Quality Improvement at the Trimming Process of a Composite Manufacturing Firm: Investigation and Implementation

by

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LIST OF ABBREVIATIONS

ACM	Aerospace Composite Malaysia
FaRSLeSS	Failure rate Reduction and Sustainability through Lean and Six Sigma

LIST OF SYMBOLS

Z	The defects percentage per type
A	The number of defects in 2018
B	The number of defects in 2019
C	The sum of all type of defects

Penambahbaikan Kualiti di Proses Penangkasan Firma Pembuatan Komposit: Penyiasatan dan Pelaksanaan

ABSTRAK

Bahan komposit untuk kegunaan industri aeroangkasa dihasilkan untuk memenuhi prestasi tinggi yang diperlukan bagi persekitaran yang mencabar. Industri ini menggunakan bahan komposit yang canggih, selaras dengan meningkatnya permintaan global. Terdapat dua sebab mengapa kualiti tertinggi bahan masuk diperlukan dalam industri ini, iaitu, bahan mentah yang digunakan adalah mahal, dan proses pembuatan yang bakal dilalui bahan mentah adalah kompleks, dan ini mungkin menyebabkan kadar kegagalan yang tinggi. Di samping itu, bahan mentah yang digunakan dalam industri ini mempunyai jangka hayat yang pendek dan proses pembuatannya pula tidak seragam persekitarannya. Dari itu, alat teknik pemeriksaan, sistem pembuatan, dan struktur automatik yang paling sesuai diperlukan. Kajian ini dijalankan di kilang pembuatan komposit aeroangkasa, khususnya di Proses Pemangkasan, di mana panel komposit dihasilkan. Terdapat tiga fasa dalam kajian ini - setiap satu merujuk kepada setiap objektif projek. Fasa pertama ialah mengenalpasti sebab mengapa pekerja sering melakukan kesilapan pada lantai bengkel. Fasa kedua ialah melaksanakan teknik yang sesuai untuk menambahbaik lantai bengkel. Teknik ini digelar 'FaRSLeSS', dan beberapa versi teknik ini sudahpun dilaksanakan dengan jayanya di stesen-stesen kerja lain di organisasi tersebut. Fasa ketiga kajian ialah membangunkan kaedah di mana dapatan Objektif 2 dimasukkan ke dalam sistem proses agar kesinambungannya dapat dicapai di lantai begkel. Untuk mencapai Objektif 1, sebuah soalselidik dibangunkan dan diagih kepada pekerja di Proses Pemangkasan. Adalah didapati bahawa para pekerja memerlukan lebih banyak latihan dalam kaedah pemangkasan dan tentang konsep pengilangan tanpa lemak agar mereka dapat melakukan kerja manual mereka dengan lebih baik. Objektif kedua, iaitu membangunkan teknik FaRSLeSS yang sesuai dan melaksanakannya di Proses Pemangkasan, telah menunjukkan bahawa penambahbaikan, dalam bentuk pengurangan kecacatan, adalah tidak mustahil. Pengumpulan data pada dua masa yang berlainan (Masa 1 ialah 'sebelum' manakala Masa 2 ialah 'sesudah' dan siri diskusi bersama pekerja lantai bengkel) menunjukkan bahawa FaRSLeSS berkeupayaan menghasilkan penambahbaikan sekiranya ia dilaksanakan sepenuhnya. Untuk ini, data dikumpul dan digunakan dalam Carta Pareto dan Rajah Sebab-Akibat, dan sebuah meja bergerak direkabentuk untuk digunakan bagi membantu pergerakan panel dari satu lokasi ke lokasi yang lain agar ketukan dan pelanggaran yang boleh menyebabkan kecacatan dapat diminimakan. Di samping itu, program latihan dibangunkan dan dilaksanakan sebahagiannya ke atas pekerja. Akhir sekali, perubahan yang dicadangkan diinstitusikan untuk memastikan kesinambungan penambahbaikan di Proses Pemangkasan.

Quality Improvement at the Trimming Process of a Composite Manufacturing Firm: Investigation and Implementation

ABSTRACT

Aircraft composite parts are manufactured to fulfil high levels of performance under demanding conditions. The aerospace manufacturing industry uses sophisticated composite materials, in line with increasing global demands. There are two main causes that lead to the need for high quality incoming materials in industry, and they are expensive raw materials and the complexity of the manufacturing process that the incoming materials are going to be subjected to, which may lead to high failure rates. To add, many raw materials used in the industry have short lifespan and a wide range of inconsistent manufacturing conditions. Hence, the most appropriate inspection techniques tooling, manufacturing systems, and automated structures are required. This study is carried out in an aerospace composite manufacturing plant, specifically at the Trimming Process where composite panels are produced. There are three main phases of the study, each corresponding to the three objectives of the work. The first phase is to identify the causes that lead to workers making frequent mistakes in the production line, while the second phase is to implement a suitable technique for improvement on the shop floor. The technique is called 'FaRSLeSS' (Failure Rate Reduction and Sustainability through Lean and Six Sigma), whereby, some versions of it have already been successfully implemented at other work stations in the company. The third phase of the research is to develop a way to incorporate the outcome of Objective 2 so that the improvement seen can be made sustainable on the manufacturing shop floor. To achieve Objective 1, a questionnaire is developed and distributed to the workers at the Trimming Process. It is found that the workers need more training on trimming methods and general manufacturing lean concepts in order to do well in their work, which is predominantly done manually. The second objective, which is to develop the appropriate FaRSLeSS technique and to implement it on the Trimming Process, has shown that improvement, in the form of reduction of defects, is possible. Collection of data at two points in time (Point 1 is 'before' while Point 2 is 'after' a series of discussions with workers on the shop floor) show that FaRSLeSS has a high potential of enabling improvement if used on a full scale. For this, data is collected and then fed into Pareto Charts and Cause-and-Effect Diagrams, and a movable table is designed to be used to aid in the movement of panels from one location to another so as to minimize knocks and bumps that would lead to defects of the panels. To add, a training program is developed and partly implemented on the workers. Lastly, institutionalization of the amendments is proposed to ensure sustainability of the improvement at the Trimming Process.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

The manufacturing industry is about the production of goods for the purpose of use or sales using workforce, machines, tools, chemicals and biological processing and formulations. It involves a group of activities that range from workmanship to sophisticated technology, of which raw materials are converted into final products. Some manufacturers purchase the finished goods of other manufacturers to be used as the raw materials of more complex finished products like aircraft components.

Aircraft composite parts are manufactured to fulfil high levels of performance under demanding conditions. The aerospace manufacturing industry uses sophisticated composite materials, in line with increasing global demands. There are two main causes that lead to the need for high quality incoming materials in the industry - expensive raw materials and the complexity of the manufacturing process that the incoming materials are going to be subjected to, which may lead to high failure rates. To add, many raw materials used in the industry have short lifespan and a wide range of inconsistent manufacturing conditions. Hence, the most appropriate inspection techniques, tooling, manufacturing systems, and automated structures are required.

Formerly, aircraft manufacturing has been predominantly carried out manually, particularly in assembly operations. This was because there used to be many changes in aircraft design, with long development times, which meant sequential manufacturing was not applicable. Investing in expensive equipment, from the economic perspective, was deemed not suitable, even though it was seen as technically suitable. Reports from Airbus and Boeing show that the amount of air travel is expected to increase by approximately 5% annually in the next 20 years. This is an obvious indicator that the demand for aircraft manufacturing will increase too. In order to achieve low costs, a shorter time for product development and manufacturing processes are needed (Tekin & Kapan, 2016).

In the aircraft composite industry, the importance of the use of quality tools in the analysis of data and information is very much needed due to the fact that the problems that occur on the manufacturing shop floor tend to be very complex and hence require good problem-solving capabilities. The problem solver should possess proper methods to identify the correct tools to be used. This could help the problem solver identify the factors that may have caused the problem to occur, hence allowing him/her to work towards finding and implementing the most appropriate solutions effectively and efficiently (Hueber et al., 2016; Balasubramanian, Sultan & Rajeswari, 2018). One of the most frequently used problem-solving tools is six-sigma. This tool enables the problem at hand to be identified, defined, and organized, leading to the proper way of solving the problem eventually.

This research looks at the implementation of problem-solving tools that use six-sigma as its base. The tool is used in a manufacturing company that assembles composite materials to be used in the aerospace industry. Because this industry involves the safety of aircraft passengers, the parts produced must fulfil all safety requirements which are of very high standards. All possible defects of the finished products must be eliminated or at least minimized (Mcilhagger, Archer, & Mcilhagger, 2015).

1.2 ACM Background

The subject of this study is an organisation called Aerospace Composite Malaysia (ACM). It produces panels for plane structure, starting from fetching raw materials and ending by shipping and exporting the finished panels. ACM was established in 1998 and is located at Bukit Kayu Hitam, Kedah, Malaysia. It was officially opened in September 2002 by Tun Dr. Mahathir Mohamad. It costed 32 million USD. ACM is the only distributor and producer of fixed leading-edge and trailing-edge composites for Boeing 737, 47, 757, 767, and 777 commercial airplane models.

In 2008, Boeing chose ACM to provide rudder machined honeycomb core and elevator for the 777 model. In 2017, ACM began to produce 777X parts, involving empennage panels and composite fixed-edge panels. In a period of 18 months before December 2018, ACM worked on 10 new programs successfully. Recently, ACM started 5 developmental programs and 34 sustaining programs. The rate of productivity of ACM is approximately 13000 parts per month, which means it produces 156000 parts annually.

1.3 Overall Process Flow in ACM

ACM has thirteen different processes. Its raw material is the “honeycomb core” that comes in blocks. The first process is cutting big blocks into small sheets called “core sheets”. This “core sheet” is then sent to the core fabrication area and further cut by using a cutting template.

Next is the chamfering process, where the chamfering station receives the "core sheet" from the core fabrication area and removes unnecessary dusts while performing the chamfering process. After that, inspectors check the parts, which are now called "core details". "Core details" are stored as inventory before they are sent for the lay-up process. There are two types of materials – flyway and non-flyway. The operators in the lay-up process station control parameters such as temperature, humidity, and particle count. Then, from the lay-up process, the parts are sent to the autoclave process. The autoclave process has three parameters, namely pressure, vacuuming, and temperature. After that, the parts go to the trimming process, where there are machines that comprise a waterjet, 5s, and DMS machine. Operators use the 5s machine to control the tolerance of the panel. Low-cost panels use the waterjet machine for trimming, while high-cost panels use 5s machines that comprise H&H machine, jackman machine, and DMS machine.

The next process is the deburr process. In this process, excessive burns on the surface of the panels are removed. From the deburr process, the parts go for trim inspection. Operators inspect the panels based on the physical condition of the panel, according to specifications that fulfil customer requirements. The next step is the non-destructive testing (NDT) process. Usually, operators just assemble the parts, but when they face work issues, usually in terms of defects, they will request that a full scan is applied on the panel. The next stage is the painting process, which is carried out based on customer requirements. After that, the panels will be sent to the final inspection process, where they are inspected by operators for their physical conditions, alongside all required documentations. The last process is the shipping process, where the panels are shipped abroad. Figure 1.1 shows the overall manufacturing process in ACM.

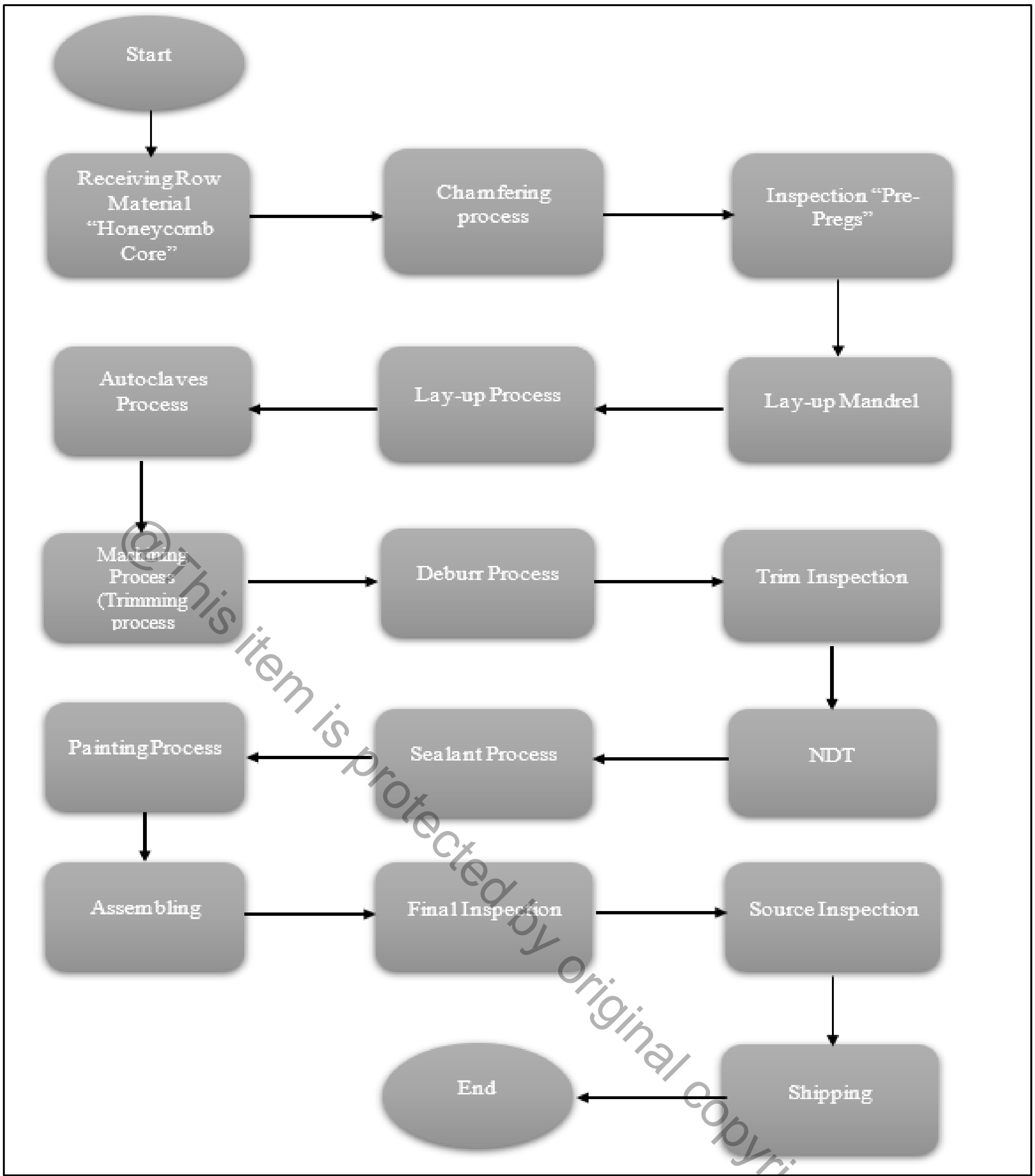

Figure 1.1 Overall Manufacturing Process Flow in ACM

1.4 Problem Statement

Currently, ACM is facing a challenge in one of its main composite manufacturing processes, namely the Trimming Process. The defects occurrence in this process is very high. Records show that the defects are due to the negligence of the workers who are performing manual tasks at the current process station. High defects lead to low quality of finished products. These products must then be discarded or reworked – both requiring high costs to the organisation.

In 2016 till 2018, there were more than 20 cases of rejected panels. The panels were rejected mainly due to Delamination, which is a failure mode that causes a fracture into layers inside the panel, costing ACM approximately RM500,000 per year. Hence, there is an urgent need to study the problem in more detail in order to propose and implement solutions to overcome the problem.

1.5 Objectives of the Study

The objectives of this study are:

1. To identify the causes that lead to workers making frequent mistakes in the production line, namely the Trimming Process, hence leading to defects to be present in the final product.

2. To implement a suitable technique (subsequently called the FaRSLeSS approach) that can minimize the problem.

3. To institutionalize FaRSLeSS into the shop floor to assure sustainability of the improvement process.

1.6 Research Questions

The main questions to be answered in this research are:

1. What are the causes that lead workers to make mistakes in the production line?

2. What can be done to minimize the occurrence of workers making the mistakes?

3. What can be done to ensure that the improvement made continues to benefit the production line?

1.7 Research Scope

This research is limited to:

1. Investigation carried out only at the Trimming process station of ACM.

2. Mistakes that are caused by tasks that are performed manually only (as opposed to mistakes or defects caused by machine problems).

1.8 Expected Outcomes

The expected outcomes of the project are:

1. A greater understanding of the circumstances that lead to workers making mistakes at the Trimming Process.

2. A process technique (called the FaRSLeSS approach) that can be used to minimize the occurrence of mistakes at the Trimming Process.

3. A method to institutionalize the FaRSLeSS approach so that the improvement made in the process continues to bring in benefit to the production line.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter presents all related topics that are important to the thesis. Section 2.2 covers the philosophy and principles of lean manufacturing. The following section, Section 2.3 describes the concept of six-sigma, which includes DMAIC process. Then, Section 2.4 discusses the integration of lean and six-sigma (FaRSLeSS) approach, with its particular tools that are related to the current case at the Trimming Process (Poka-Yoke, 5S, Pareto, Cause and Effect). Following that, Section 2.5 covers aerospace composite manufacturing and the process of composite fabrication. The last two sections, namely Section 2.6 and Section 2.7, discuss the Trimming Process (trimming of the aircraft model), and about workers' issues in terms of their performance and consistency in the production line.

2.2 Lean Manufacturing

Waste reduction is the main aim in manufacturing lean philosophy. Recently, many manufacturing companies pursue many available modern tools and technologies in order to affirm and show themselves to be good global suppliers of manufactured goods. Researchers define the terminology of "lean manufacturing" to be the fundamental mechanism to ameliorate and enhance production with minimum resources.

Lean manufacturing comprises two basic words - lean and manufacturing. "Lean" is reported to bring in much value for customer and industry (Kumar & Kumar, 2015).

Lean manufacturing practices (LMP) are aimed to improve the sector by reducing as much waste as possible (Balakannan, 2015; Zhu, Sarkis, & Lai, 2007). In terms of accomplishing competitive advantage through operational benefits, lean manufacturing has demonstrated how it can drive to higher volumes of production through the minimum use of resources. Productivity improvement through lean manufacturing is seen to be a combination of optimization and co-ordination of the input resources to reduce the amount of waste so that total cost is cut down, as suggested by Ade & Deshpande (2012).

Carrying out lean manufacturing, as suggested by Rameez & Inamdar (2010), means eliminating non-essential steps to fulfil customer demands and expectations. A researcher, Hudli Hohd investigated the ways to improve and develop techniques that can be utilized to evaluate the implementation of lean manufacturing practices and decision making (Rameez & Inamdar, 2010). Another study by Ramesh (2009) discussed a simulation conducted for a single piece lean line design with some features of lean manufacturing. He used standardized work for the lessening of cycle time, work-in-progress, number or setups and number of workers. There are other steps taken too, and they include modifying the design of visual management techniques, and introducing Kanban replenishment system (Ramesh, 2009).

2.3 Six Sigma

Six Sigma is a systematic approach that relies on data, utilizing the DMAIC process. DMAIC comprises Define, Measure, Analysis, Improve, and Control. In addition to that, there is also the DFSS, which is Design for Six Sigma, that complements the traditional six sigma framework. Six sigma makes it possible for an organization to rise to an improved level through the rigorous application of statistical tools and techniques. It is generally applied to the manufacturing shop floor in order to cut down the occurrence of problems that are common to production (Kwak & Anbari, 2006).

2.3.1 DMAIC Process

DMAIC is a closed loop process that eliminates unproductive steps. It has several key steps, and is often focused on new measurements. It applies technology for continuous improvement. Table 2.1 presents the key steps of six sigma using DMAIC process.

Table 2.1 Key steps of six sigma using DMAIC process (Kwak & Anbari, 2006)

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

	Develop a strategy to monitor and control the improved process.
	Implement the improvement of system and structures.

The literature shows that six sigma has many merits, and has helped the manufacturing industry improve tremendously. One author claimed that Six Sigma is more comprehensive compared to previous quality initiatives such as Continuous Quality Improvement (CQI) and Total Quality Management (TQM). Apart from its use one the manufacturing shop floor, there are many areas that benefits from six sigma, including project management, measuring and reporting of financial results, projects on customers, and several others that use more advance data analysis tools (Kwak & Anbari, 2006). Six-sigma management can be summarized as follows:

Six Sigma = TQM (or CQI) Stronger Customer Focus + Additional Data Analysis Tools + Financial Results + Project Management.

2.4 Integration of Lean and Six Sigma

To-date, in the aerospace composite manufacturing and assembly line, there are not many studies that look into maintaining production yield at a desired value using both lean manufacturing and Six Sigma. Rather, a review of the literature finds that if ever both lean manufacturing and six sigma are used on the production line, they are used separately (M. S Ismail et al., 2018). Thus, the integration of lean and six sigma (sometimes referred to as "lean six sigma") seems to be a good option to further explore. Given the effectiveness of both techniques as reported in literature, it is only to be expected that their combination is likely to result better waste reduction, higher quality of product, superior productivity, and improved sustainability.

2.4.1 FaRSLeSS Approach

The FaRSLeSS approach is an integration of lean and six sigma approaches to reduce failure rate in the manufacturing production line. FaRSLeSS stands for “Failure Rate Reduction and Sustainability through Lean and Six Sigma” (Ismail et al., 2018). FaRSLeSS is developed to enhance the quality of the manufacturing process of which it is expected that the resultant product will also be high in quality. It comprises systematic steps to be taken in order to lower the failure rate in the production line rapidly and efficiently. Once the failure rate reaches the final target, the current approach proposes on how to sustain the performance in the future. Hence, it is imperative to first determine how to reduce failure rate, and then to determine how to sustain the reduced failure rate so that whatever improvement made earlier on can still be seen over a long period of time.

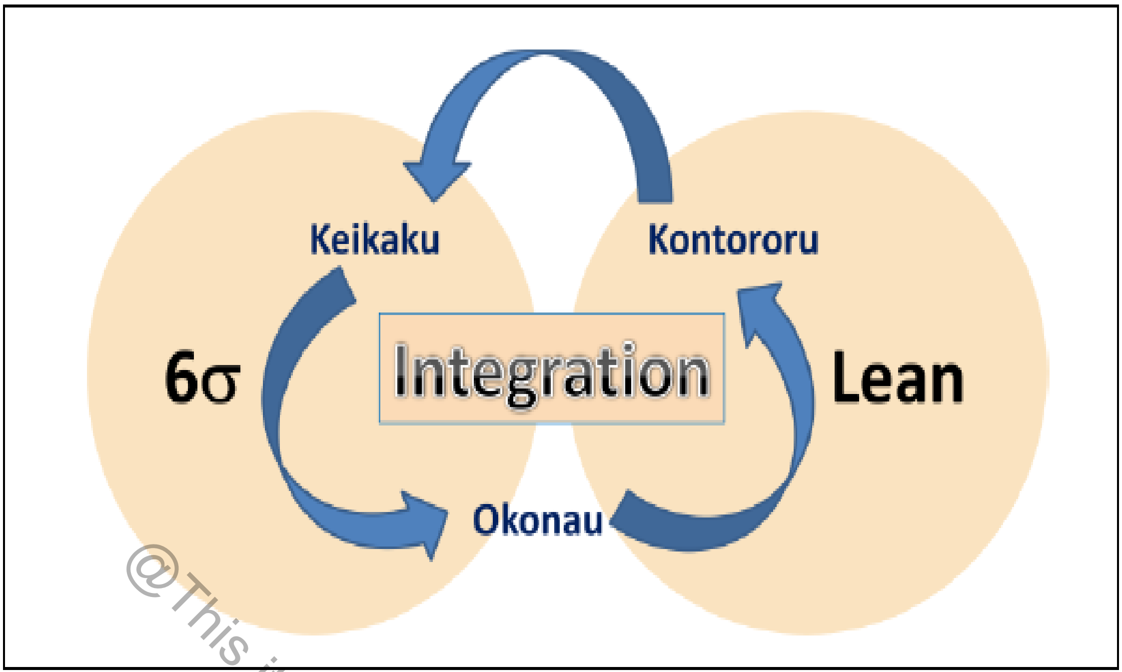

Figure 2.1 FaSLeSS Approach Model (M. S Ismail et al., 2018)

Figure 2.1 represents the integration between lean and six sigma approaches in FaRSLeSS model, which is guided by Keikaku, Okanau, and Kontororu (KOK) cycle. KOK is from three Japanese words that represent three main steps involved in a cycle in order to complete the implementation of the process.

2.4.1.1 Step 1 – Keikaku (Planning)

Keikaku is the first step in FaRSLeSS. This first step requires appropriate planning to be managed by a qualified team that includes top management and production engineers. There are several factors that should be pursued to identify the problem on hand and to be transparent to all team members. The problem to be solved must be identified, recognized, and defined. Thereafter, the problem statement, objectives and scope of the project should be determined, discussed, written, and exhibited to all team members. It is a good practice if a project name is allocated for the visibility of the project as well as for easy monitoring. For example, in the aerospace composite manufacturing industry, there was one case that happened in 2014, which was considered very serious and had a very high impact in terms of parts disposal cost. Many in the industry agreed that parts disposal of 50% only would be the Key Performance Index (KPI) that should be targeted, and that lean manufacturing and six sigma approaches should be implemented to achieve this target (Ismail et al., 2018).

2.4.1.2 Step 2 – Okonau (Executing)

Okonau means executing the project by measuring, analysing, and improving all activities carried out in the process. There are two main purpose in measuring – the first is to collect data to quantify and validate the problem in order to discover the causes that lead to the occurrence of the problem. The second purpose is to analyse the data so that the appropriate tools can be selected to eliminate or at least reduce the problem (Ismail et al., 2018). In many cases, advanced statistical techniques must be used to verify and identify the cause of the problem.

The traditional method to improve and solve the problem involves engineers to completely rely on temporary solutions or countermeasures and neglecting the root cause of the problem that typically occurs whether directly or indirectly. Even after the problem seems to have been solved, there is a significant chance of the problem to be repeated in the future. This happens when the actual root cause is not eliminated yet, and this is the main disadvantage of this traditional method. Therefore, the problem must be solved by going into the deep root causes that make the problem to happen, using a systematic way in the lean six sigma approach. In lean perspective, the implementation of continuous waste management practices could continuously improve the process in the long term. There are different tools to help in the improvement process such as Kaizen, 5S and 3M's (Muda, Muri, Mura). From six-sigma perspective, statistical and non-statistical results that come from the process should be analysed, and actions must be taken based on the statistical results to ensure that real improvement is achieved.

2.4.1.3 Step 3 – Kontororu (Controlling)

The two most essential steps to maintain ideal enhancement of the process are controlling and sustaining. Without these two, the problem might be repeated later on, which will bring many troubles in the long run. The enhancement of the items should be reviewed periodically. The reasonable frequency for reviewing the process is on a weekly basis, depending on the production output. If the result is found to divert from the lower and upper control limit that have been pre-calculated, then, action must be taken immediately.

The responsible team that has been assigned to investigate the shop floor problem should be capable of creating a system of standard documents for process sustainability and easy monitoring. There are multiple tools with regards to lean six sigma to help this purpose, and they include Work Instruction (WI), Standard Operating Procedure (SOP), continuous Kaizen activities, Continuous Quality Improvement (CQI), Process Flow, and Statistical Process Control Chart (SPC). The team should develop a monitoring process to complete specific control tasks and to keep track of changes that take place in the process. An important step is to create a response plan that may help to deal with problems which might emerge. The plan must also take into account on how to get management's attention on a few critical measures so that actual information can be relayed to the management rapidly (Ismail et al., 2018).

2.4.1.4 Poka-Yoke Approach

Poka-Yoke is a lean manufacturing tool and an approach that can applied to prevent the occurrence of defects (Smith, 1993). Poka-Yoke is invented by Shigeo Shingo in the 1960s. It alerts workers on the production floor that defects are going to occur, and hence the workers must fix the errors immediately. Fixing of errors in the early stage would save many problems later in the process flow. Hence, Poka-Yoke enables for the occurrence of mistakes to be very minimal or at least easily detected (Smith, 1993). Obtaining zero defect products is the main objective of Poka-Yoke, whereby it prevents mistakes by utilizing simple approaches of assembling, warning, fixing and other related tools. This approach acts as a tool that indicates or cautions workers of potential mistakes. It switches off machines if there is an emergency case. A device is called ‘anti-error’ can be installed and used to prevent and detect errors (Vinod et al., 2015). The concept of Poka-Yoke may be applied in a range of work activities, such as when developing new products, or when the cost of the error might be significantly high.

2.4.1.5 Pareto Chart

An Italian sociologist and economist, Vilfredo Pareto, who lived more than hundred years ago, observed that 20% of the population owned 80% of property in Italy (Dunford et al., 2014). After period of time, he developed a mathematical formula to characterize the unequal distribution, which is known as the Pareto Distribution. One business management consultant named Juran found that the 80-20 rule was applicable in most manufacturing set-ups in the late 1940s. This was then known as the Pareto Principle (Dunford et al., 2014).

The Pareto principle states that in many instances, 80% of the outcome or results are produced by 20% of the input or causes. This principle is utilized in the management, business and economics sectors in order to enhance productivity and develop better decisions. Furthermore, it is also utilized in many human activities and also in the field of computer science. It aids in the recognition of the majority of outputs that comes from a minority of inputs.

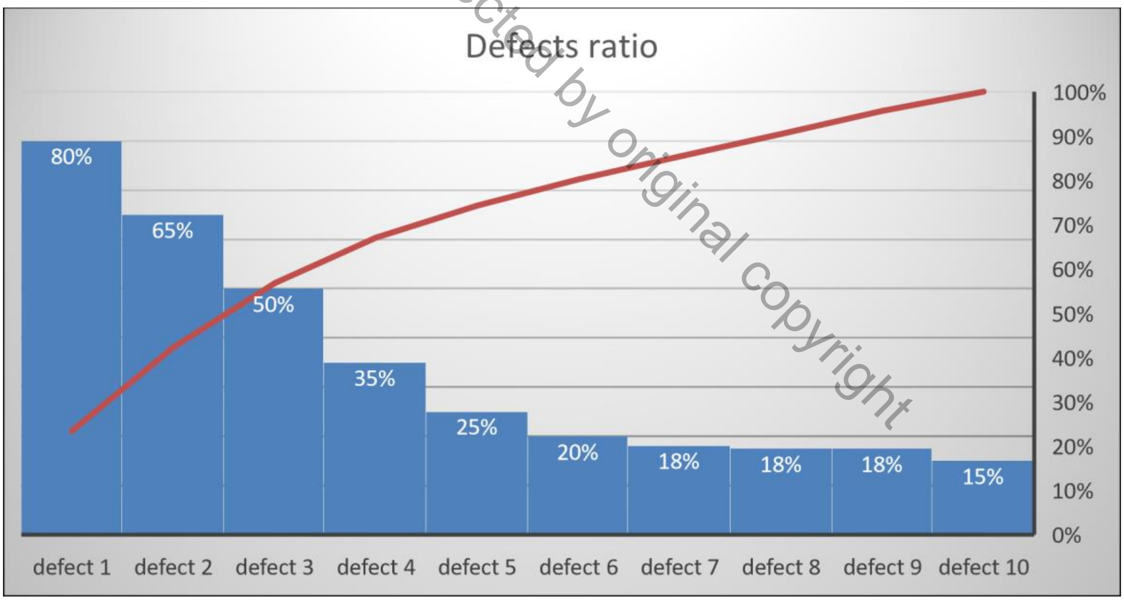

Figure 2.2 A Sample of Pareto Chart for Defects

2.4.1.6 Cause-and-Effect Diagram (Fishbone Diagram)

The fishbone diagram is one of many lean six sigma tools that can be used on the manufacturing shop floor. The fishbone diagram is sometimes known as the cause and effect diagram or Ishikawa diagram. It is a graphical and systematic method to illustrate multiple causes of a specific event or phenomenon. The main purpose of the fishbone diagram is to identify the causes and effects of certain items or features. The analysis that goes with the diagram assists in the categorization of the complex interactions that happen in a particular problem or phenomenon. Ishikawa (1990) developed this diagram when he was doing research field of quality management (Coccia & Niversity, 1957).

The cause and effect diagram started was initially mainly used as a tool for quality control. It was put to use to study the occurrence of quality defects in manufacturing and product design. Each cause is a source of variation of the phenomena under study. The causes are normally grouped into main categories in order to classify the total sources of variation that drive the occurrence of a main effect.

Generally, the diagram can be applied as a convenient visual impersonation of events that include the realization of several Cause and Effect factors and how they interconnect with one another (Coccia & Niversity, 1957). Two researchers, Ramakrishna and Brightman (1986), studied the workings of the diagram and compared it to other types of diagrams and techniques like Fact Net Model and Tregoe & Kepner method to investigate their similarities and variances. Generally, they found that the fishbone diagram is a suitable tool to clarify the interconnected drivers of complex phenomena.

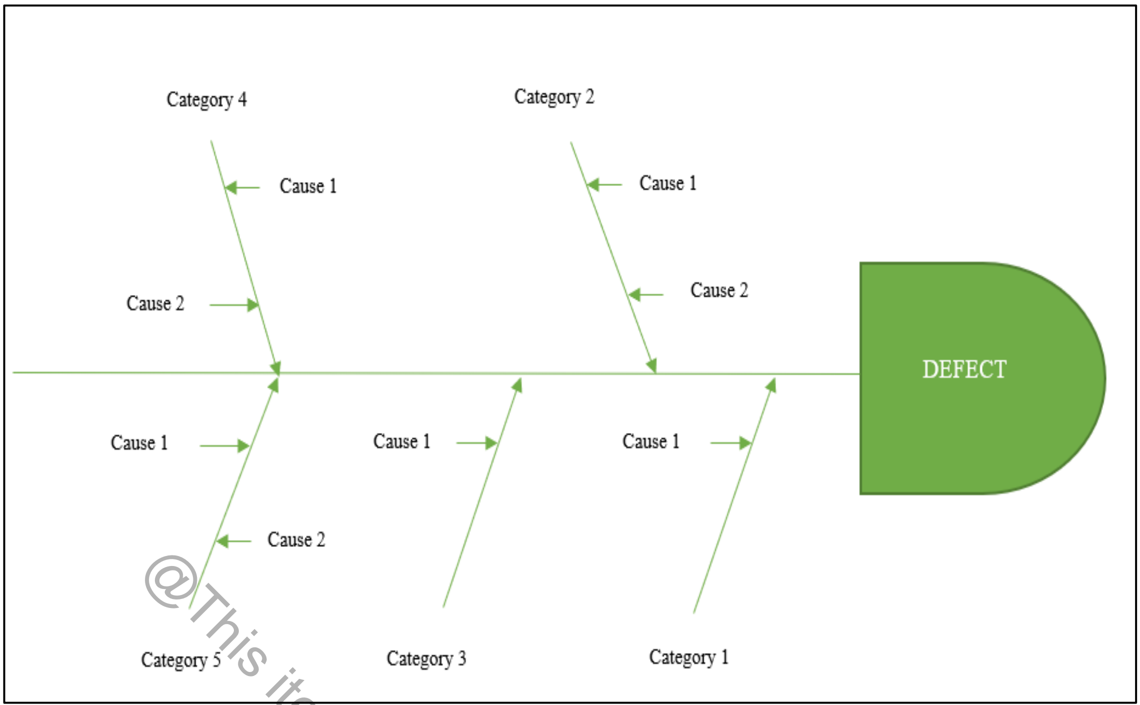

Figure 2.3 A Sample of Cause and Effect Diagram for Defects

2.4.2 PaDLeSS Approach

The PaDLeSS approach is created from the integration of lean manufacturing and six sigma tools, followed by RDMAIC-S cycle. The R-DMAIC-S cycle consists of seven steps, namely, Recognize (R), Define (D), Measure (M), Analyse (A), Control (C), and Sustain (S).

The main objective of the PaDLeSS approach is to improve the overall process of a given manufacturing line. The term of PaDLeSS stands for Part Disposal Reduction through Lean and Six Sigma. Because of the high unit price of composite panels of aircraft, a systematic approach to improve, control and sustain the process is essential. 'Process' here is not necessarily referring to manufacturing process only, but also customer process and outgoing process as well (Ismail & Hussain, 2017).

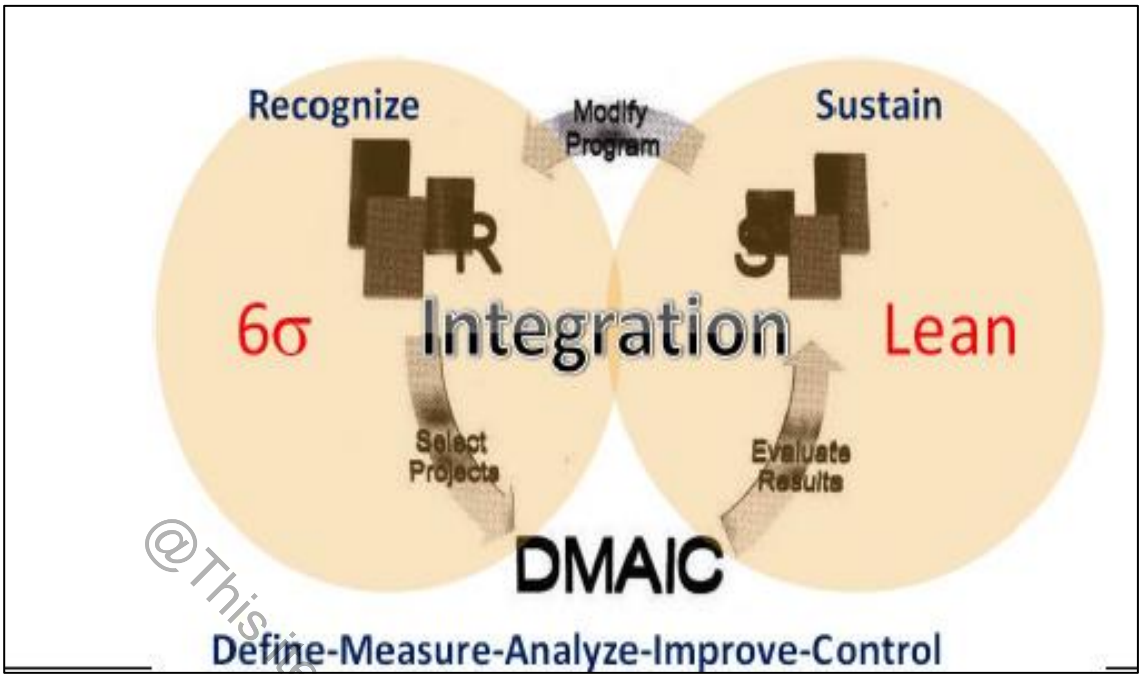

Figure 2.4 PaDLeSS Approach (Ismail & Hussain, 2017)

2.5 Composite Manufacturing in the Aerospace Industry

Composites are new advanced materials now commonly used in engineering applications. A composite material comprises ceramics, metals, and woods. Composites are used in replacement of conventional materials due to their stable performance and ideal properties. There are two main advantages for using composites - they improve aircraft performance, and help reduce fuel consumption. In Figure 2.5 shown below, composites are widely used in aerospace applications recently.

The manufacturing of composite parts is designed to achieve superior levels of performance to adapt with conditions of high demands that are regularly found in the aerospace industry. International demand is growing for composites materials to be used in aircrafts. Nevertheless, there is always the possibility of increasing risks when the materials are in use. This is because the manufacturing process related to aircraft parts is very complex, and hence there are many instances where mistakes and errors can take place. Aircrafts carry passengers, and therefore safety is a very important factor. Hence, risks must be reduced as much as possible. Risks can be reduced by taking some issues seriously. For example, raw materials with short shelf life and the wide range of manufacturing variables must be suitably controlled. There are some necessary factors that must be thought of and acted upon during the manufacture and assembly of aircraft parts, such as automated manufacturing, appropriate tooling, cutting-edge inspection methods for composite materials, and advanced manufacturing techniques.

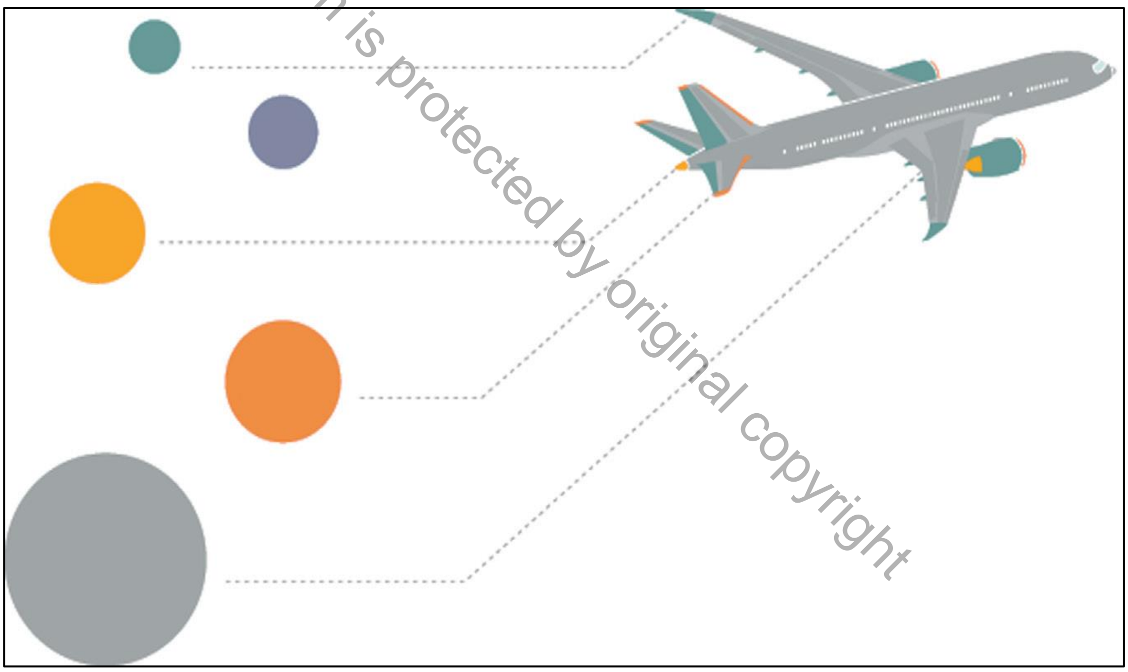

Figure 2.5 Composite Application on the Boeing 787 Aircraft (Up, n.d.)

Since World War II, composite materials have been utilized in wide range in aircraft manufacture, as stated by the Federal Aviation Agency (FAA). The approximate content of composite materials in the structure of a typical aircraft is up to 70%. Because of the high production cost of composites to be used in the aircraft, the related manufacturing process must be effective and efficient. Figuring out the costs of manufacturing in the early stage is essential.

As stated earlier, safety is a very important factor in the aircraft industry. Hence, a study of materials stress points is vital. The possibility of occurring stresses in aircraft structures is very high, and hence it is essential for the raw materials used to have maximum creep resistance and strength. There are three elements that require monitoring to achieve consistency of the final product, namely, lay-up direction, thickness, and volume of the core panel materials. By considering the tooling and composite configurations used during the process, safety of the parts can be assured (Balasubramanian et al., 2018).

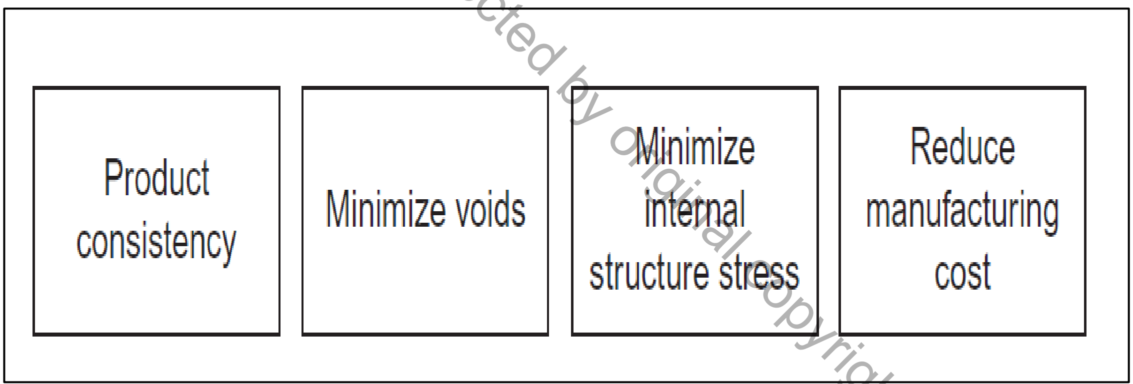

Figure 2.6 Aims to Composite Manufacturing in Aerospace Industry (Balasubramanian et al., 2018)

Composite materials carry with them some problems that occur frequently. The problems include polymer degradation, dry spots, porosity, and voids. To produce good quality final products, manufacturing cost is increased. In other words, a good manufacturing process (or a process that results in good products) always cost much, particularly on the cost of tooling and equipment. Hence, to keep manufacturing cost as low as possible, engineers on the shop floor must think of ways to implement methods that do not need high financial requirements.

Generally, there are four categories of composites, namely, hybrid composite, woven fibre composites, chopped fibre composites, and continuous fibre composites. The types of composites are shown below in Figure 2.7.

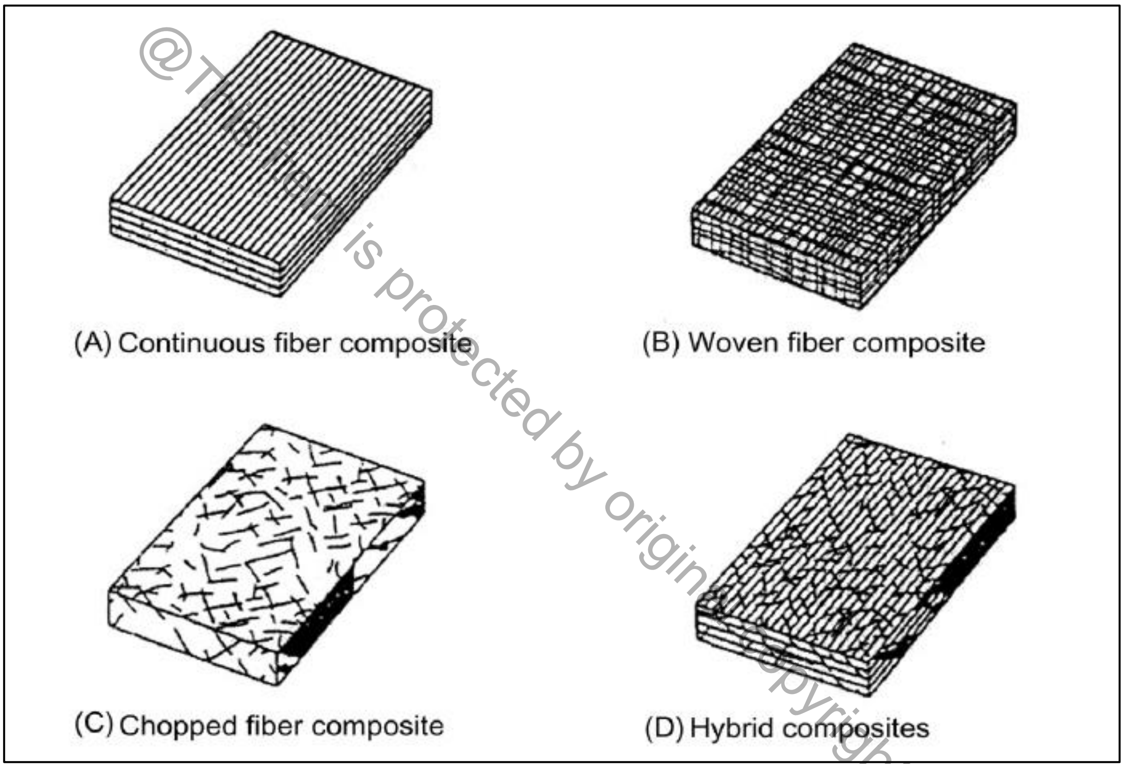

Figure 2.7 Types of Fiber-Reinforced Composite (Balasubramanian et al., 2018)