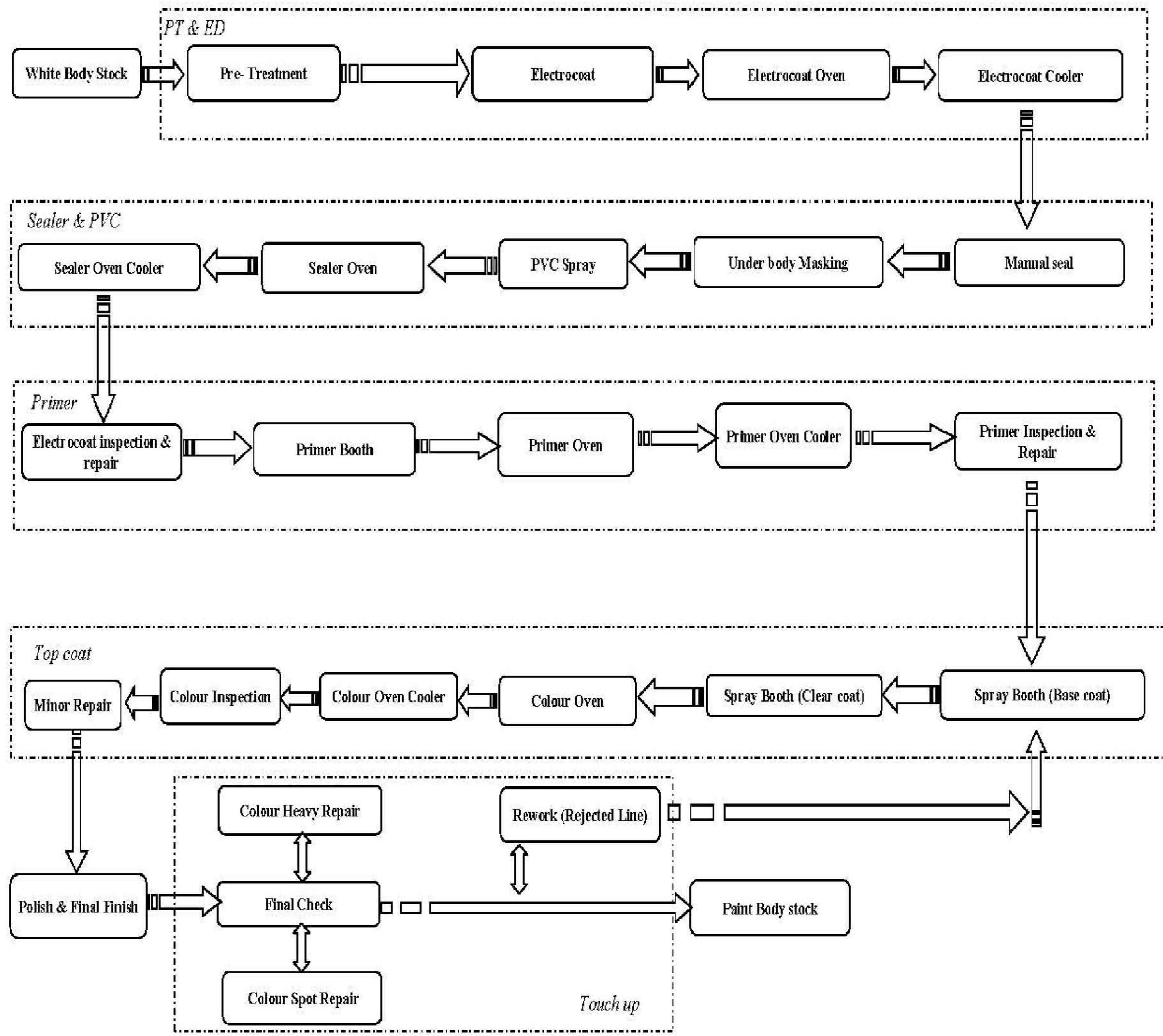



Figure 4: Paint Process Lay-out

One of the primary areas of waste generation in the paint shop is the touch up module. After the polishing line quality inspectors check the painted body, defective products are sent to off-line stations for further rework. In the worst case, the entire body would be repainted. The main issue is that after application of a third layer of top coat the thickness of the paint may exceed the standard. Consequently, several paint defects may occur, including peeling, lack of adherence, sagging, pin-hole, etc. Rework wastes time, raw materials, water, and energy. These can lead to lower production levels and economic and environmental costs, including failure to reach quality and environmental objectives. Unidentified defects may lead to product recalls or customer claims. These claims are consistent with the literature, which identifies the following costs associated with pollution: direct costs which include product, process or project costs. Examples include operating costs (material, labor, waste disposal) and capital costs (building, equipment, R&D). There are hidden costs, such as compliance costs (or overhead costs). In some cases contingent liability costs may be considered, which are related to liability because of accidental releases and legal damages for pollution, compensation or recall costs for defectives products to consumers, and penalties for emission. Finally, intangible costs consist of corporate image, customer acceptance, and goodwill (Bhat, 1998).

It is clear that if the case company generates less waste, it will spend less on waste management and have more money for investment and growth. Consequently, the CEO of the case company and the paint shop director were convinced that green processes and products will increase yields, improve use of by-products, reduce material handling costs, decrease energy consumption, reduce product cost, make work places safer, optimize utilization of resources, reduce liability costs and reduce waste disposal costs. They recognized that applying the familiar tools of Six Sigma to the company's processes could yield many potential improvements for the EMS.

*4.3. Approach employed in the case company*

This research was focused on applying Six Sigma methodology to the case company's EMS for waste reduction. The purpose of the case study was to demonstrate that, in addition to traditional outcomes, the Six Sigma methodology is highly applicable in the environmental domain for waste reduction, decrease of energy consumption, and emission reduction.

The application of Six Sigma to the case company's EMS was guided by the conceptual framework described in Section 3. Four elements were described which, considered together, form the basis for a distinctive integration method. These elements are: initiation of the process, development of the integrated system, implementation of the integrated system, and maintaining the integrated system, which are consistent with EMS PDCA cycle and in line with the Six Sigma DMAIC methodology. In this strategy, Six Sigma methodology emphasizes the need to utilize quality tools and techniques for fixing process problems and helping the EMS to define objectives & improvement opportunities, implement corrective actions, and monitor improvements. The Six Sigma methodology provides a sequential and disciplined process for applying the tools of quality management and control in this fashion. Each tool and technique within the Six Sigma methodology has a potential role to play, though it is important to note that different organizations may employ different tools at different times. The DMAIC methodology provides a clear indication of when, where, why and how tools or techniques should be applied. Choosing the right tool is one of keys to success of Six Sigma and the integration of these tools with an EMS. In this case study, Six Sigma utilises the concept of statistical thinking and encourages the application of well-proven statistical tools for waste reduction through process variability reduction. The important point to consider here is that integration at this stage is meant for efficient allocation and utilisation of resources to make sure that true benefits of integration are attained by waste and cost reduction. The other advantages of utilizing Six Sigma tools to reach the targets of the case company's EMS include overcoming the implementation limitations of the EMS, involvement of employees through the Belt system, the establishment of a cross functional team (the participants were specifically selected to ensure a broad range of perspectives, specifically quality and environmental professionals), management support and leadership by defining a Champion for the project, and joint training. As Table 9 illustrates, the case study was completed in four phases with Six Sigma tools to fulfill EMS and process requirements.

Table 9: Approach of case study

| Phase | EMS & process requirements | Selected Six Sigma tool |
|---|---|---|
| **Initiating the process** | Defining integrated objectives | Project charter |
| | Assessment of current situation | SIPOC map, Sigma level calculation |
| | Clarification of customer needs from process and quality aspect | VOC table, CTQ tree diagram |
| | Definition of environmental aspects and customer needs in environmental domain | VOC table, CTE tree diagram |
| | Prioritize data collection and clarify important variables that affect quality and environmental performance | FMEA |
| **Developing the integrated system** | Define root causes of the problem, confirm root causes, training and arrangement for implementing solutions | Fishbone, Pareto chart |
| **Implementing the integrated system** | Implementing creative solutions, feedback, comparison | Sigma level recalculation |

| Phase | EMS & process requirements | Selected Six Sigma tool |
|---|---|---|
| **Maintaining the integrated system** | Monitoring the system to make sure results are sustained, correcting errors (corrective actions), verifying correctness and adequacy of solutions, revisions & keeping documents current, internal audits, management review | Control charts, cost impact analysis, presentation and closure meeting and forms |

With the above in mind, the following sub-sections present the process and results of the case study. The details are organized around the proposed framework which is a combination of PDCA cycle and DMAIC methodology. Each sub-section emphasizes the key areas where the principles of Six Sigma were integrated with the case company's EMS.

### *4.4. Initiating the process*

This phase emphasized the identification of objectives and the definition of customer needs. Building on the key components of an EMS, it also emphasized defining environmental policies and assessment of current situation. From the Six Sigma toolbox and EMS PDCA cycle, this phase was completed through the application of SIPOC analysis, voice of the customer analysis, critical to quality analysis, FMEA, and Sigma level calculation. Further details are provided in the sub-sections below.

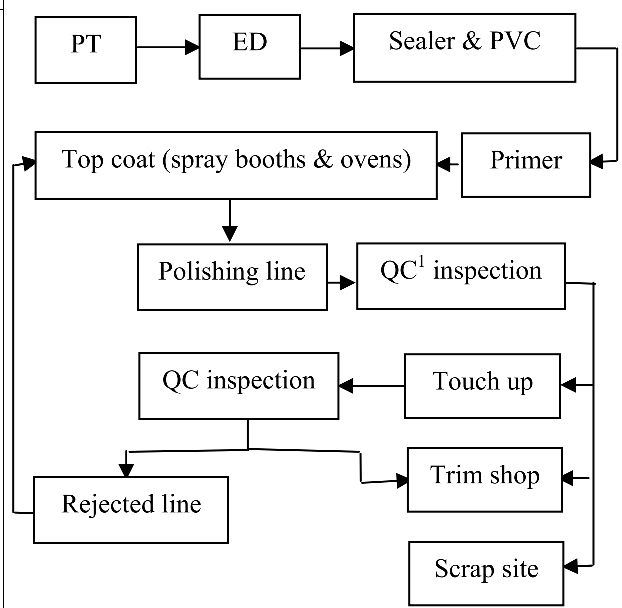
#### *4.4.1. Plan*

The first step of this integrated phase was to form a cross-functional team with professionals from a number of departments at the case utility to support the author. In this project, the paint shop director and the head of the Environment, Health and Safety (EHS) department served as the internal co-champions. Other members of the team were drawn from the quality department, the EHS department, the production department, the maintenance department, and the engineering department. A total of 9 internal experts participated in the project. This project team directly reported to the case company's management committee. The role of the project team in the case study was to ensure that the author had access to the needed data and to implement the suggestions developed in the case study. Further detail on the data collected and the suggestions implemented is provided in the following sub-sections. To ensure that project boundaries were defined and all responsibilities were clear, a project charter was developed. This is a common step in Six Sigma initiatives. The project charter identified the project title, the project target, the project scope, the name of individuals involved, their responsibilities, the target date of completion, the approval date and authorization. A copy of the project charter is available in Appendix 2. As recommended in the literature, time frames were kept short enough to maintain interest, but long enough to avoid interfering with daily operational activities (Block & Marash, 1999).

#### *4.4.1.1. SIPOC map (Supplier, Input, Process, Output, and Customer)*

The second step in this phase was to review the current process and assess the current situation. The development of the SIPOC map (Table 10) provided a starting point and essential information that was required for more detailed project activities, such as inputs, the suppliers who provide these inputs, process flow diagram, outputs and those affected by the outputs. For example, walking through the process in detail helped to identify the key environmental impacts of the painting process, including: raw material overconsumption, waste of energy, generating waste (wastewater/scrapped bodies), impacts on operators' health and depreciation of the machinery system.

Table 10: Project SIPOC map

<table>
<tr><th>Suppliers</th><th>Input</th><th>Process</th><th colspan="2">Output</th><th>Customer</th></tr>
<tr><td>Body shop</td><td>White body</td><td rowspan="6">
</td><td colspan="2">Painted body</td><td>Trim shop</td></tr>
<tr><td rowspan="3">Paint & material Suppliers</td><td rowspan="3">Paint, sanding paper, pad and polish</td><td rowspan="5">Non-confirmed bodies</td><td rowspan="2">Scrapped</td><td>Environme-ntal dept.</td></tr>
<tr><td>Paint shop director</td></tr>
<tr><td rowspan="3">Returned for repaint</td><td>Waste site (Scrap site)</td></tr>
<tr><td>Maintenanc-e dept.</td><td>Equipment</td><td>After sale dept.</td></tr>
<tr><td>Method engineering</td><td>Procedures, work instructions</td><td>Consumer</td></tr>
</table>

Note: (1) Quality Control

### *4.4.1.2. VOC (Voice of Customer) table*

The development of the process map was supplemented by a VOC exercise to develop a detailed list of what was important to the customer. As illustrated in Table 11, the VOC exercise addressed both quality and environmentally-focused issues. The purpose of VOC is to identify and describe customer needs and customer perception of the product. Customers could be either internal (for example, the EHS department was a key internal customer in this case) or external, such as consumers, regulations, community and environmental groups or even the environment itself and future generations. The VOC exercise provided needed insight into several environmental impacts in the paint shop. For example, Table 11 shows that it helped identify where problems were occurring, when they were happening, and why they were happening. VOC development helped to identify the environmental impacts of paint shop activities.

Table 11: VOC table

<table>
<tr><th colspan="2">Customer characteristics</th><th colspan="7">Use</th><th rowspan="2">Voice of customer</th></tr>
<tr><td>Who</td><td>VOC</td><td>What</td><td>When</td><td>Where</td><td colspan="2">Why</td><td>How</td></tr>
<tr><td rowspan="6">Environmental dept.</td><td rowspan="6">Waste generation increase</td><td rowspan="6">Scrapped bodies</td><td rowspan="6">Always</td><td rowspan="6">Environment</td><td rowspan="6">Environmental contamination due to,</td><td>over consumption of raw material</td><td rowspan="6">Increasing number of scrapped bodies</td><td rowspan="7">Reduce number of scrapped bodies in Paint shop</td></tr>
<tr><td>generating wastewater</td></tr>
<tr><td>increase of energy consumption</td></tr>
<tr><td>emission increase</td></tr>
<tr><td>more solid waste in landfill</td></tr>
<tr><td>jeopardizing health of operators</td></tr>
<tr><td>Paint shop director</td><td>Cost increase</td><td>Scrapped bodies</td><td>Always</td><td>Paint shop</td><td colspan="2">Increase cost per unit, decrease productivity and direct flow</td><td>Increasing number of scrapped bodies</td></tr>
</table>

*4.4.1.3. CTQ (Critical To Quality) tree diagram*

The purpose of CTQ analysis is to translate customer language into quantified requirements for the process and product. As depicted in Table 8, the conceptual framework highlights opportunities for integration in planning and implementation strategies. Building on CTQ, a practical tool for integration in this field is the development of a CTE (Critical To Environment) tree. CTE characteristics are product or service characteristics that significantly influence one or more CTSs (Critical to Satisfaction) in the environmental field. The concept of CTE was developed by the author to help translate environmental requirements and mandates into technical language which was measurable and controllable. Building on the VOC exercise summarized in Table 11, Figure 5 provides a practical example for both CTQ and CTE for the case company's scrapped bodies in the paint shop.

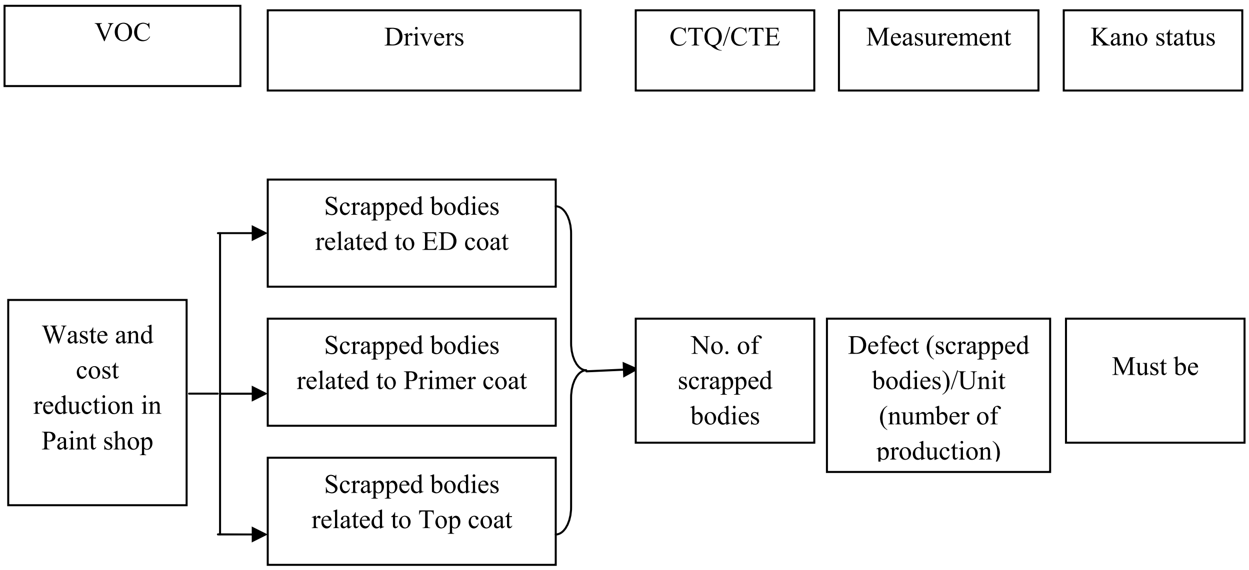



Figure 5: CTQ/E tree diagram

As illustrated in the last box on the far right of Figure 5, a key element in this exercise is determining the "Kano status". Kano defines three categories of customer needs (Sireli *et al.*, 2007): *Must be*, *More is better*, and *Delighters*. *Must be* refers to the needs expected by the customer. If they are unfulfilled, the customer will be dissatisfied, but even if they are completely fulfilled the customer would not be particularly satisfied. In this case there is no satisfaction even after corrective actions; it's just back to normal. *More is better* needs have a linear effect on customer satisfaction. The more these needs are met, the more satisfied are these customers. *Delighters* needs do not cause dissatisfaction when not present but satisfy the customer when they are. The Kano model is particularly important when project team wants to select the most important CTSs. By aid of CT tree, VOC (Voice Of Customer) table and Kano model, it could be ensured that the project team has understood the current situation from the customer's perspective and prioritize the project focus and corrective actions.

### *4.4.2. Measure*

The purpose of this step is to evaluate what the company is currently capable of doing. This evaluation helps identify the company's existing process capability with respect to meeting the EMS requirements and facilitates the identification of key gaps. Accordingly, in this step of the case study, the quality tools of Six Sigma helped identify the key environmental improvement areas in the process and to select the focal point for data collection. This phase was completed through the application of failure modes and effect analysis (FMEA) and sigma level calculations.

#### *4.4.2.1. FMEA (Failure Mode & Effect Analysis)*

FMEA was used in the case study to identify, prioritize and evaluate risk, with an emphasis on failure prevention. In other words, FMEA helped to prioritize data collection and to provide clarification about what the important variables are and how they affect output quality. In order to complete the FMEA in the case study, several steps were conducted. The first step was to identify and rate the severity of potential failure modes and their effects. In the case study, the primary failure mode of interest was scrapped bodies in the paint shop while potential effects could include increased waste generation, cost, and rework. The second step was to identify the cause of the effects and to rate their likelihood of occurrence; potential causes could include improper sanding, improper maintenance, and poor quality of paint. Next, the ability to detect each failure mode was rated. The multiplication of severity, occurrence and detection gave a RPN (Risk Priority Number), for example for first potential effect (waste generation increase) RPN was calculated as follows: 5 (severity) × 5 (occurrence) × 5 (detection) = 125. Appendix 3 provides a sample of rating scale for severity, occurrence and detection.

The next step was to identify ways to reduce or eliminate risk associated with high RPNs. As depicted in Table 12, dimple and pimple (deformation) related to PBS (Painted Body Stock) and tools, improper maintenance, quality of paint provided by different suppliers, and improper sanding in the rejected line (which the product would be prepared for repaint) were found to be the major causes for the increase of scrapped bodies and waste generation. Short term corrective actions or quick solutions include on job training of touch up operators for repairing recoated bodies, precise supervision on body transfer from WBS (white body stock) to paint shop and from paint shop to PBS (painted Body Stock), quality control, and standard tests for every batch in the engineering lab (in addition to routine central lab tests). Further corrective actions are discussed in detail in the Implementation phase (Table 13).

Table 12: Failure Mode and Effect Analysis

| Process function/requirements | Potential failure mode | Potential effect(s)of failures | Severity | Potential cause(s)/mechanism (s)of failure | Occurrence | Current process controls | Detection | RPN |
|---|---|---|---|---|---|---|---|---|
| **Production of confirmed bodies according to quality standards** | Scrapped bodies | Waste generation increase | 5 | Weak adhesion | 5 | Scratch test on repainted bodies | 5 | 125 |
| | | Cost increase | 5 | Improper sanding in rejected line (wet sanding) which prepares body for reprint | 8 | Survey plan by QC | 6 | 240 |
| | | Direct flow Decrease | 5 | Quality of paint provided by different suppliers | 8 | Test plan by central lab | 6 | 240 |
| | | Rework increase | 5 | Dimple & pimple (deformation) related to PBS and tools | 8 | Foreman supervision | 7 | 280 |
| | | Productivity decrease | 5 | Improper maintenance | 7 | PM (Preventive Maintenance) | 7 | 245 |

#### 4.4.2.2. Sigma level calculation

The sigma level is a practical tool to determine and evaluate how the targeted process is currently doing. This evaluation helped assess the case company's existing process capability with respect to meeting the EMS requirements and to identify how far the company was from its objectives. The sigma level calculation also helped establish an indicator of process/environmental improvement. The reason for using process Sigma as a metric for this study was that Sigma level is a more sensitive indicator than percentage and it focuses on defects (Williams *et al.*, 2001). Process Sigma is the capability of the process relative to the specifications for the process. In practice, it is an expression of process yield based on DPMO. While process sigma shares some features with process capability indices, process sigma may also be applied to any situation where defects can be counted in meeting customer specifications (Setijono, 2008). DPMO is calculated as:

$$DPMO=\left(\frac{D_t}{O\times U_t}\right)\times 10^6$$

- Where $D_t$ is defect (per period of time) = any event that does not meet a customer specification = number of scrapped bodies
- O is defect opportunity = a measurable chance for a defect to occur = 1
- $U_t$ is unit (per period of time) = the item produced or processed = number of produced units

Defect opportunities count the number of times a requirement could be missed, not the ways in which it can be (Williams *et al.*, 2001). It is important to note that number of opportunities per unit must stay constant before and after improvement. An opportunity should be based on a defect that can reasonably happen. An opportunity for a defect is a measured characteristic on a unit that needs to confirm to a customer standard, for example the ohms of an electrical resistor, the time it takes to deliver a package, etc. (Sheehy *et al*., 2002). In this case, the entire scrapped unit was considered a defective, because an entire unit fails to meet acceptance criteria, regardless of the number of defects on the unit (Sheehy *et al*., 2002). Therefore the defect opportunity in this case is one, because the produced unit could be either confirmed or scrapped.

Before starting the case study, the number of scrapped bodies was 170 (between May-July, 2010). The number of units produced in that period was 57995. Accordingly, the DPMO would be 2931 and the Sigma level (from *Z to DPMO conversion table* in Appendix 1) is 4.25. The results demonstrated that the company was far from the ultimate target of Six Sigma (or 3.4 defects per million opportunities), and to meet the environmental requirements (which for this project basically was waste reduction).

### *4.5. Developing the integrated system*

Once the type of data was determined, it was necessary to define how to collect count data from the information obtained about the company's environmental aspects and existing documents. The team decided to use two common Six Sigma tools, a Cause & Effect diagram (C&E) and a Pareto chart, in order to analyse the problem and related environmental concerns. The rationale for this phase of the case study was that understanding the magnitude and types of variations, as well as where and when variation occurs, can provide insight into the root cause of the problem.

Based on the results of the C&E, data was collected. A Pareto chart was created to understand the pattern of occurrence for the problem with its environmental impacts, tracking down the biggest contributors to a problem and deciding where to focus efforts. Further details on the C&E diagram and the Pareto analysis are provided in the sub-sections below.

### *4.5.1. Cause and effect diagram*

The purpose of a cause and effect diagram is to graphically display the potential causes of a problem and to provide insight into the relationship between the causes. A cause & effect diagram allows a team to identify, explore, and graphically display, in increasing detail, important possible causes related to the problem or condition to discover its root causes (Sheehy *et al*., 2002). A C&E diagram enables the project team to focus on the content of the problem, not on the history of it or differing personal interests of team members. It also creates a snapshot of the collective knowledge and consensus of the team around a problem (Williams *et al*., 2001). This builds support for the resulting solutions. In the case study, C&E analysis was used to stimulate thinking during brainstorming of potential causes, to understand the relationship between potential causes, to track which potential causes have been investigated, and to determine which causes significantly contributed to the problem. The C&E diagram for the case study is provided in Figure 6.

As depicted in Figure 6, the main causes of the problem of scrapped bodies were categorized into 5 groups: material, man (personnel), environment, method and machine. For example, the Figure 6 highlights that one problem was operators' negligence in sanding and choosing improper sanding paper. Additionally, the lack of a clear work instruction for preparing recoated bodies in the rejected line lead to operator confusion and severe paint defects. These in turn lead to generating waste and overconsumption of raw material. The other main problems included violation of several clauses in ISO 14001 related to training, awareness and documentation, non-conformances in EMS audits, and failure in resource management.

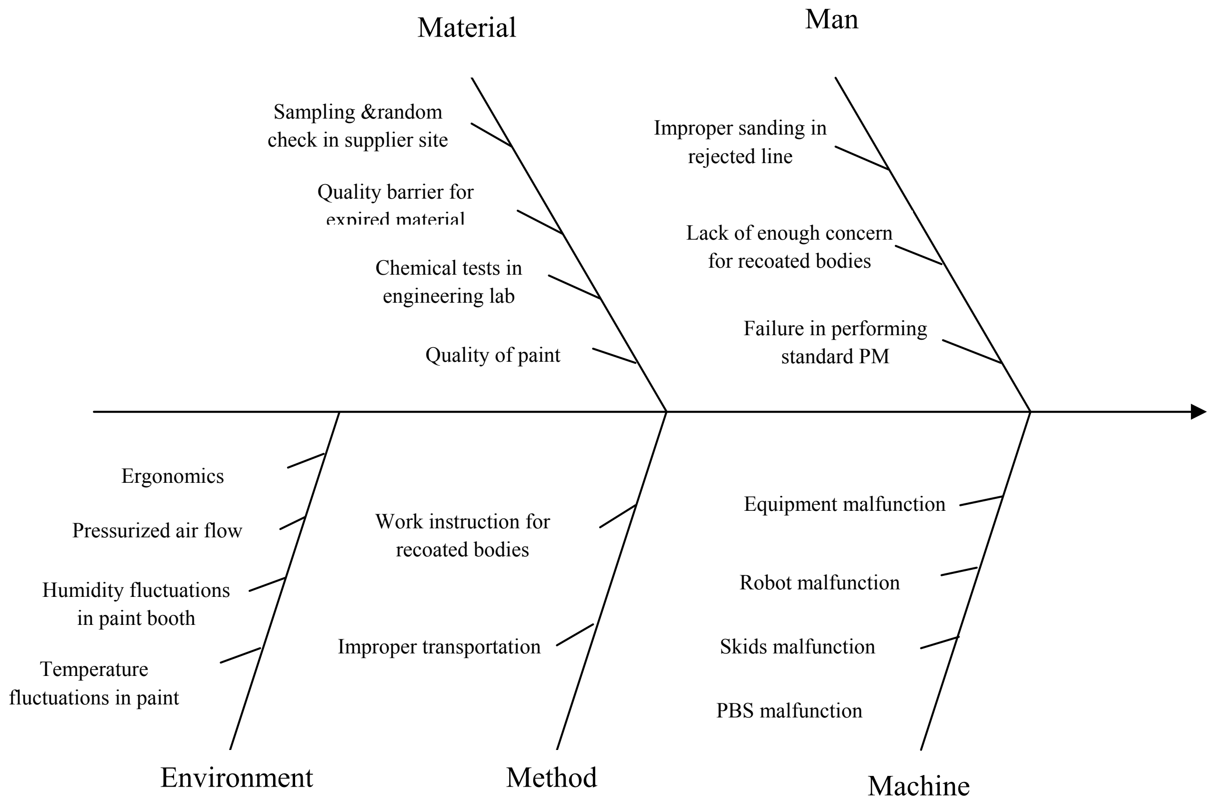



Figure 6: Cause & Effect diagram

### *4.5.2. Pareto chart*

While a Pareto chart may help provide new insights into problems, C&E diagrams only identify potential causes. In the case company, it was therefore necessary to collect data to confirm which potential causes actually contributed to the problem. This was complicated by the fact that some important causes may be hard to measure or observe. Additionally, knowing which potential causes could be really changed in practice helped to focus efforts. Based on the type of collected data, a Pareto chart was selected to understand the pattern of the occurrence, track down the biggest contributors, and to demonstrate the relative frequency or impact of data by dividing them into categories. Figure 7 demonstrates that the highest occurrences were related to poor adhesion of paint for recoated bodies (high thickness), improper transportation, and deformation (by tools, hangers or PBS). In other words, if the case company could eliminate or reduce occurrence of the aforementioned problems, consequently waste generation would be reduced in the paint shop.

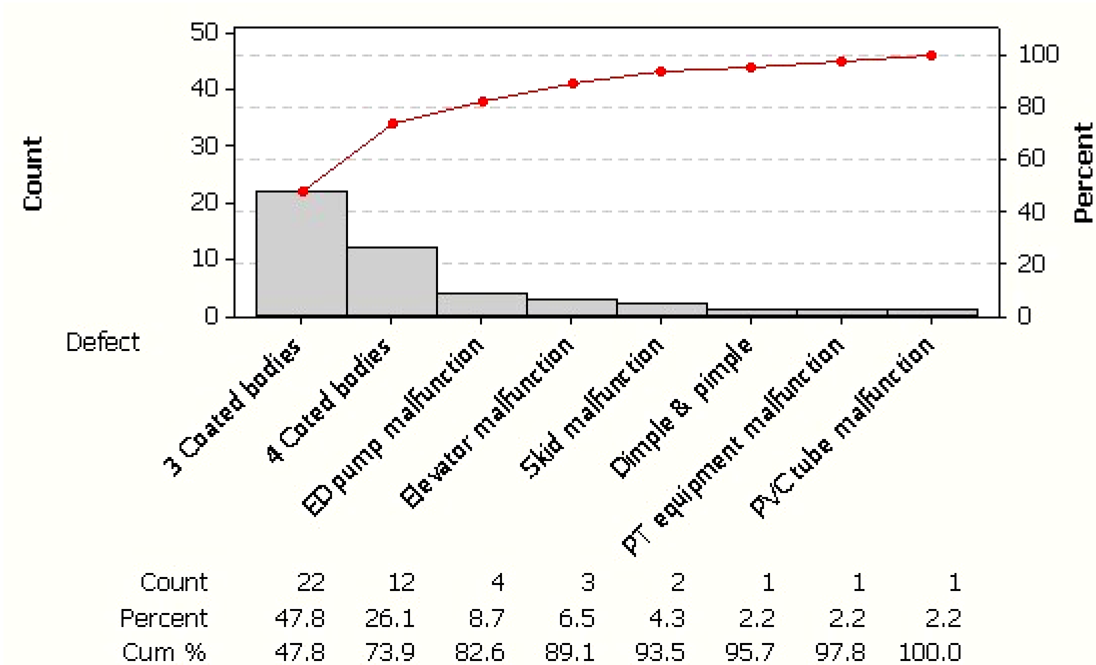



Figure 7: Pareto chart for main causes

*4.6. Implementing the integrated system*

An effective corrective and preventive action program is one of the fundamentals for any system, including an integrated quality and environmental management system (Culley, 1998). This step in the sequence is about implementing creative solutions and corrective action plans in order to find ways of improving and to achieve defined targets based on EMS objectives. In the case company, this entailed modifying existing procedures and creating new ones. A quality procedure for controlling records might be revised in order to track environmental records. In the case company, this step focused on designing a data bank for scrapped bodies (record management). It was determined that revisions to existing procedures and instructions were necessary. It was also necessary to create some new procedures and instructions. Other changes included, on the job training and corrective actions in the system i.e., installation of new detecting devices and implementing preventive maintenance according to revised schedule. The goal of this phase was to demonstrate, with data, that solutions are available to solve the identified problems and lead to improvement. In this stage of the case study, an improvement plan was developed based on the results of the Analyze phase. The key outputs of the process are summarized in Table 13. As previously noted, the project team assisted with the implementation of the suggested actions.

Table 13: Solutions, corrective and preventive actions

| **Root cause** | **Solution** | **Start date** | **Finish date** |
|---|---|---|---|
| Recoating | On the job training for the polishing line, touch up and rejected line (operators and foreman) | December 1, 2010 | December 21, 2010 |
| | Preparing a *Quality Alert* (case company's internal agreement for preventing errors in the production line) for recoated bodies | October, 2010 | |
| | Revising the touch up procedure | November 15, 2010 | November 30, 2010 |
| | Installation of heater in offline repair cells for minor and even major curable defects without repainting | November, 2010 | December, 2010 |
| Deformation | Installing sensors in the PBS entry to adjust skid and conveyer height | November, 2010 | December, 2010 |
| Equipment malfunction | Modification of PM schedule (for skids, PT & ED, Sealer & PVC modules) | November, 2010 | December, 2010 |
| Quality of paint | Over-bake workability test for every batch | December 2010 | |
| All aforementioned items (troubleshooting) | Data bank design for scrapped bodies (record management) instead of keeping a hard copy | November, 2010 | January, 2011 |

As a result of implementing the aforementioned improvements (pictures are included in Appendix 4), the Sigma level increased. The Sigma level was recalculated and compared with the Sigma level before the improvements to examine the effectiveness of the proposed solutions. The key calculations are presented in Table 14. Based on the production plan and difficulties that were encountered during production, the number of units produced may vary in each month. As depicted in Table 14, before improvement (between May-July 2010), 170 out of 57997 painted bodies were defective (defined as scrapped bodies). However, following the implementation of the improvements this rate dropped to 6 out of 19436 produced bodies in January 2011. This means that the Sigma level increased from 4.25 to 4.92 (Figure 8 demonstrates the improvement trend of the sigma level). While this represents an almost 80% reduction in the number of scrapped bodies (waste reduction), the process is clearly still far from perfect. At this point, the process owner and environmental department head decided that improvement was sufficient to comply with environmental regulations and also achieving cost reduction goals. However, they agreed that there should be further action taken to improve the process and achieve the ultimate target of the Six Sigma methodology, which is 3.4 defects per million opportunities.

Table 14: Sigma calculation

| | **Month (2010, 2011)** | **No. Of production in paint shop # 1** | **No. Of scrapped bodies in paint shop # 1** | **DPMO** | **Sigma level** |
|---|---|---|---|---|---|
| **Before starting project** | May | 57995 | 170 | 2931 | 4.25 |
| | June | | | | |
| | July | | | | |
| **After starting project** | August | 13770 | 28 | 2033 | 4.38 |
| | September | 18657 | 32 | 1715 | 4.43 |
| | October | 17302 | 18 | 1040 | 4.57 |
| | November | 16841 | 11 | 653 | 4.71 |
| | December | 17605 | 10 | 568 | 4.76 |
| | January | 19436 | 6 | 308 | 4.92 |

Special cause: 11 painted bodies were scrapped due to defective dark gray primer

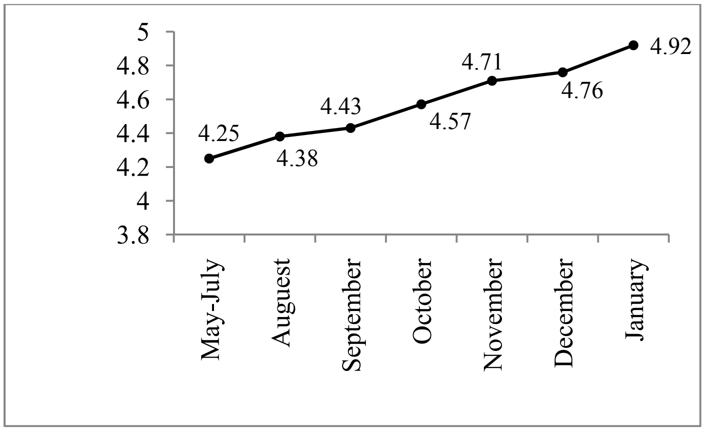



Figure 8: Sigma level improvement

*4.7. Maintaining the integrated system*

During the previous phase, the solution was piloted, and plans were made for full-scale implementation. It was recognized that putting a solution in place can fix a problem momentarily, but that particular attention is needed in this phase to make sure the problem stays fixed and that the new methods can be further improved over time. This includes correcting errors in the system, verifying correctness and adequacy of instructions and procedures, and keeping documents current. Guidance on completing this step is provided by the literature. After an agreed period, an internal audit must be performed to verify implementation and identify any procedural problems that may have arisen. To assure that the EMS functions effectively, the auditor may choose to examine performance measures to see whether progress in achieving a stated target is being made. As each element of the system is reviewed, a decision must be made whenever there is a discrepancy between what has been planned and what is actually taking place and, if necessary, the system should be adjusted to meet the requirements (Bhat, 1998; Culley, 1998; Block, 1999). Again, after this adjustment, the implementation of the changes must be audited. Since the essence of the proposed conceptual framework is continuous improvement, this process of review, adjust, implement, and audit should be continuous.

One of the keys to major improvement in environmental performance is executive commitment. Furthermore, as previously noted, environmental management is not the responsibility of one department or one person but of everyone in the organization. Executive commitment combined with a collaborative approach makes it easier to assess environmental performance using broadly supported approaches to measurement. This phase therefore focused on developing agreed-upon performance tools with an emphasis on control charts to monitor the environmental performance of the system. The role of EMS personnel in internal auditing was heavily emphasized. In the case company, both EMS personnel and Six Sigma experts participated in the management review meetings to ensure an ongoing commitment to corrective and preventative action.

This integrated approach for developing and implementing the programme ultimately lead to 80% waste reduction (in terms of the number of scrapped bodies). Six Sigma provided the case company with a systematic approach to measuring and improving its environmental performance in the area under study. Furthermore, the application of Six Sigma in this context helped build needed support from production managers for the company's environmental activities. Selected tools from the Six Sigma toolbox for the closure included a cost analysis, the development and application of control charts, and project closure.

*4.7.1. Cost impact analysis*

Based on the collected data, the analysis in Table 15 shows that the cost per unit for recoating the body is $89. Figure 7 clearly illustrates the main cause behind scrapped bodies is poor adhesion due to high thickness for recoated bodies, which are usually 3 or 4 coated bodies. Therefore the annual cost saving was calculated as follows:

- Cost per unit of first coat: $89 = A
- Cost of recoating (A*3): $267 = B
- Cost per unit of white body (from Table 15): $1,525 = C
- Total cost per unit of a recoated body (B+C): $1,792 = D
- Number of scrapped bodies in three months before improvement: 170 = E
- Number of scrapped bodies in three months after improvement: 27 = F
- Number of saved bodies (E-F): 143 = G
- Cost impact for three months (D*G): $256,256 = H
- Annual cost saving ($\frac{H*12}{3}$): $1,025,024

An analysis of the cost savings achieved due to the improvements made in the case study was conducted. As Table 14 indicates, the number of scrapped bodies before improvement was 170 in three months. This quantity dropped to 27 for the three months following the implementation of the improvements. Additionally, waste generation in the paint shop was reduced by 80%. Given that the total cost of a recoated body is $1792, the total annual cost reduction was $1,025,024. Significantly, this achievement was accomplished within a time frame of just a few months. Future work at the case company should focus on whether these results could be further improved. Non-confirmed products must eventually be scrapped and result in numerous side effects for the quality, production, and environmental domains. Although, improving from 170 scrapped bodies in 3 months to 27 is a significant improvement, it is still far from ideal. Further thinking is needed about what should be tackled next in the process to further improve in the sigma level.

Table 15: Cost analysis for rejected (recoated) bodies

| Material | BOM[1] | Price/Unit | Total price ($C) |
|---|---|---|---|
| Sanding paper (Grade 500) | 6 | 0.524 | 3.14 |
| Sanding paper (Grade 800) | 0.46 | 0.265 | 0.121 |
| Fabric for body cleaning | 2.42 | 0.653 | 1.58 |
| Rag | 5 | 0.35 | 1.75 |
| Metallic base coat | 5.5-6.5 litre | 6.97 | 45.30 |
| Clear coat | 1.5-2 litre | 7.72 | 15.44 |
| Paint thinner | 2.7-3 litre | 0.98 | 2.94 |
| Varnish thinner | 0.5-1 litre | 0.98 | 0.98 |
| Imported sanding paper | 20 | 0.656 | 13.12 |
| Polishing pad | 0.41 | 5.77 | 2.36 |
| Polishing paste | 0.042 litre | 41.13 | 1.72 |
| Covering paper | 1 meter | 1.07 | 1.07 |
| Total[2] | | | 89.501 |
| White body | | | 1,525 |

Note: (1) Bill Of Material, (2) Total cost, excluded person-hours required for Top coat cabins, polishing line, and Touch up module.

### *4.7.2. Control/Run chart*

Ongoing monitoring of a process is typically managed with a control or run chart which plots time-ordered data. Control/Run charts track performance over time, evaluate progress after process improvements, focus attention on detecting and monitoring process variation over time, and point towards *special causes (*Williams *et al*., 2001; Sheehy, *et al*., 2002*)*. A *special cause* variation means something different happened at a certain time or place which needs immediate action or remedy any damage (Lind *et al.*, 2008). In contrast *common causes* are the process inputs and conditions that contribute to the regular, everyday variation in a process (Brue, 2002).

When the process has defective rates measured in parts per million, traditional control charts such as the p chart (the control chart for attribute data when counting defective and sample size is variable) are no longer effective (Nelson, 1994). One suggested monitoring tool for this attribute data in a discrete environment is a control chart of the number of defectives or the time between defectives (Montgomery, 1991; Nelson, 1994; McCool & Joyner-Motley, 1998). Using the time or number of good units between observed defective units as a test statistic is a clever idea to mitigate discreteness inherent in monitoring the number of defectives (Nelson, 1994). For this purpose, researchers may employ sequential procedures such as Geometric charts (Montgomery, 1991; Nelson, 1994). Geometric charts (known as G-Chart) are statistical control charts that monitor the count of confirming items between two nonconforming products (Yang *et al.*, 2002). These control charts are useful for high Sigma processes that operate above three-sigma (Lakshminarasimhan & Kannan, 2007). Since in this case study the calculated Sigma level was 4.25, and the process has defective rates measures in part per million, the Geometric control chart was selected to monitor and control the process. More details about choosing the appropriate control chart are provided in Appendix 5.

In this case, a *Geometric chart* was developed to understand variation of the process, compare performance before and after implementation of solutions, and to detect trends and shifts in the process based on collected discrete data. The building blocks of the control chart were collected by counting produced units (confirmed bodies) between two defective units (scrapped bodies). In order to judge whether the defective product is something that can be repaired or should be scrapped, a team of quality, engineering and production professionals should come to a joint decision. In this specific type of control chart, a raising trend (or number of produced confirmed units) was a good sign; it meant that number of scrapped bodies declined. In the following graph (Figure 9), the vertical line (Y axis) represents the number of produced units or confirmed products, while the horizontal (X axis) line represents the time between observed defective units (scrapped bodies). Control limits define the bounds of common cause variation in the process and establish process capability to separate common causes and special cause variation; therefore points outside statistical limits signal a special cause (Williams *et al.*, 2001). In contrast to the other control charts (Shewhart control charts such as p chart), "in G chart, points below the lower control limit indicate deterioration of quality whereas points above the upper control limit show improved quality" (Nelson, 1994).

As illustrated in Figure 9, unlike other types of control charts where the gap between control limits after improvement should be tighter, in this type of control chart, the gap between LCL (Lower Control Limit) and UCL (Upper Control Limit) increased (Appendix 6 provides equations for control limits of Geometric chart). This means that the rate of production and direct flow were increased, consequently the number of scrapped decreased. This control chart provided a common language between EHS and quality personnel for discussing process performance.

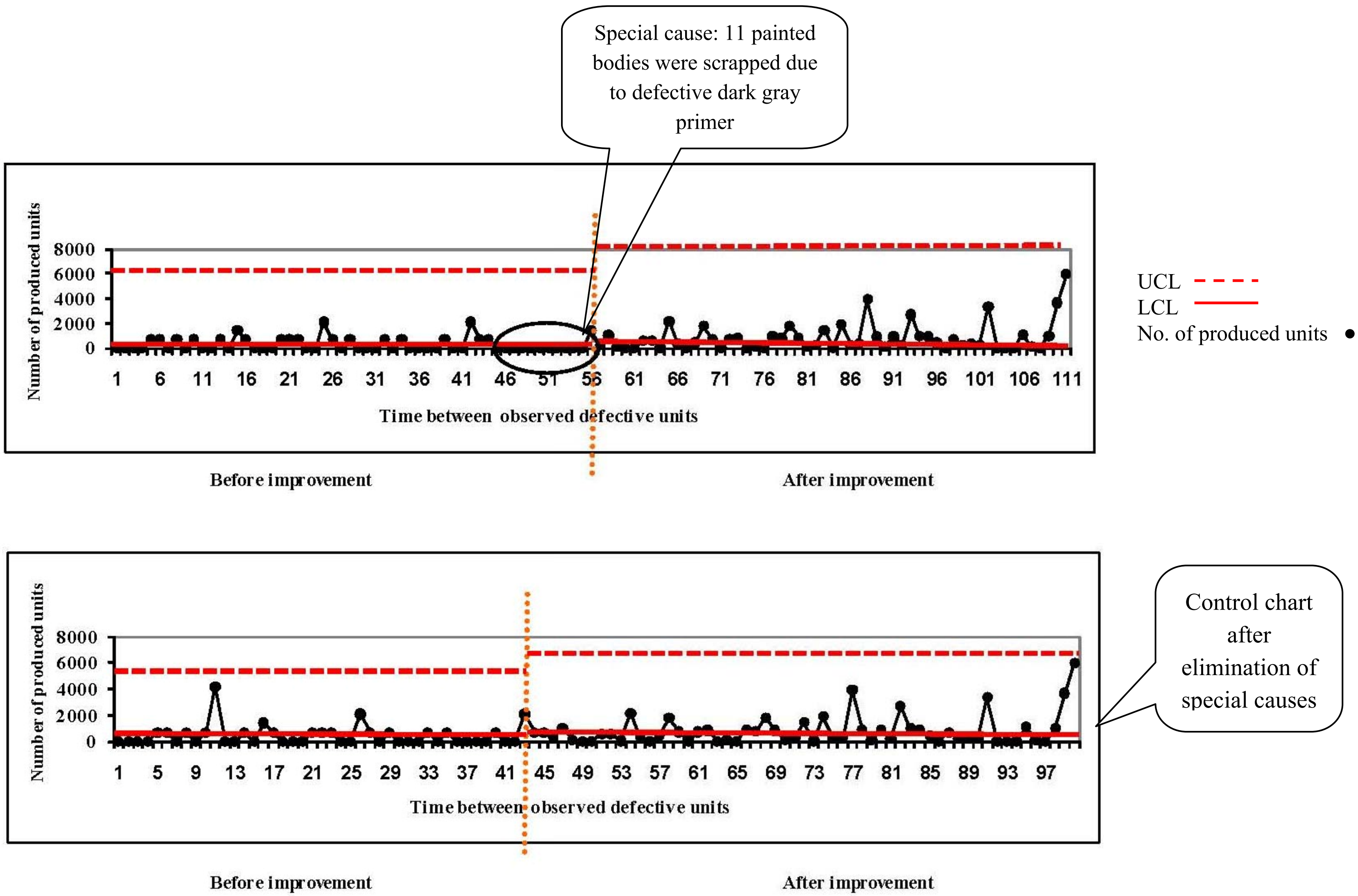



Figure 9: Geometric Control chart

### *4.7.3. Project Closure*

To effectively maintain the new integrated methods, it was necessary to verify the results and validate the changes to ensure that they adhere to all operating and environmental policies in the case company. This was done through internal audits. The new methods were clearly documented and were used to help provide training to everyone who would use the new methods. Lessons learned were summarized and shared with co-workers involved in similar projects, with internal customers, and with managers who needed to know the final outcome. Implementation of the improvements was monitored and corrections (such as modification of PM schedule, revising the touch up procedure, installation of heater in offline repair cells) were made.

After presenting the project results and achievements and reporting the audit results in a management review meeting, the project closure form was approved and signed by the internal project champions. As previously indicated, these were the paint shop director and the head of the EHS department. This document (Appendix 7) shows that, in addition to satisfactory performance of hitting the EMS targets, there is evidence that the project team also furthered its understanding of Six Sigma tools by successfully applying the appropriate tools in the context of an EMS.

## 5. Conclusion

The trend in modern business management points toward comprehensive and complex management systems that ensure competitive performance in the global economy and satisfy multiple stakeholders in addition to customers. Both quality and environmental management systems share similar roots and objectives. As has been noted in the literature, the continuing expansion of the scope of quality concerns within organizations helps facilitate the integration of quality and environment management systems (Karapetrovic & Willborn, 1998). One major goal of this integration is to translate stakeholder wants and expectations to reality. There are few methods that can translate stakeholder environmental needs into product and process characteristics. One such method is Six Sigma. Six Sigma offers strong potential in this area for a variety of reasons, including (Antony, 2004): clear focus on achieving measurable and quantifiable financial returns, integration of the human elements and process elements, application of well proven quality/statistical tools/techniques for fixing problems and defect reduction in the processes in a sequential and disciplined fashion, and finally emphasis on the importance of data and decision making based on facts and figures.

### *5.1. Summary*

The literature review showed that extensive research had been conducted on EMSs, Six Sigma, integration of QMSs and EMSs, and the significance of integration. However, there is a lack of information provided on the implementation strategies in real life, and/or applicable tools to convert theory to practice. Therefore, the objectives of this thesis were (1) to examine the applicability of Six Sigma in implementing an EMS; and (2) to investigate potential benefits, strengths, weakness and shortcomings associated with using Six Sigma to implement an EMS.

These objectives were addressed through a comprehensive literature review, the development of an original conceptual framework for applying the principles of Six Sigma to an EMS, and by conducting an in-depth case study.

The conceptual framework emphasized that integration can provide the traditional benefits associated with Six Sigma, including cost reductions and reduced defects, while also addressing key environmental issues associated with a product or process. To demonstrate the applicability of the conceptual framework, a case study was conducted with a major Middle Eastern manufacturer. In the case study, various elements of the Six Sigma toolkit, such as Failure Mode and Effect Analysis, DPMO calculation, a SIPOC map, a CTQ tree diagram, a VOC table, Pareto chart and a Cause & Effect diagram, were used to discover the root cause underlying a particular problem and to prioritize action. It was explicitly shown how these tools could be used to set and achieve environmental objectives. The results at the case company show the tangible benefits of pursuing such an approach. At the case company, development of a cost effective strategy for monitoring and reducing the number of scrapped bodies led to waste reduction from 170 scrapped bodies per three months to 27 scrapped bodies per three months. This 80% achievement in waste reduction resulted in $1,025,024 cost saving as well as environmental benefits. These included reduction of solid waste sent to the landfill, a decrease in the amount of waste water produced, a reduction in emissions to the air, a reduction in energy consumption, potential improvements in spill and leak prevention, longer resources life through reduced usage, and improvement in employee health and safety due to less exposure to harmful chemicals. Lower pollution and less waste affected the case company in a variety of ways, including enhanced employee relations, improved operating procedures, increased stakeholder satisfaction, and raised financial performance. Additional improvements were made to document control, auditing, training and other aspects of business performance. The key outcomes of the case study are summarized in Table 16.

Table 16: Summary of the case study

<table>
<tr><th>Phase</th><th>Tools</th><th>Outcomes</th><th>Summary of final results</th></tr>
<tr><td rowspan="6">Initiation of the process</td><td>Project charter</td><td>- Problem statement<br>- Project scope<br>- Project goals</td><td rowspan="14">- Cost reduction<br><br>- Waste reduction<br><br>- Direct flow increase<br><br>- Productivity increase<br><br>- Complying with environmental regulations<br><br>- Energy consumption decrease<br><br>- Reduction of raw material consumption<br><br>- Decrease of emissions<br><br>- Improvement in employee health and safety due to less exposure to harmful chemicals<br><br>- Less waste in landfill<br><br>- Progress towards a sustainable culture</td></tr>
<tr><td>SIPOC map</td><td>Detailed process map</td></tr>
<tr><td>VOC table</td><td>Customer requirements</td></tr>
<tr><td>CTQ diagram</td><td>Translates VOC to technical language</td></tr>
<tr><td>FMEA</td><td>Risk prioritization</td></tr>
<tr><td>DPMO</td><td>Sigma level of current process</td></tr>
<tr><td rowspan="2">Development of the integrated system</td><td>C&E</td><td>Root causes</td></tr>
<tr><td>Pareto chart</td><td>Cause prioritization</td></tr>
<tr><td rowspan="2">Implementation of the integrated system</td><td>Brainstorming</td><td>Creative solutions</td></tr>
<tr><td>DPMO</td><td>Sigma level after improvement</td></tr>
<tr><td rowspan="3">Maintaining the integrated system</td><td>Cost analysis</td><td>Cost reduction calculation</td></tr>
<tr><td>Control chart</td><td>Monitoring</td></tr>
<tr><td>Closure</td><td>Approval</td></tr>
</table>

### *5.2. Contributions*

As highlighted by the literature review, there are relatively few published examples regarding the integration of Six Sigma and EMSs. This study helped provide insight into the potential areas of integration and also Six Sigma tools which could help to address environmental objectives and reach the quality and environmental performance targets. This helps address key gaps in the academic knowledge base. Indeed, an integration strategy is provided, along with a case study to examine the applicability of the suggested approach. This is the first study to provide such information.

The case study demonstrates that there were numerous benefits to applying the principles of Six Sigma to EMSs. An approach based on the conceptual framework was successful in reducing waste in the case company's paint shop by 80%. In addition to the traditional outcomes of Six Sigma, including waste and cost reduction and decreasing the consumption of raw materials, there were other benefits of applying the principles of Six Sigma to the case company's EMS. Finally, the application of Six Sigma's proactive approach can permit the early identification of problems that could be expensive to resolve and damaging to the environment. Early management awareness of problems would offer the best opportunity for efficient resolution and planning to reduce negative impacts. This integrated strategy demonstrates that the organization is proactive about reducing pollution and committed to continual improvement. Overall, the case study showed that Six Sigma could provide a systematic and applicable method to implement an EMS. These original contributions provide a much needed baseline to advance research on applying Six Sigma principles to improve the environmental performance of the corporations.

It is anticipated that the results of this research will find application among corporations that want to embrace integrated systems as a way of doing business and enjoy the many benefits of using Six Sigma methodology in order to improve their environmental performance. It also could help overcome implementation issues associated with existing EMSs. Insight into how integration will improve their management systems could encourage companies to avoid doing business as usual and to try new and promising models. Nevertheless, literature reviews along with the results of this thesis show that the methods used to design and implement integrated systems may be explored in greater depth to get a better understanding and a more accurate measure of the progress towards sustainability.

### *5.3. Limitations*

It is important to acknowledge that there are some limitations to the research. First, as in any single case study, there are questions regarding the generalizability of the research. As noted in the recommendations for further research, this obstacle could be tackled by implementing multiple cases to attain some form of replication. Second, the linkage between Six Sigma and organisational culture was not addressed in this study. For example, the challenges and opportunities of implementing Six Sigma in a non-North American culture was not explored in depth. Finally the amount of reduced emission and energy consumption are not calculated in this study, this could provide an opportunity for further survey and estimation on these topics.

### *5.4. Recommendations for future research*

Further research in this area will need to focus on a more detailed description of how Six Sigma and EMS can be combined in order to attain full integration. Additional case studies will help determine the applicability of the conceptual framework in other situations and may help highlight possible modifications. In addition, there are some challenges in Six Sigma methodology which create opportunities for future research. For example, data availability, expensive solutions, and the start-up cost of Six Sigma may discourage small and medium size corporations. Further guidance on the application of specific tools in Six Sigma initiatives would also be beneficial. This study did not address the applicability of many of these tools (such as, QFD, SPC, MSA, hypothesis tests, regression analysis, and DOE) in an environmental domain.

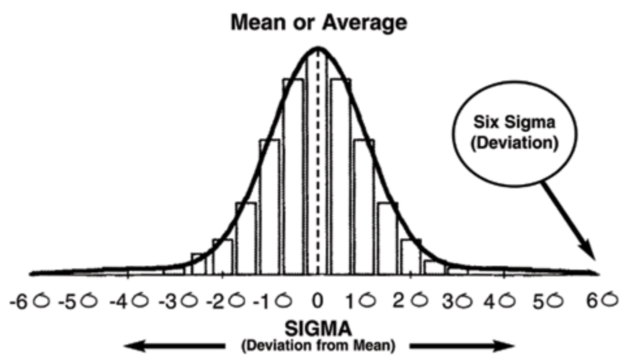
It could be interesting and helpful to explore the use of other Six Sigma / quality tools in an EMS context. In addition, the rate of improvement in the paint shop production process as a function of time or the rate of change in average cost as a function of cumulative output could be studied as a learning curve in the form of a chart to track resulting knowledge against time spent learning. This could help to demonstrate the efficiencies gained from experience.

Appendix 1: The statistical meaning of Six Sigma

In the statistics realm, the Greek letter sigma (σ) stands for standard deviation, which is a measurement of variation. For a population of *N* measurements the standard deviation is:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$

Where $x_i$ is actual measurement and $\mu$ is the mean of the population (Lind *et al*., 2008). Sets of values that can be characterized by the mean and standard deviation can be modeled by the normal distribution or bell-shaped curve. "A centered six-sigma process has a normal distribution with a mean equal to target and specifications placed 6 standard deviations to either side of the mean" (Sekhar & Mahanti, 2006). For Six Sigma the total range spans 12 standard deviations, 6 below the average and 6 above the average. When the sigma value increases, a larger area is under the bell curve. In above Figure, the concept of standard deviation is illustrated. Conceptually, the Sigma Level of a process or product is where its customer-driven specifications intersect with its distribution (Sekhar & Mahanti, 2006). In other words, Sigma level is difference between average performance and the specification limit, divided by the standard deviation. There is a standard conversion table which is known as *Z to DPMO conversion table* that translates Sigma level into a corresponding number of defects. For example, a process operating at Sigma level of 1 could be expected to have 691,500 defects per million opportunities and consequently Yield of the process is 30.85%, or a process operating at



Statistical meaning of Six Sigma (Lean Transformation, 2011)

6 Sigma level produces 99.9997% yield or accuracy, with only 3.4 defects per million opportunities (DPMO) (Liebermann, 2011). In many industries 99% yield is viewed as an exceptionally good measure, but in others such as medical or aerospace even 1% defect rate means people may die. In Six Sigma terms, the best means 99.99% accuracy. A good example of process sigma level estimation is provided in the first chapter of Harry & Schroeder (2000).

Z to DPMO conversion table (Sheehy *et al.*, 2002)

| | **Sigma level-Hundredth** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sigma level-Tenths** | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
| 1.5 | 500,000 | 496,000 | 492,000 | 488,000 | 484,000 | 480,100 | 476,100 | 472,100 | 468,100 | 464,100 |
| 1.6 | 460,200 | 456,200 | 452,200 | 448,300 | 444,300 | 440,400 | 436,400 | 432,500 | 428,600 | 424,700 |
| 1.7 | 420,700 | 416,800 | 412,900 | 409,000 | 405,200 | 401,300 | 397,400 | 393,600 | 389,700 | 385,900 |
| 1.8 | 382,100 | 378,300 | 374,500 | 370,700 | 366,900 | 363,200 | 359,400 | 355,700 | 352,000 | 348,300 |
| 1.9 | 344,600 | 340,900 | 337,200 | 333,600 | 330,000 | 326,400 | 322,800 | 319,200 | 315,600 | 312,100 |
| 2.0 | 308,500 | 305.000 | 301,500 | 298,100 | 294,600 | 291,200 | 287,700 | 284,300 | 281,000 | 277,600 |
| 2.1 | 274,300 | 270,900 | 267,600 | 264,300 | 261,100 | 257,800 | 254,600 | 251,400 | 248,300 | 245,100 |
| 2.2 | 242,000 | 238,900 | 235,800 | 232,700 | 229,700 | 226,600 | 223,600 | 220,700 | 217,700 | 214,800 |
| 2.3 | 211,900 | 209,000 | 206,100 | 203,300 | 200,500 | 197,700 | 194,900 | 192,200 | 189,400 | 186,700 |
| 2.4 | 184,100 | 181,400 | 178,800 | 176,200 | 173,600 | 171,100 | 168,500 | 166,000 | 163,500 | 161,100 |
| 2.5 | 158,700 | 156,200 | 153,900 | 151,500 | 149,200 | 146,900 | 144,600 | 142,300 | 140,100 | 137,900 |
| 2.6 | 135,700 | 133,500 | 131,400 | 129,200 | 127,100 | 125,100 | 123,000 | 121,000 | 119,000 | 117,000 |
| 2.7 | 115,100 | 113,100 | 111,200 | 109,300 | 107,500 | 105,600 | 103,800 | 102,000 | 100,300 | 98,530 |
| 2.8 | 96,800 | 95,100 | 93,420 | 91,760 | 90,120 | 88,510 | 86,910 | 85,340 | 83,790 | 82,260 |
| 2.9 | 80,760 | 79,270 | 77,800 | 76,360 | 74,930 | 73,530 | 72,140 | 70,780 | 69,440 | 68,110 |
| 3.0 | 66,810 | 65,520 | 64,260 | 63,010 | 61,780 | 60,570 | 59,380 | 58,210 | 57,050 | 55,920 |
| 3.1 | 54,800 | 53,700 | 52,620 | 51,550 | 50,500 | 49,470 | 48,460 | 47,460 | 46,480 | 45,510 |
| 3.2 | 44,570 | 43,630 | 42,720 | 41,820 | 40,930 | 40,060 | 39,200 | 38,360 | 37,540 | 36,730 |
| 3.3 | 35,930 | 35,150 | 34,380 | 33,630 | 32,880 | 32,160 | 31,440 | 30,740 | 30,050 | 29,380 |
| 3.4 | 28,720 | 28,070 | 27,430 | 26,800 | 26,190 | 25,590 | 25,000 | 24,420 | 23,850 | 23,300 |
| 3.5 | 22,750 | 22,220 | 21,690 | 21,180 | 20,680 | 20,180 | 19,700 | 19,203 | 18,760 | 18,310 |
| 3.6 | 17,860 | 17,430 | 17,000 | 16,590 | 16,180 | 15,780 | 15,390 | 15,000 | 14,630 | 14,260 |
| 3.7 | 13,900 | 13,550 | 13,210 | 12,870 | 12,550 | 12,220 | 11,910 | 11,600 | 11,300 | 11,010 |
| 3.8 | 10,720 | 10,440 | 10,170 | 9,903 | 9,642 | 9,387 | 9,137 | 8,894 | 8,656 | 8,424 |
| 3.9 | 8,198 | 7,976 | 7,760 | 7,549 | 7,344 | 7,143 | 6,947 | 6,756 | 6,569 | 6,387 |
| 4.0 | 6,210 | 6,036 | 5,868 | 5,703 | 5,543 | 5,386 | 5,234 | 5,085 | 4,940 | 4,799 |
| 4.1 | 4,661 | 4,527 | 4,396 | 4,269 | 4,145 | 4,024 | 3,907 | 3,792 | 3,681 | 3,572 |
| 4.2 | 3,467 | 3,364 | 3,264 | 3,167 | 3,072 | 2,980 | 2,890 | 2,803 | 2,718 | 2,635 |
| 4.3 | 2,555 | 2,477 | 2,401 | 2,327 | 2,256 | 2,186 | 2,118 | 2,052 | 1,988 | 1,926 |
| 4.4 | 1,866 | 1,807 | 1,750 | 1,695 | 1,641 | 1,589 | 1,538 | 1,489 | 1,441 | 1,395 |
| 4.5 | 1,350 | 1,306 | 1,264 | 1,223 | 1,183 | 1,144 | 1,107 | 1,070 | 1,035 | 1,001 |
| 4.6 | 968 | 935 | 904 | 874 | 845 | 816 | 789 | 762 | 736 | 711 |
| 4.7 | 687 | 664 | 641 | 619 | 598 | 577 | 557 | 538 | 519 | 501 |
| 4.8 | 484 | 467 | 450 | 434 | 419 | 404 | 390 | 376 | 363 | 350 |
| 4.9 | 337 | 325 | 313 | 302 | 291 | 280 | 270 | 260 | 251 | 242 |
| 5.0 | 233 | 224 | 216 | 208 | 200 | 193 | 186 | 179 | 172 | 166 |
| 5.1 | 159 | 153 | 147 | 142 | 136 | 131 | 126 | 121 | 117 | 112 |
| 5.2 | 108 | 104 | 100 | 96 | 92 | 89 | 85 | 82 | 79 | 75 |
| 5.3 | 72 | 70 | 67 | 64 | 62 | 59 | 57 | 55 | 52 | 50 |
| 5.4 | 48 | 46 | 44 | 43 | 41 | 39 | 38 | 36 | 35 | 33 |

| | Sigma level-Hundredth | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5.5 | 32 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 |
| | 5.6 | 21.0 | 20.0 | 19.0 | 18.0 | 17.0 | 17.0 | 16.0 | 15.3 | 14.7 | 14.0 |
| | 5.7 | 13.4 | 12.9 | 12.3 | 11.7 | 11.3 | 10.8 | 10.3 | 9.9 | 9.4 | 9.0 |
| | 5.8 | 8.6 | 8.2 | 7.9 | 7.5 | 7.2 | 6.9 | 6.6 | 6.3 | 6.0 | 5.7 |
| | 5.9 | 5.4 | 5.2 | 5.0 | 4.8 | 4.6 | 4.4 | 4.2 | 4.0 | 3.8 | 3.6 |
| | 6.0 | 3.4 | 3.3 | 3.1 | 3.0 | 2.9 | 2.7 | 2.6 | 2.5 | 2.4 | 2.3 |

Appendix 2: Sample of Project charter

| **Six Sigma project charter** | | |
|---|---|---|
| Department:<br>*Production Engineering* | Project title:<br>*Reducing number of scraped bodies in paint shop* | Project code:<br>*PA8901* |
| Revision no.:<br>*1* | Start date:<br>*August 2010* | Finish date:<br>*January 2011* |
| Background of the project:<br>*Increasing number of scrapped bodies resulted in direct flow decrease, productivity decrease and failure in reaching environmental objectives* | Aim of the project:<br>*Decrease number of scrapped bodies at least by 50%* | Scope of the project:<br>*Paint shop #1: Top coat & touch up modules* |
| Team members:<br>*Production engineering supervisor, production engineering experts (3), production manager, quality senior expert, maintenance manager, EHS senior expert* | | Advisor/Master Black Belt:<br>*Paint shop's MBB* |
| Characteristics:<br>*Scrapped bodies* | Measures:<br>*Number of scrapped bodies/number of produced bodies* | Defect definition:<br>*Any produced body which cannot meet quality criteria* |
| Expected benefits:<br>*Waste & cost reduction* | | Required resources:<br>*Access to records and existing data bank, budget for possible modifications, involvement of all departments for solution implementation, and support from top managerial level* |
| Team leader:<br>*A. Jami*<br>*Co-leader: Paint shop MBB*<br>Signature | Coordinating Champion:<br>*EHS director*<br>Signature | Functional Champion:<br>*Paint shop director*<br>Signature |
| CC: Financial department | Cost impact approval by Financial department:<br>*Financial analyst/project division* | |

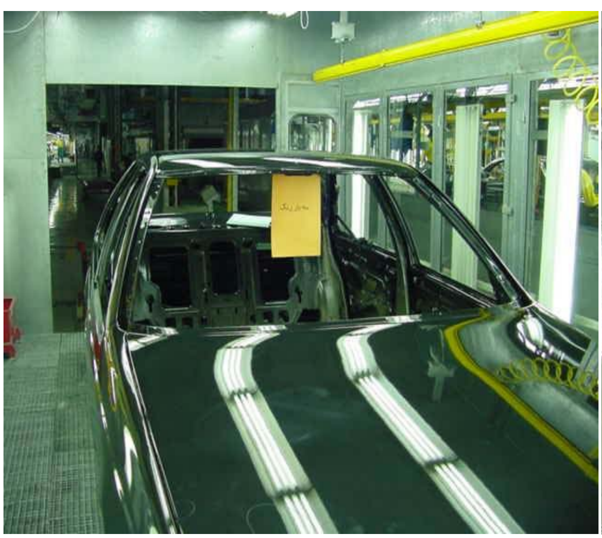
Appendix 3: Sample of rating scale (Williams *et al*., 2001)

| **Severity** | | **Occurrence** | | | **Detection** | | |
|---|---|---|---|---|---|---|---|
| Rating | Criteria: Failure could..... | Rating | Time period | Probability | Rating | Criteria: Failure could..... | |
| 10 | Injure customer or employee | 10 | More than once per day | >30% | 10 | Defect caused by failure is not detectable | Bad |
| 9 | Be illegal | 9 | Once every 3-4 days | <=30% | 9 | Occasional units are checked for defects | |
| 8 | Render the product or service unfit for use | 8 | Once per week | <=5% | 8 | Units are systematically sampled and inspected | |
| 7 | Cause extreme customer dissatisfaction | 7 | Once per month | <=1% | 7 | All units are manually inspected | |
| 6 | Result in partial malfunction | 6 | Once every 3 months | <=0.03% | 6 | Manual inspection with mistake-proofing modifications | |
| 5 | Cause a loss of performance likely to result in a complaint | 5 | Once every 6 months | <=1 per 10,000 | 5 | Process in monitored (SPC) and manually inspected | |
| 4 | Cause minor performance loss | 4 | Once per year | <=6 per 100,000 | 4 | SPC used with an immediate reaction to out of control conditions | |
| 3 | Cause a minor nuisance; can be overcome with no loss | 3 | Once every 1-3 years | <=6 per million | 3 | SPC as above with 100% inspection surrounding out of control conditions | |
| 2 | Be unnoticed ; minor effect on performance | 2 | Once every 3-6 years | <=3 per 10 million | 2 | All units are automatically inspected | |
| 1 | Be unnoticed and not affect the performance | 1 | Once every 6-100 years | <=2 per billion | 1 | Defects is obvious and can be kept from affecting customer | Good |

Appendix 4: Pictures

Preventive maintenance based on modified PM

Quality Alert for recoated bodies, means more consideration of operators and carefulness in preparing such a body in rejected line

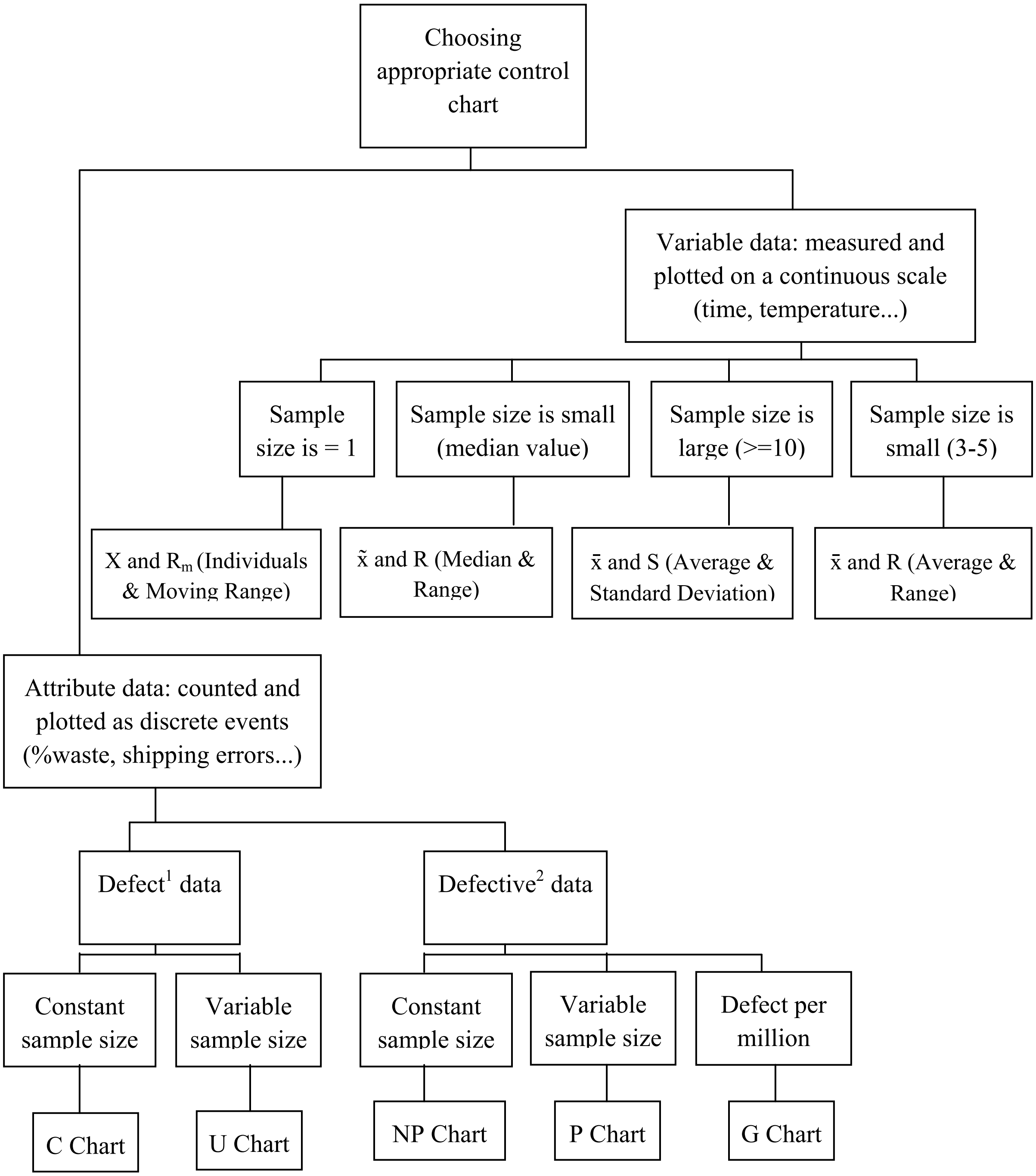


Heater installation in off-line station in order to repair non-confirmed bodies (instead of recoating)

On job training

Installing sensor in the entrance of PBS, this led to prevention of deformation. When the body is not fully adjusted on skid, sensor detects it and line will be stopped automatically.

Appendix 5: Choosing the right control chart (Sheehy *et al*., 2002)




Note: (1) A defect is a failure to meet one of the acceptance criteria; a defective unit might have multiple defects. (2) Defectiveness is when an entire unit fails to meet acceptance criteria, regardless of the number of defects on the unit (Sheehy *et al*., 2002).

Appendix 6: Control limit equations for Geometric chart

$$UCL = \frac{ln\ \frac{\propto}{2}}{ln(1 - P_o)} \times \gamma_\alpha$$

$$LCL = \frac{ln(1-\frac{\propto}{2})}{ln(1-P_o)} \times \gamma_\alpha$$

$$P_o = \frac{\text{No.of scrapped bodies}}{\text{No.of produced units}}$$

$\gamma_\alpha = 1.2844$

$\alpha = 0.0025$

Appendix 7: Sample of Project Closure Form

| Project code & title: *Reducing number of scraped bodies in paint shop, PA8901* | Project leader: *Anahita Jami & Co-Leader: Paint shop MBB* | Date: *January15, 2011* |
|---|---|---|
| Define | Status | Requirements |
| Project charter | ✓ | Mandatory |
| SIPOC | ✓ | Mandatory |
| CTQ Tree | ✓ | Mandatory |
| VOC table | ✓ | |
| Champion(s) Comments | | Champion(s) signature |
| Measure | Status | Requirements |
| FMEA | ✓ | Any two tools from the Measure phase should be selected to meet the minimum requirements; however initial Sigma level calculation is mandatory |
| DPMO | ✓ | |
| Data collection | ✓ | |
| MSA | NA | |
| Champion(s) Comments | | Champion(s) signature |
| Analyze | Status | Requirements |
| C&E diagram | ✓ | Any two tools from the Analyze phase should be selected to meet the minimum requirements |
| Hypothesis test | NA | |
| Regression Analysis | NA | |
| DOE | ✓ | |
| Pareto chart | ✓ | |
| Champion(s) Comments | | Champion(s) signature |
| Improve | Status | Requirements |
| Implementation plan | ✓ | Any two tools from the Improve phase should be selected to meet the minimum requirements |
| Risk Analysis | NA | |
| Sigma level | ✓ | |
| Champion(s) Comments | | Champion(s) signature |
| Control | Status | Requirements |
| Control plan | NA | Any two tools from the Control phase should be selected to meet the minimum requirements |
| Control chart | ✓ | |
| Cost impact analysis | ✓ | Mandatory (where applicable) |
| Champion(s) Comments | | Champion(s) signature |

| Summary of results /achievements:<br>*Waste reduction by 80%*<br>*Cost reduction by $1,025,024 per annum* | Approvals<br>*Coordinating Champion*<br>*Functional champion*<br>*Financial dept. director* |
| --- | --- |

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