Lean Transformation for Composite-Material Bonding Processes

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Abstract

Composite materials can greatly reduce production and transportation costs and so that they are widely used in the aerospace industry. Traditional composite materials manufacturers are facing competitive challenges such as shorter delivery time, high quality, and quick response to customer demand. Lean methods have been effectively applied to various industries for improving production quality and efficiency. In this study, a framework of lean transformation are organized and presented in a systematic way. The proposed lean transformation techniques are implemented in an aerospace company to improve the composite-material bonding process. Implementation results suggest the overall productivity of the composite-material bonding process increase significantly due to the elimination of bottlenecks, reduction of cycle time, and decrease of WIP inventory. The proposed approach can be applied to other manufacturing enterprises for improving their productivity.

1. Introduction

Composite material is one of the most important airplane body structure components. The advantage of composite materials lies in the capability to hold the merits of original materials while preventing from their weakness [1, 2]. Compared with traditional metal materials, composite materials possess many special features, such as lighter mass density, stronger structure, better anti-corrosiveness, better anti-fatigue, and like [3].

So, the utilization of composite materials is widely seen in many industries such as aerospace industry, vehicle industry, construction industry, etc. In particular, composite materials are gradually replacing metal materials for manufacturing components and used in aerospace industry.

For many domestic composite materials manufacturers, their production facility and manufacturing process have been designed for small-to-medium production scale with push production systems. Due to market competition, the customers always demand shorter delivery, more cost effectiveness and higher quality. Therefore, those domestic manufacturers must somehow improve their manufacturing techniques and efficiency in order to strengthen their competitive.

Lean methods are originated and developed from Japanese Toyota Production Systems. The original idea of lean techniques is to eliminate waste or non-value-added activities in production process and reduce production cost. The core

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skills and tools for lean methods may include: 1) applying value stream mapping to analyze the enterprise value chain, 2) using takt time to accommodate customer demand, 3) setting up pull-systems to replace push-systems, and 4) implementing line balancing, heijunka scheduling, and just-in-time for production planning.

In the early 1980s and 1990s, several scholars dedicated to lean production research and obtained significant results. Issues of multi-function work design, just-in-time production process, small batch size, pull-type kanban systems, and quick changeover production line have been studied by several scholars [4, 5, 6, 7]. Lee and Ebrahimpour [8] applied the value stream mapping tool to find roots of production problems and provided necessary information for improvement. Mabry [9] studied methods of applying small batch size, eliminating non-value-added activities, relocating facility layout and material flow, and designing efficient work study for improving efficiency for auto parts suppliers. Jones et al. [10] stressed on the importance and benefit of using value stream mapping for analyzing production process. Bamber and Dale [11] reported some findings of their research which studied the application of lean production methods to a traditional aerospace manufacturing company. Two main stumbling blocks to the application were identified, that is, the redundancy program and a lack of employee education in the concepts and principles of lean production. Lewis [12] argues that lean production can improve competitive advantage if the firm is able to have the productivity savings. It creates by combining normative and critical theory with empirical material drawn from three case studies.

Recently, Sullivan and Aken [13] summarized 7 tools from value stream mapping and types of major waste. Arbos [14] proposed a methodology for implementation of lean management in a telecommunication service. Wantuck [2002] dedicated to continuous improving, just-in-time production process, small batch size, pull-type kanban systems, and quality control management. Womack and Jones [15] pointed out that by using lean thinking way, the company can have many benefits, such as gaining more outputs with less input, transforming waste into valuable activities, quick responding to feedback, and making people feel satisfactory. Hines et al. [16] provided a framework to understand the evolution of lean which is not only a concept, but also an implementation within an organization, and pointed out areas for future research. Bruuna and Mefford [17] explored the implications for lean production systems of the Internet and presented some case examples of using the Internet for these purposes. Beachum [18] pointed out that under an ideal lean environment, the company can shorten lead time, reduce work-in-process inventory, improve product quality, and increase the on-time delivery rate if one piece flow with pull systems is implemented.

Regarding the recent study on principles and philosophy of lean operations, Dahlgaard and Dahlgaard-Park [2006] analyzed the principles and results of lean production, compared the lean production philosophy with the six sigma quality process and the principles of total quality management and discussed how to build the necessary company culture for having success with these principles and management philosophies. Treville and Antonakis [2006] tried to explain the theoretical relationship between job characteristics and motivational outcomes in lean production and suggested a configuration of lean production practices. Bonavia and Marin [2006] presented some findings for reflecting on the application of different lean production practices which are in isolation and the impediments limit the use of some of them in the sector. Conti et al. [2006] presented a multi-industry empirical study of the relationship of job stress between a range of lean practices and the degree of lean implementation and found that lean production is not inherently stressful. The stress levels significantly related to management decisions in designing and operating lean production systems. Persoon et al. [2006] used principles of lean production to redesign preanalytic processes and improved turnaround time of chemistry test in a central laboratory. Abdulmalek and Rajgopal [2007] used value stream mapping as the main tool to identify the opportunities for various lean techniques and described a simulation model that was developed to contrast before and after scenarios in detail. Shah and Ward [2007] conducted an extensive literature review by using a historical evolutionary perspective to trace its main

components and identify a key set of measurement items by charting the linkages between measurement instruments. Rubio and Corominas [2008] analyzed a production-management model that considers the possibility of implementing a reverse-logistics system for remanufacturing end-of-life products in a lean production environment. Pettersen [2009] investigated the definition of lean production, the methods and goals associated with the concept and how it differs from other popular management concepts. In addition, Pettersen argued that the organization should not accept any random variant of lean, but make active choices and adapt the concept to suit the organization's needs.

Lean methods have been effectively applied to several industries such as vehicle, electronic and shoes industries. For the aerospace industry, manufacturers can expect to gain much more benefits if lean methods and tools are properly designed and implemented which are due to the special demand for manufacturing process, change of engineering, order quantity, and cost control.

The objective of this study is to develop a framework of lean transformation for improving the composite-material bonding process. The proposed approach provides a series of lean tools and methods in a systematic manner. The developed techniques are implemented in a domestic aerospace company to improve the composite-material bonding process. The results suggest that the overall productivity of the composite-material bonding process significantly increase by eliminating bottlenecks, reducing cycle time, and decreasing inventory level. The developed approach can be expected to extend to other various manufacturing processes for improving productivity.

2. Development of Lean Transformation Techiques

The methodology of lean transformation consists of a series of continuous improvement tools and methods. In this study, a series of lean methods and tools are reorganized in a systematic way that can be effectively applied to improve manufacturing process. The proposed lean transformation techniques may include five stages: 1) value stream mapping, 2) 5S, kanban, and cellular-layout planning, 3) standard work, visual management and jidoka, and 4) line balancing and heijunka scheduling. The tools applied in this study can be found in some related references [28, 29, 30]. Fig. 1 shows a framework for the proposed lean transformation. The detailed procedures are described as follows.
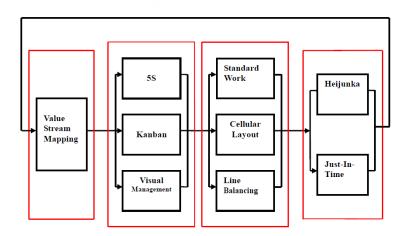

Fig. 1 A Framework for Lean Transformation

Stage 1: Value Stream Mapping

The aim of value stream mapping is to analyze the value chain within the enterprise and help employees see the whole process. A value stream map includes process flow, information flow, and timelines. The basic construction of the map is: (1)

Information flow appears on the top; (2) Process flow appears in the middle; (3) Timelines are shown on the bottom; and (4) Icons used in the map represent process, entities, inventory, and associated data; flow, communication, signals, and labels; and people and transportation, The analysis of value chain via value stream mapping provides details of current operational states within the enterprise and opportunities for improvements.

The procedures for value stream mapping are given as follows.

Step 1: Analyze suppliers, input, processes, output, and customers within the value chain.

Step 2: Select product family. The selection of major product family can be done by using product flow analysis for group products that share common flow patterns into families and value streams.

Step 3: Collect process data. The process data include manual cycle time, down time, flow time, changeover time, work-in-process inventory, defect rates, and yield rate.

Step 4: Perform gemba. Gemba is to see where the operations are and quantify value-added, non-value-added, and necessary non-value-added components of each particular activity.

Step 5: Draw the current-state value stream map. The drawing of current state value stream map can be done by using some articulate tools, icons, and techniques. The basic icons used in value stream mapping are a combination of flowcharting icons and unique shapes which are used to visually represent the various tasks and functions within a map.

Value stream mapping can be expected to help an enterprise focus on managing the value chain for all products and services from suppliers, input, processes, output, and customers. Through the analysis of enterprise value stream, a company can grasp the customer demand and provides value-added activities for meeting customer demand.

In order to identify and quantify the bottleneck workstations, several formulas are developed and used to provide necessary information. The development of equations are given as follows.

Step 1: Define variables. The variables defined in this study are:

(1) Operation Time (OT): Operation time is the sum of primal time (PT) and additional time (AT);

(2) Standard Time (ST): Standard time is an operation time (OT) with some additional allowance (r);

(3) Standard Capacity (SC): Standard capacity is the reciprocal of the number from ST divided by 3600 seconds;

(4) Needed Person (NP): Needed person is the number from dividing the multiplication of ST and order quantity (D) by total working hours (TH);

(5) Workload (WL): Workload is the number from NP divided by setting persons (SP); and

(6) Takt Time (TT): Takt time is the number from total working hours divided by order quantity (D).

Step 2: Formulate equations. The equations for computing the variables are:

(1) $OT = PT + AT$;

(2) $ST = OT \times (1 + r)$;

(3) $SC = 3600 \div ST$;

(4) $NP = (ST \times D) \div TH$;

(5) $WL = NP \div SP$;

(6)   TT = TH ÷ D.

Step 3: Compute number for the variables.

Stage 2: 5S, Kanban, and Visual Management

The aim of stage 2 is to organize the shop floor. Among these techniques, 5 S is a set of basic disciplines that can help enterprises ensure a clean and organized workplace. Those five basic disciplines are: sorting, straighten, shine, standardizing, and sustain. The sorting discipline is to clearly distinguish needed items from unneeded ones and eliminat them. The straightening discipline is to keep needed items in the correct place to allow for easy and immediate retrieval. The shining discipline is to keep the workplace neat and clean. The standardizing discipline is to make the disciplines of sorting, straightening and shining habitual. The sustaining discipline is to maintain established procedures.

Kanban can be a useful approach to simplify and manage the flow of production and inventory control. A kanban system can be seen as a loop of information and materials which are circulating between two stores of inventory. There are three distinct types of kanban systems that can be considered in this study. There are product-specific kanban, generic kanban, and hybrid kanban. The kanban system is used to trigger a variety of pull mechanisms that draw work through an entire value stream according to demand and downstream capacity. A scenario with multiple stores of inventory at various stages of production is carefully planned.

Stage 3: Standard Work, Cellular Manufacturing, and Line Balancing

Tools applied in stage 3 are used for designing and implementing to improve shop floor processes. Standard work is a tool for maintaining productivity, quality, and safety. Standard work provides a consistent framework for performing work in the designated takt time, illuminating opportunities and making improvement in work procedures. Standard work is structured around takt time, working sequence, and standard work-in-process stock. Takt time is the pace of sales in the marketplace; the working sequence is the series of steps that represent the best way to perform the task, and standard work-in-process stock is the minimum number of work pieces needed to maintain a smooth flow of work without accumulating inventories.

The cellular manufacturing is a product-oriented layout that places various machines which are required to process a family of parts in the exact sequence. The cellular manufacturing can be done by using the following procedure.

Step 1: Apply U-shape layout principles.

Step 2: Design balanced material flow.

Step 3: Allocate facility and hardware.

Line balancing is to balance the assignment of operations to workstations so that idle time and the number of people working on the line are minimized. The procedures for line balancing are:

Step 1: Complete work measurement and record all data.

Step 2: Obtain takt time and compare with cycle time. Takt time is calculated by dividing total effective working time for the period of total demand.

Step 3: Depict a balance analysis sheet.

Step 4: Analyze production line and use takt time and cycle time to identify the location of bottleneck stations.

Step 5: Improve the bottleneck stations by relocating or redesigning workstations. A balanced cell is preferred, where the cycle time of all operations are within 30% of one another.

Stage 4: Heijunka and Just In Time

Heijunka and just in time used in this stage are applied to connect with supply and demand. The heijunka method is also referred to as rate-based, level, or campaign scheduling. Heijunka scheduling works as a shock absorber, buffering variations in supply and demand and providing the shop floor and suppliers with a stable short-term production plan. A heijunka schedule requires a forecast of quantity and mixs for each value stream. Then some batching is required. The batch size can be determined by calculating a changeover interval, which is the period of time required to produce one full cycle of a product family. The interval can be calculated by using a method called the every-part-every interval (EPE). EPE interval = (effective working time in period – run time × quantity for period) ÷ (number of products in mix × setup time). The heijunka scheduling can be summarized as follows.

Step 1: Break down the total volume of orders for a given planning period into scheduling intervals.

Step 2: Define a repetitive production sequence for scheduling interval by a heijunka calculation.

Step 3: Dictate the model mix scheduled on a given line.

Step 4: Use kanban cards or signals for the mix of products to put that schedule into operation.

The goal of just in time is to supply exactly the required products at the required time. Just in time deliveries need for all processes at every step through delivery of the final product to the external customer. The procedures for just-in-time production are:

Step 1: Leveled production. Distribute the production of different kinds of items evenly through the day and week to allocate work equally and use resources optimally.

Step 2: Pull system. Link each process organically to the proceeding and following processes.

Step 3: Continuous-flow processing. Make items literally one at a time wherever possible and emulate one-at-a-time processing in batch processing by reducing the size of batches.

Step 4: Takt time. Establish a timeframe for linking the pace of work in every process to the pace of sales in the marketplace.

3. Analysis of Composite-Material Bonding Processes

Composite materials are made of two or more single materials through different synthesis and fabrication methods. The configuration of composite materials, which are used in this study, is a sandwich-type structure and fabricated by using carbon fiber with pre-fitting cloth to serve as outer covering, filling with honeycomb structuring material in-between, and gluing those components together by adhesives. The bonding process for composite materials consists of material cutting, lay-up, autoclave curing, de-molding, bench work, pre-fitting, sanding and filling, painting, assembly, marking, and stocking. Fig. 2 displays the sequence of bonding process for composite materials. The detailed bonding process is described as follows.

(1) Material Cutting: Before releasing of materials, task of materials and mold preparation are needed. The preparation of materials includes thawing procedure and cutting procedure.

(2) Lay-Up: Lay-up operation includes glue injection, laying, and bagging for honeycomb apertures.

(3) Autoclave Curing: After bagging, insert molds into the heat furnace for autoclave curing operation. Autoclave curing operates under the holding condition of high temperature and pressure.

(4) De-molding: When autoclave curing operation is finished, remove molds from the heat furnace, tear down bagging material, and take parts out of mold.

(5) Bench-work: Fix parts at the winding stand and polish broken filaments by using tools.

(6) Pre-fitting: Fix parts at the drilling stand and drill bores needed.

(7) Sanding and Filling: Remove impurities and pollutants on surface by using abrasive paper.

(8) Painting: Before painting, cover up the unpainted surface area by screen and then remove it after painting.

(9) Assembly: Apply glue on the connecting surface between parts, hinges, and binder bolt, and then rivet them.

(10) Marking: According to the indication by a blueprint, mark the part number using printing ink and then pack for stocking.
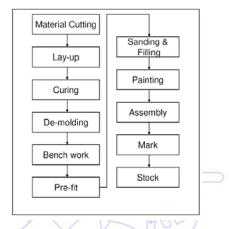

Fig. 2 Bonding process for composite materials used in this study

After the analysis of composite-material bonding process, several production problems are diagnosed. First, the plant space is getting crowded due to an increasing customer order and inappropriate plant layout and material flow design. Second, lots of WIP inventory can be found in-between each workstation due to bottleneck stations. Third, manufacturing quality is getting worse due to pollutants and waste activities scattered within production lines. Finally, production capability is going down due to unbalance of production lines. Traditional improvement methods have been utilized to somehow tackle the production problems, but no significant improvement is obtained [31].

4. Implementation of Lean Transformation Techniques

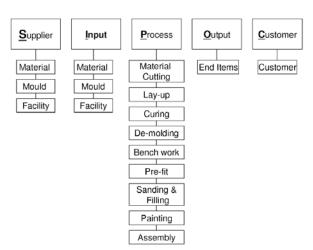*4.1. Implementing Value Stream Mapping*

Fig. 3 Analysis for suppliers, input, process, output, and customer

During the value stream mapping phase, suppliers, input, processes, output, and customers within the value chain are analyzed. Fig. 3 displays the relationships of value chain among supplier, input, process, output, and customer.

Product family is selected by using product flow analysis. Processing data such as cycle time, down time, flow time, changeover time, defect rate, and work-in-process inventory are collected. The takt time, workforce, workload, and process cycle efficiency are calculated as follows. This information can be used to determine a suitable batch size and balance a production line.

(1)   Daily Demand = Monthly Demand ÷ Monthly Work Days

$$= 256 \div 20 = 12.8 \text{ pieces}$$

(2)   Total Daily Available Time = 460 minutes

(3)   Takt Time = Total Daily Available Time ÷ Daily Demand

$$= 460 \div 12.8 = 35.9 \text{ minutes per piece}$$

(4)   Material Cutting Workforce = 49.2 ÷ 35.9 = 1.4 persons

(5)   Honeycomb Cutting Workforce = 22.8 ÷ 35.9 = 0.6 persons

(6)   Lay-Up Workforce = 214 ÷ 35.9 = 5.9 persons

(7)   Autoclave Curing Workforce = 39 ÷ 35.9 = 1.1 persons

(8)   Remolding Workforce = 38 ÷ 35.9 = 1.1 persons

(9)   Mechanical Processing Workforce = 90 ÷ 35.9 = 2.5 persons

(10) Prepare Workforce = 48 ÷ 35.9 = 1.3 persons

(11) Wet Grinding Workforce = 12 ÷ 35.9 = 0.3 person

(12) Painting Workforce = 144.6 ÷ 35.9 = 4.0 persons

(13) Assembly Workforce = 63.7 ÷ 35.9 = 1.8 persons

(14) Marking Workforce = 15.6 ÷ 35.9 = 0.4 person

The operations are observed, and value-added, non-value-added, and necessary non-value-added components of each particular step are quantified. Then, a current-state value stream map is drawn using some articulate tools, icons, and techniques.

Fig. 4 shows the obtained current-state value stream map. The icons used in the current-state value stream mapping are broken into several groups, including (1) process, entities, inventory, and associated data, (2) flow, communication, signal, and labels, and (3) people and transportation. A control point box or production control box is placed at the top middle of the map. The supplier to the value stream is drawn on the far left side, while the customer is on the right-hand side. The collected supplier and customer data are used to connect the supplier, control point, customer, and processes with manual or electronic communication lines.
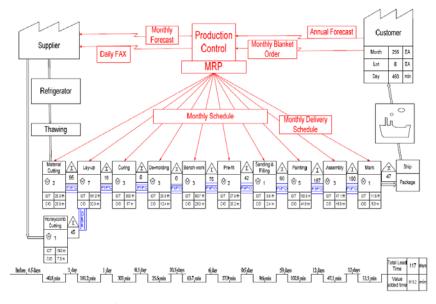
Fig. 4 The current-state value stream map

The process flow was drawn left to right. Each process box containing information of process title, number of setting persons, cycle time, and changeover time, represents where flow starts and when it stops. The first-in-first-out (FIFO) lanes for controlling stocks, depicted as triangle shapes, provide the quantity of inventory in-between processes. Those cycle times and waiting times from work in process are documented on the timeline underneath each process and inventory is at the bottom of the map. The total cycle time and production lead time are calculated and placed in the box at the right side of the map.

From this map, one can see the whole honeycomb sandwich panel production process, grasp the connection between material flow and information flow, and identify the sources of waste and bottleneck stations. Large variation from one process to another in cycle time shows where bottlenecks may occur. The total cycle time represents the amount of time required for one unit of work to be processed through all processes of the value stream, without any waiting time between processes. The production lead time is the total expected elapsed time. From the moment raw materials are received, the finished good is shipped to the customer. Using the data from total cycle time and production lead time, one can compute the process cycle efficiency, an indicator used to measure the relative amount of value which is added and contained within the whole production process. The process cycle efficiency can be defined as a percentage ratio of total cycle time to production lead time. The total cycle time from the current state is 813.2 minutes, while the production lead time is 117 days. So the resulting process cycle efficiency for the current state is 1.99%.

4.2. Implementing 5S, Kanban, and Cellular Manufacturing

When implementing systematic lean techniques, 5S is the fundamental discipline for employees and should be enforced into the routine operations in the workplace. The requirements for 5S discipline are:

(1) Unnecessary tools, equipment, and procedures are removed from the workplace.

(2) Unsafe conditions or damaged equipment are dealt with early in the process.

(3) Define how a task should be done and let everyone involved know the best way to perform tasks.

(4) Put everything in its place and organize material according to how frequently they are used.

(5) Ensure that all housekeeping policies are adhered to.

In the current-state value stream map, only FIFO lanes were used to control the material flow. The kanban system is proposed to regulate the work-in-process inventory in order to implement the pull-type production system. The location of kanban is selected mainly at the connection between suppliers and production line, and between the customer and final assembly workstations in order to facilitate the pull system and visual workplace. Also, the kanban container is used in-between each workstation to control the work-in-process inventory. The work-in-process inventory is reduced to 424 pieces from 802 pieces by using the kanban system.

The cellular manufacturing principle is used to improve the material flow and space utilization in the shop floor. Fig. 5 displays the facility layout and material flow before the implementation of the cellular layout principle. Under such a layout environment, there are too many waste occupied spaces cause congestion for people, materials, and equipment. The movement of people and materials is unsmooth and hindered.
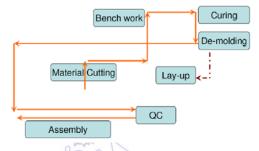
Fig. 5 Material flow layout before implementation

The cellular manufacturing principle is applied to improve the facility layout. Fig. 6 shows the resulting cellular manufacturing on the shop floor. The travel distance decreases from 504 meters to 258 meters due to the cellular-layout implementation, which suggests that travel distance of people and materials is significantly reduced. The cellular manufacturing environment also increases space utilization due to the shortening the distance between each process.
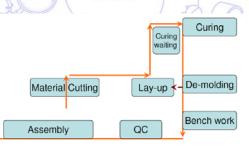
Fig. 6 Material flow of cellular manufacturing after implementation

4.3. Line Balancing and Heijunka Scheduling

The times for value-added and non-value-added activities in each workstation are measured. Also, the calculated takt time and observed cycle time from each workstation are used to identify the location of bottleneck stations. The calculated takt time from customer demand is 35.9 minutes per piece. The cycle times observed from each process are collected. Fig. 7 shows the production schedules and the associated cycle time in minute for each operation before implementation. Fig. 7 also displays value-added time and non-value-added time for each process via the effort of gemba identification and analysis. The difference between the largest cycle time and the smallest cycle time is significant. This big gap results in serious bottleneck stations and large number of work-in-process inventory. One can find that lay-up, autoclave curing, bench-work, painting and assembly are bottleneck stations. In addition, the cycle times from those bottleneck stations exceed the takt time.

In order to balance the production line, the production line was reallocated by combination and simplification of workstations. Particularly, honeycomb cutting process was combined with material cutting process into a single process. The

lay-up process was simplified by removing non-value-added activity. Curing process and demolding process were combined together and rescheduled as a work cell. Bench-work process, pre-fit process, and sanding and filling process were combined together to form a work cell. The painting process was simplified by eliminating waste activities. Assembly process and mark process are combined together to form a work cell. Also, the number of needed persons for each workstation was recalculated by using the takt time. The obtained balanced production schedule is depicted in Fig. 8. The number of rescheduled workstations is reduced to 6 from 11. The difference between the largest cycle time and the smallest cycle time is negligible.
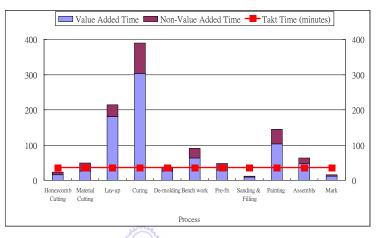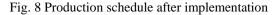

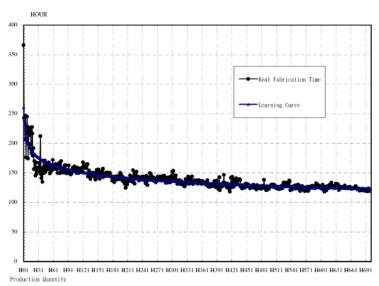Fig. 7 Production schedule before implementation

Fig. 8 Production schedule after implementation

Fig. 9 Decreasing learning curve for honeycomb bonding panel production

Fig. 9 shows the trend of decreasing learning curve during the implementation of systematic lean technique. The learning curve after finishing 691 products decreased from the initial 250 hours to 124 hours. The significant decrease of learning cure resulted from the effort of employee involvement and accelerated improvement workshops. During the accelerated improvement workshops, employees were encouraged to propose a variety of suggestions and ideas.

Also, the process lot size is reduced from the current batch size 256 pieces to 12.8 pieces by estimating every-part-every interval (EPE). Lot size reduction has impact on the waiting time and quantity of work-in-process inventory. Fig. 10 gives the trend of waiting times in buffers after implementing systematic lean technique. This downturn trend is very obvious. After 12 months of implementing systematic lean technique, the accumulating waiting time in buffers decreased from 117 days to 43 days.

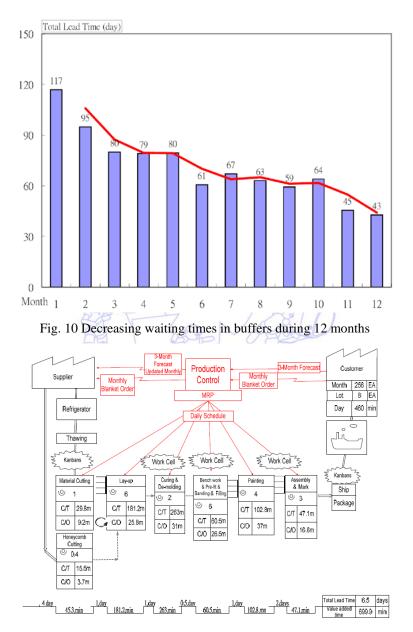Fig. 10 Decreasing waiting times in buffers during 12 months

Fig. 11 Value stream map after implementation

The value stream map after implementing the proposed lean transformation techniques is shown in Fig. 11. From this map, one can find that lots of improvements are created, compared to the current-state value stream map in Fig. 4. The total cycle time is reduced from 813.2 minutes to 699.9 minutes. The production lead time decreases from the previous 117 days to 6.5 days. Hence, the resulting process cycle efficiency is 4.97%. The major improvements resulted from the efforts of

simplification of production schedule, reduction of production cycle time and fabrication time, adoption of pull-type kanban system, and decrease of workforce and WIP inventory. Particularly, the work-in-process inventory is reduced from 802 pieces to 424 pieces by using the kanban system and lot size reduction.

5. Results

It took more than two years to implement the developed approach, not including training and education for the employees. With the exception of phase one, value stream mapping, the lean tools and methods have been, and continue to be, implanted concurrently and repeatedly, not sequentially.

Comparisons are performed by using the production data collected for 12 indicators before and after the implementation of the proposed approach. The indicators used in this comparison are batch size, material flow, travel distance, work-in-process inventory, production cycle time, fabrication time, workforce, process cycle efficiency, production cost, quality failure cost percentage, and throughput. The major differences after implementation of the proposed lean transformation techniques are shown in Table 1.

From Table 1, the benefits obtained can be summarized as follows.

(1)   The batch size is reduced from 640 pieces to 16 pieces as a result of implementing the takt time and the heijunka schedule.

(2)   The travel distance decreases from 504 meters to 258 meters due to the cellular-layout implementation.

(3)   The work-in-process inventory is reduced from 802 pieces to 424 pieces by using the kanban system.

(4)   The production cycle time decreases from 117 days to 43 days followed by the use of line balancing technique.

(5)   The fabrication time per piece is reduced from 18.13 hours to 15.31 hours due to the elimination of non-value activities and waste.

(6)   The workforce decreases from 30 persons to 23 persons followed by the using line balancing technique.

(7)   The process cycle efficiency increases from 1.99% to 4.97% by comparing the value stream maps before and after lean techniques Implementation.

(8)   Production cost is reduced from $225,000 to $214,000 as a result of lean techniques implementation.

(9)   The quality failure cost percentage is reduced from 0.399% to 0.099% as a result of lean techniques implementation.

(10) The throughput per run increased from 8 pieces to 16 pieces.

Table 1 Comparison of performances before and after implementation

Indicator	Before	After
Batch Size	640 pieces	16 pieces
Material Flow	Back and forth flow	U-shape flow
Travel Distance	504 meters	258 meters
Work-in-Process Inventory	802 pieces	424 pieces
Production Cycle Time	117 days	43 days
Fabrication Time	18.13 hrs per piece	15.31 hrs per piece
Workforce	30 persons	23 persons
Process Cycle Efficiency	1.99 %	4.97 %
Production Cost	NTD 225, 000	NTD 214, 000
Quality Failure Cost Percentage	0.399%	0.099%
Throughput	8 pieces per run	16 pieces per run

6. Conclusions

In this study, lean transformation techniques are proposed and implemented for improving composite-material bonding process. The developed lean transformation techniques encompass five stages and in each phase detailed steps are designed and provided for displaying how lean transformation techniques are implemented. The proposed approach is implemented in a composite-material manufacturing plant owned by a local aerospace company. Twelve Indicators from production lines are used to compare the performance before and after implementation. Significant improvements can be found by using these 12 indicators. Implementation efforts result in streamlining material flow, reducing waste and cost, and increasing productive capability and flexibility of order fulfillment. The results from this study indicated that the proposed systematic lean techniques are effectively implemented in composite-material bonding process and may also be applied in different manufacturing processes.

The major contribution of this study is the development of systematic lean methods for improving the composite-material bonding process. There are very few efforts have been found to devote to the study of lean application to composite-material bonding processes. The developed approach can be applied to similar process improvements. However, there are several limitations on this study. The first limit is that the employees involved in this study should be familiar with the principles and methods of lean production and composite-material bonding processes because the implementation needs the frontline worker. The other one is that the lean transformation is fully supported by the high-rank managers in the organization. Without the full support from the high-rank managers, the implementation could not be done smoothly.

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