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Implementing lean standard work to solve a low work-in-process buffer problem in a highly automated manufacturing environment

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Over the past few decades, a considerable number of studies have been reported on assembly lines or less automated factories. Little attention has been given to implementing lean tools to a highly automated manufacturing environment. It is, therefore, necessary to make a more highly automated factory lean by considering both the manufacturing system variability and demand uncertainty. The purpose of this paper is to propose an effective lean tool to help practical lean participants successfully implement lean practices in a highly automated manufacturing environment. This study presents an example of how lean standard work is implemented and the throughput of a pacemaker workstation is improved by solving the low work-in-process buffer problem. A practical case from a photovoltaic module process with a semi-automated production line is used to illustrate the proposed method. The implementation results are promising. They showed a 37.5% labour reduction prior to the pacemaker workstation and a 304.7% increase in the daily throughput at the bottleneck workstation.

Keywords: capacity buffer; lean production; photovoltaic module; semi-automated; standard work; WIP buffer

1. Introduction

Lean manufacturing has been increasingly adopted as a potential solution for many organisations, particularly within the petrol, automotive and aerospace manufacturing industries (Sullivan, Mcdonald, and Van Aken 2002; Browning and Heath 2009). Over the past few decades, a considerable number of studies have been conducted on assembly lines or less-automated factories (Womack, Jones, and Roos 1990; Lee and Jo 2007; New 2007; Mann 2012; Vinodh and Joy 2012). The philosophy of lean production focuses on solving a practical problem (Shah and Ward 2003; Green, Lee, and Kozman 2009; Laganga 2011; Ramesh and Kodali 2012; Azadegan et al. 2013). However, little attention has been given to implementing lean tools to a highly automated manufacturing environment.

The limitation of most past studies is that the firms operate in highly variable environments where the general belief is that lean is not really helpful (Lander and Liker 2007). Another reason is that the current literature related to lean production is mostly a number of successful case studies of the assembly industry, which is devoted to lean manufacturing, and there is a lack of studies about the use of a highly automated machine production line considering system variability or case studies of the beginning stages of lean manufacturing. It is, thus, necessary to make a more highly automated factory lean by considering both the manufacturing system variability and demand uncertainty.

Some equipment makers propose using an ideal semi-automated production line, which connects two workstations by robots or transfer lines. This may seem attractive on paper because it reduces the quantity of operators, but the complexity of practical operation often reduces the process flexibility, which makes lean implementation more difficult (Rother and Harris 2001).

In this study, a semi-automated production line defined by automation devices transfers semi-finished products, referred to by Rother and Harris (2001) as Level 5 of the automation production line. In the production environment, each machine (or workstation) is decoupled by the FIFO (first-in-first-out) lane, even the supermarket before the pacemaker or bottleneck. Of course, this type of design fulfils lean pull-control concepts. However, when there is significant system variability in the pacemaker workstation, there is no supermarket to absorb of statistical fluctuations of the practical production line, which increases the difficulty of the building's high efficiency lean production system. Therefore, it is necessary to increase pacemaker utilisation by reducing the blockage and starvation of the upstream workstation. In addition, buffering a pacemaker with a supermarket is impossible, but a buffer pacemaker with an effective station

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upstream from the pacemaker workstation makes starvation less frequent. Hopp and Spearman (2008) proposed reducing the process variability to improve the effective process time upstream of the bottleneck, which increases bottleneck utilisation by a buffered bottleneck with a capacity.

There are several studies in the literature that consider applying the effective tool to solve bottleneck problem. Pegels and Watrous (2005) adopt the theory of constraint (TOC) to solve bottleneck problem of a manufacturing plant. Kohli and Gupta (2010) apply TOC on a small family owned pizza restaurant. Yang and Lu (2010) propose a hybrid dynamic pre-emptive and competitive neural-network approach to solve a two-workstation multi-objective dispatching decision problem from TFT-LCD manufacturing. Three production objectives are considered in this research as: cycle time, slack time and throughput. Aziz et al. (2013) propose Petri Net model with Card Authorisation (POLCA) to minimise waiting time of downstream bottleneck process by constraining inventory of semi-finished products at the upstream of production. However, most of the solutions did not consider sufficient variability, i.e. random set-up times, yield loss, etc. Hopp and Spearman (2008) provided another option of a capacity buffer by increasing the throughput after reducing the process variability of the upstream workstation to reduce bottleneck starvation.

Lean manufacturing is a management approach to manufacturing that strives to make organisations more competitive in the market by increasing efficiency and decreasing variability through the elimination of non-value-added steps in the process (Hodge et al. 2011; Deif 2012). In the past studies, various tools and techniques of the lean production system that aim to improve the operational performance of industries have been discussed in academics (Modarress, Ansari, and Lockwood 2005; Rubio and Corominas 2008; Lu, Yang, and Wang 2011; Yang, Hsieh, and Cheng 2011; Saurin, Rooke, and Koskela 2013).

Just-in-time (JIT) philosophy is designed to achieve high volume production using minimum inventory at the right time based on planned elimination of all wastes and continuous improvement. JIT is a system of production that where only the necessary item in the necessary quantity at the necessary time is produced (Shah and Ward 2007; Zambrano Rey et al. 2014). Bortolotti, Danese, and Romano (2013) studied the effect that demand variability and product customisation have on JIT practices and how this further impacts operational performance at varying degrees of repetitiveness. Sandanayake, Oduoza, and Proverbs (2008) found that applying the paradigm of JIT manufacturing, components must be better coordinated to enable consistent, constant, and uniform assembly times at each station in an ideal JIT environment. Total productive maintenance (TPM) is a method which aims to reduce machine breakdowns, set-up and adjustment loss; this helps in increasing capacity of equipment (Brah and Chong 2004; Hofer, Eroglu, and Rossiter Hofer 2012; Attri, Grover, and Dev 2014). However, Ghosh (2013) found that TPM has a negative impact on productivity and manufacturing lead time. Chen, Li, and Shady (2010) pointed out that the implementation of programmes like kaizen helps to make operations more flexible. Nevertheless, there are difficulties in effectively implementing this concept in companies (Drohomeretski et al. 2014).

This present study proposes implementing ‘standard work’ (called standardised work at Toyota), which allows processes to be completed in a consistent, timely, and repeatable manner to eliminate variability and concurrently improve the throughput of the workstation before the pacemaker, which forms a capacity buffer to replace the inventory buffer of the supermarket (Monden 1993). Concurrently, standard work is an effective tool for most manufacturing cases irrespective of the level of automation. The methodology is a very generic one, and industries are using most of it while implementing any lean tools (Parry and Turner 2006; Miltenburg 2007; Rivera and Chen 2007; Shewchuk 2008).

The literature review shows that there is limited research focusing on the implementation of lean practices in a highly automated manufacturing environment that considers manufacturing system variability. In present literature studies, there is a lack of attention to the random features of both machine work and operator work from the real-world applications of lean practices. Moreover, implementing lean method is a complex task that generally comes up against many obstacles (Scherrer-Rathje, Boyle, and Deflorin 2009). Therefore, implementation of lean production needs to be done over many years in most cases (Yang and Lu 2011). Hence, little extant research proposes a lean implementation procedure that can quickly implement lean production system for industry applications (Bhasin and Burcher 2006; Staats, Brunner, and Upton 2011). Simultaneously, there are few studies in which the focus was to investigate the relationships among lean implementation practices and principles (Saurin, Marodin, and Ribeiro 2011; Marodin and Saurin 2013). Based on these requirements, this article proposes a lean standard work that can concurrently consider the manufacturing system variability and demand uncertainty in a highly automated manufacturing environment to make the production system lean. A photovoltaic semi-automated production lines case study has been adopted in this research to illustrate the performance of lean standard work implementation.

Accordingly, the objective of the present study can be summarised as follows: (1) to propose a lean standard work to solve a practical highly automated manufacturing environment, (2) to provide an effective lean tool that can consider both the manufacturing system variability and demand uncertainty and (3) to buffer the pacemaker workstation with increased capacity upstream of standard work implementation.

This study considers both the theoretical and practical aspects of the preparation for the introduction of lean systems and expects short term to improve the effectiveness of the company by proposing general steps to construct lean practices. The remainder of the paper is organised as follows. In Section 2, details of the proposed lean standard work implementation procedure are described. Empirical illustrations are discussed in Section 3. The conclusion and future research are addressed in Section 4.

2. Proposed methodology

This paper is based on implementing standard work in industries. Standard work is a lean tool that documents the sequence of operator work, operator movement and machine work, which is a standardised and optimised operating procedure required to produce one unit of product within its cycle time (Miltenburg 2007). With standard work, everyone in the team is playing at the same tempo at the same time. Concurrently, standard work keeps variability out of the process and enables engineers, managers, supervisors and operators to work together by following the same operating procedure. A schematic of the proposed methodology is shown in Figure 1.

The subject of the proposed lean standard work approach, shown in Figure 1, will be discussed further in the following section.

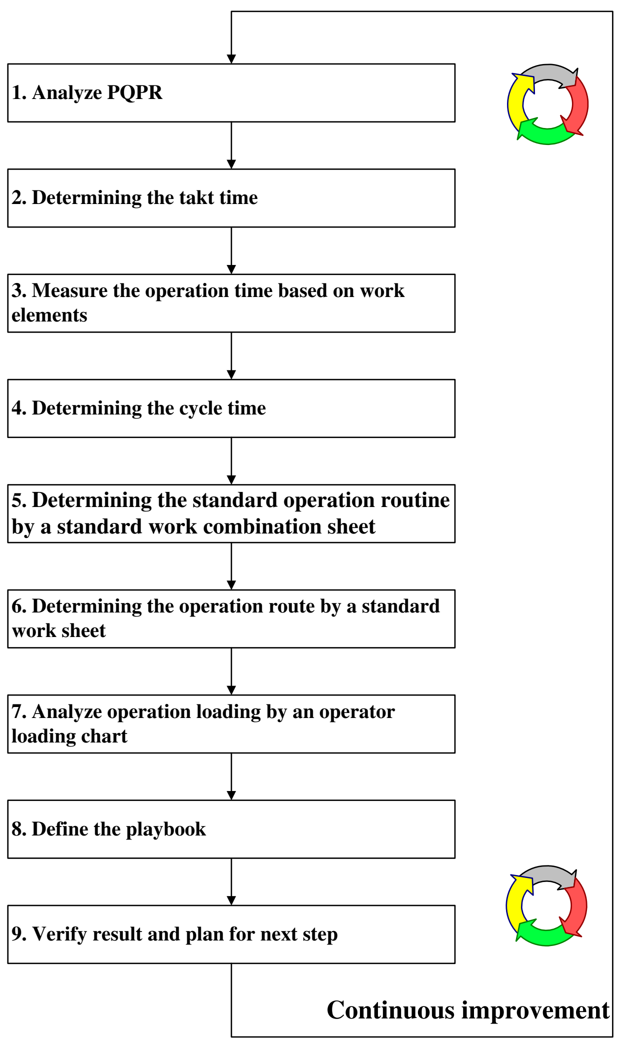


Figure 1. Proposed methodology implementation procedure.

2.1 *Assumption and notation*

Lean implementation is concerned not only with the factory's internal manufacturing capabilities, but is also heavily dependent upon supplier involvement within the supply network (Levy 1997; Crute et al. 2003). The assumption used for this research is that all supplier parts have 100% on-time delivery and in-coming quality. The methodology is developed using the following notations.

C_m	mth product code, $m = 1, 2, \dots, 6$
k	The required takt time
n	Number of operators
T_j	The required takt time for demand level j, $j = 1, 2, 3$
OP_n	nth operator
P_i	ith workstation, $i = 1, 2, \dots, 9$

2.2 *Analyse part quantity and process route (PQPR)*

The first step of the framework consists of identifying the product families and the process flow and selecting one major product family as the initial target for improvement. Performing a PQPR analysis is a classical approach for displaying the product mix in the form of a PQPR form (Rother and Shook 1998). It is then possible to understand how the total demand quantity and product price are distributed and what process will be followed among different product types. Therefore, focusing on a high demand ratio, a high price product value stream should boost the overall performances of the high revenue contribution of the factory (Braglia, Carmignani, and Zammori 2006). An example of a PQPR analysis is shown in Table 1.

Table 1 shows that C_1 products made the greatest revenue contribution to the company. They are defined as the target of this study.

2.3 *Determining the takt time*

The operation of standard work must be standardised, observable and repetitive to match the product output rate with the customers' purchasing rate. The operation is used to synchronise the pace of production with the pace of sales. The rate at which customers purchase products from the production plant is called the takt time (Rother and Shook 1998). The takt time (k) is measured by Equation (1).

$$k = \frac{\text{available work time per shift/day}}{\text{customer demand rate per shift/day}} \tag{1}$$

2.4 *Measure the operation time based on work elements*

Standard work defines the optimised work content performed by each operator to achieve a balanced flow and consistent output rate within the cycle time. Therefore, work must be broken down into elements, which are the smallest increment of work that could be moved to another person in order to identify and eliminate waste from details (Rother and Harris 2001). This process includes detailed instructions informing the operator of the required processing sequence. The first step is timing the elements of the work sequences and writing the numbers from the stopwatch on the time observation

Table 1. PQPR analysis matrix.

				Process route								
Product code	Demand ratio (%)	Price weight	Revenue contribution (%)	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
W_2#	55	1.00	53.96	①	②	③	④	⑤	⑥	⑦	⑧	⑨
A_S#	39	1.10	42.09	①	②	③	④	⑤	⑥	⑦		⑧
S_E#	3	0.85	2.50	①	②	③	④			⑤	⑥	⑦
G_O#	1	0.90	0.88	①	②	③	④	⑤	⑥	⑦		
G_Y#	1	0.30	0.29							①	②	③
K_P#	1	0.28	0.27							①	②	③

form. The next step is to define the optimised work sequence and making sure the operators follow the same sequence. The final step is to establish the most efficient sequence and allocation of work steps.

2.5 *Determining the cycle time*

The cycle time must be less than the takt time so that the customer demand can be fulfilled. The takt time and time observation of the element work helps distribute work based on the takt time to determine the number of operators needed to staff the line or workstation (Monden 2012). The number of operators (n) is measured by Equation (2).

$$n = \frac{\text{Total work content (sum of all task/operation cycle time)}}{k} \tag{2}$$

Figure 2 shows an example of the takt time with the relevant cycle time.

If an increase in the customer demand reduces the takt time from T_1 to T_2, the cell will have to redistribute tasks from OP_1 and OP_2 and add a new OP_3. Likewise, if the demand goes down, i.e. the takt time increases, then the tasks should be combined, and the number of operators should be reduced.

2.6 *Determining the standard operation routine by a standard work combination sheet (SWCS)*

After determining the manual operation time and cycle time for each operation, the number of different operations that each worker should be assigned must be calculated. Concurrently, the order of actions that each worker must perform within a given cycle time must be defined.

An SWCS is a tool of standard work that is based on the time observation form and describes the sequence in which machines will be visited and the interaction between operators or machines (Monden 1993). An SWCS uses the takt time as a basis for allocating the work of the time observation form. Moreover, this step visually distinguishes between operator work and machine work. It also exposes problems related to a combination of the operator and machine.

2.7 *Determining the operation route by a standard work sheet (SWS)*

The allocations of the various operations among workers must be such that each worker can finish all of his assigned operations within the specified cycle time. An SWS is a visual control tool to help operators, supervisors and managers maintain current standard work procedures. This tool shows the roles of each team member and concurrently documents standard WIP, quality checks and safety precautions. An SWS shows the minimum required WIP that enables the operator to repeat the same predetermined sequential operation within the cycle time.

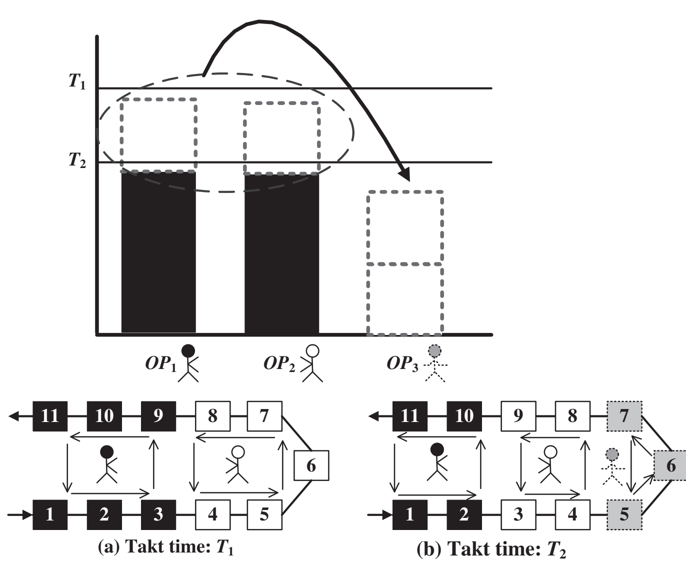


Figure 2. Illustration of the change in the takt time to reallocate a job within the cycle time.

2.8 *Analyse operation loading by an operator loading chart (OLC)*

An operator loading chart is a simple visual quantitative tool to eliminate waste, balance workload and establish a new standard work scenario. This tool takes the takt time as the threshold to compare cycle times and gives a visual representation of how well balanced the operator workload in a production line is. The OLC is a bar chart with a line drawn at the takt time and can identify an area that does not meet the takt time requirement or labour waste. Figure 3 shows an example of an operator loading chart.

The takt time is defined as 150 s. If an unloading process cannot meet the takt requirement, OP_3 is significantly overproduced and OP_1 cannot meet the takt time requirement.

2.9 *Define the playbook*

Because there is always uncertainty in the demand, standard work must identify and improve production response times to changes in the demand. Different profiles are used to create varying playbooks to react to the demand volatility. This step clearly identifies how the factory will respond to a variation in the demand. The developed plan for the diversify demand is shown in Figure 4.

Figure 4 develops three playbooks for the demand uncertainty. Playbook 1 is the average demand; playbook 2 is the ramp-up demand, in which the manufacturing department needs operators to work overtime or another shift; and playbook 3 is the ramp-down demand, in which the decision-maker needs to cut work shifts or days and even reduce the number of operators to rollover the demand downtrend.

2.10 *Verify result and plan for next step*

No design can be made perfect on paper. Once we have a future-state VSM and implementation plan, it is time to get to work on our target (Rahani and Al-Ashraf 2012). As we implement our lean kaizen activities on the shop floor, we will find more waste to be eliminated. This presents the opportunity to get further input from our implementation effort that we will plan for the next step to form a continuous improvement cycle.

3. Case study and empirical result

An anonymous company, Company G, is a solar cell and module manufacturing company in Taiwan. The company's cell production began in 2007, and module production began in 2010. The presented case study concerns a semi-automated solar module production line undertaken in a single plant. The main mass production processing steps are described in Figure 5.

The first step is an appearance check of the in-coming cells carried out by the operators. The cells are then conducted by a Stringer workstation to form strings of solar cells electrically connected by soldering them with a copper alloy tape (ribbon) and then inspected for visualised defects after being transported to the auto-layup machine. The cell series are placed on an encapsulating material (EVA), and glass gives mechanical resistance to the front of the module

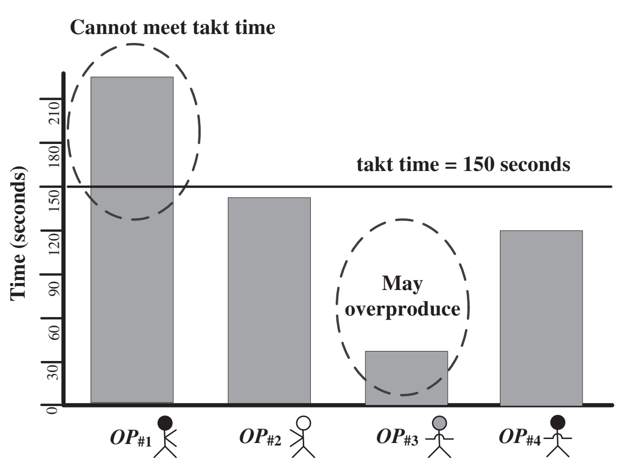
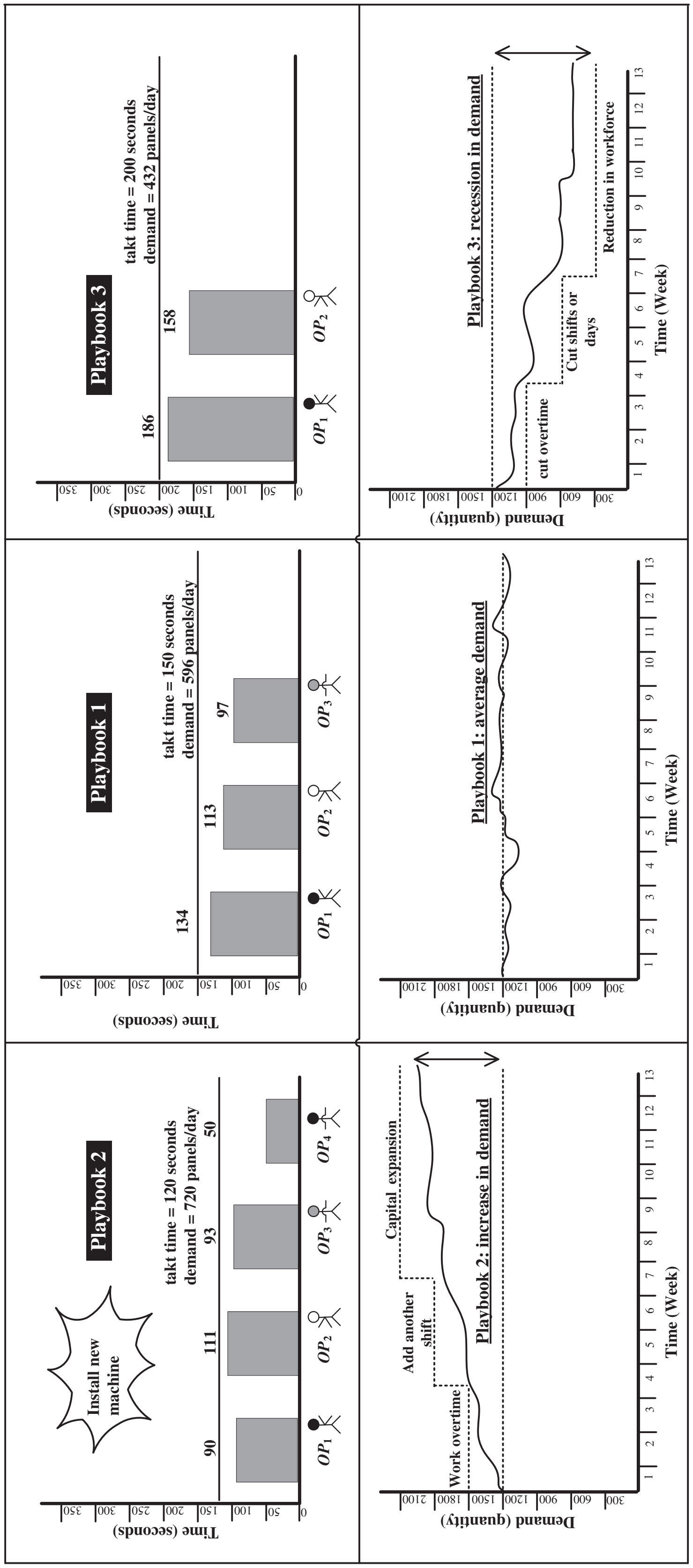


Figure 3. Example of an operator loading chart.



(a) Increase in demand: playbook 2

(b) Average demand: playbook 1

(c) Recession in demand: playbook 3

Figure 4. Playbooks 1, 2 and 3 for average demand, increase in demand and recession in demand.

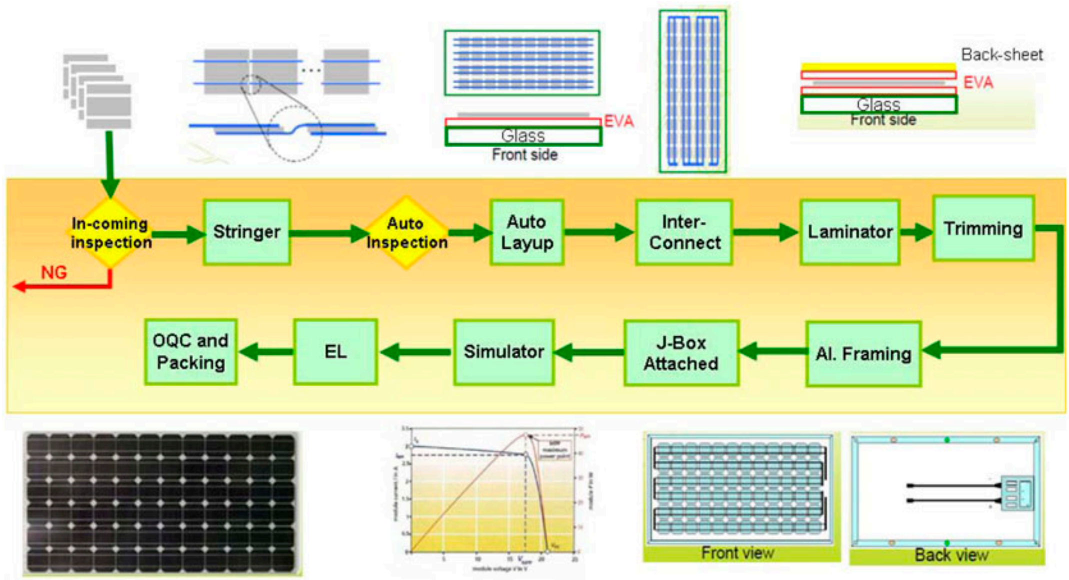


Figure 5. Photovoltaic module process flow.

and a polymer (back-sheet) placed at the back of the module. The operator connects two cell strings by soldering ribbons to let this module conduct at an Inter-Connect workstation.

After finishing this process, these semi-finished goods are sent to a laminator machine to ensure the cells are completely insulated. Lamination lasts approximately 15 min, and there are four modules per batch. After this process, a horizontal cut is artificially made in the EVA at the trimming workstation, and the module is framed with an anodised aluminium frame and sealed with a polymer tape to ensure air-tightness at an aluminium-framing workstation. The junction box is then placed at the J-box attached workstation. The solar panels are then subjected to measurement tests in a solar simulator to test their power under standard conditions. This company conducts an inspection of defective solar cells in electroluminescence (EL) images to highlight the intrinsic and extrinsic deficiencies that degrade the conversion efficiency of a solar cell. A visual inspection is carried out by an operator before and after packaging to detect any possible defects in the panels and in the OQC and packing workstation.

3.1 *The technical challenge of developing a lean system in a highly automated manufacturing environment*

Figure 6 shows a value stream of the process before the lean initiative began.

The box symbol in the map represents the workstation, and each process has a data sheet shown below, including the process time (PT) of each workstation, workstation names numbered sequentially from P_1 to P_9, the number of machines in each workstation, set-up time, mean time between failures (MTBF), mean time to repair (MTTR) and batch sizes. Regarding the demand from customers, it is assumed that the average daily demand is 576 panels of photovoltaic modules with a nominal power of 235 watts per module to achieve 4 megawatts per month. It is worth pointing out that each workstation is connected by a conveyor or robot as a semi-automated production line, which is a FIFO lane between the P_1 to P_9 workstations, to reduce the labour cost, as shown in Figure 6.

It is apparent that the company's manufacturing environment has the following features: quality issue induces rework, random break downs, batch process and set-up time. The number of such complexities increases by the highly automated production line by adopting a few WIPs, reducing the manufacturing capability and flexibility to face system variability and demand uncertainty. The bottleneck workstation of P_3 is especially severely affected by a low buffer, high system variability and long process time of the upstream so that the daily throughput of 149 panels is significantly lower than the daily demand.

Company G's managers took serial lean kaizen activities to improve the factory, i.e. 5S, visual system, cross-training, etc. They implemented build-in quality and problem-solving skills to improve the rework rate of the P_1 and P_2 workstations from 3% and 3% to 0.5% and 0.25%, respectively, which helped to improve throughput of P_3 workstation. They successfully improved the set-up time of the P_5 workstation from 600 to 300 min. Moreover, installing a second

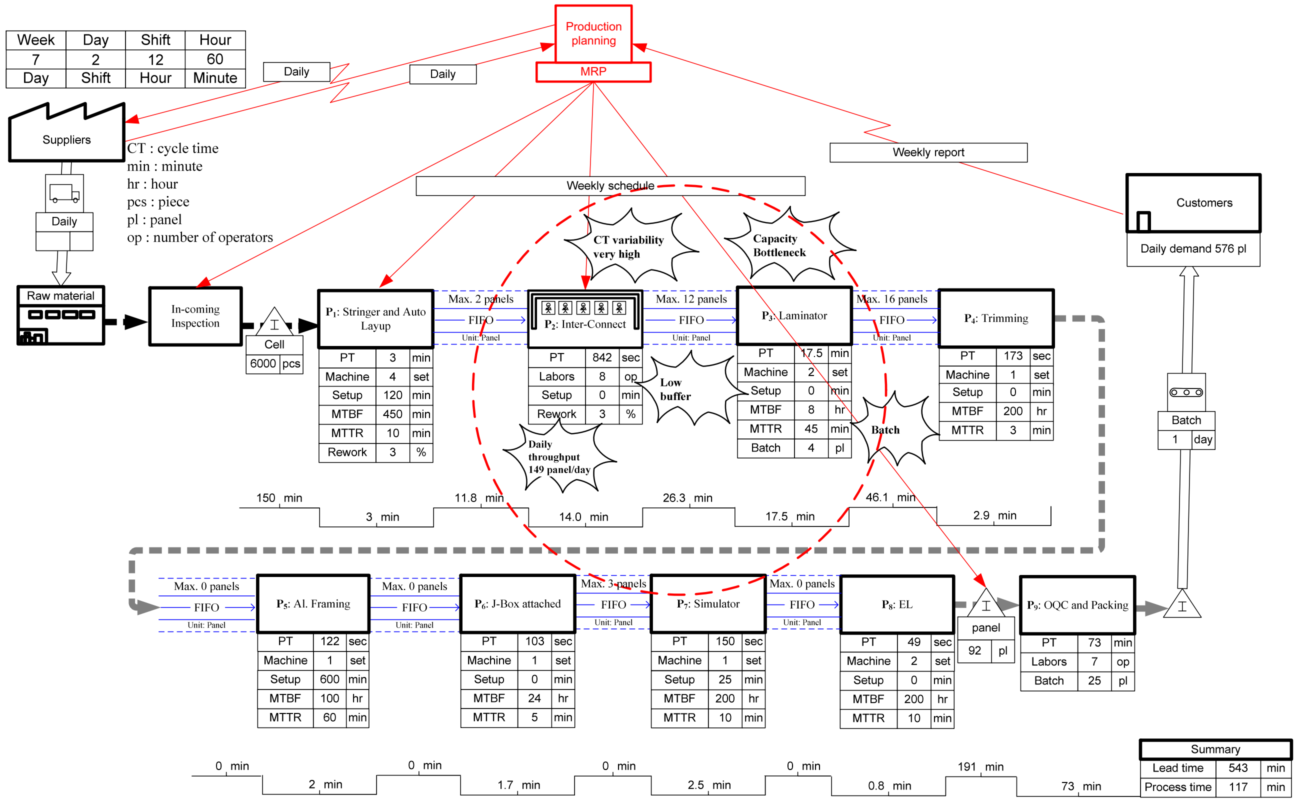


Figure 6. Current-state VSM.

machine at the P_4, P_5 and P_6 workstations is cheap, so a new machine is bought and placed downstream of the pacemaker to maintain continuous flow. Although they implemented many lean tools to improve their factory, what they most needed was a way to increase the utilisation of the P_3 workstation by reducing the blockage and starvation of the upstream workstation. In addition, buffering the P_3 workstation with a supermarket was impossible in this case study, but buffering the P_3 workstation with an effective station upstream of the P_2 workstation by reducing process variability to improve the effective process time increases bottleneck utilisation by a buffered bottleneck with a capacity.

In this research, we proposed lean standard work to eliminate the variability of the workstation before the pacemaker that forms a capacity buffer to replace the inventory buffer of the supermarket. The presented study implemented standard work by reducing the average and standard deviation of the cycle time at the P_2 workstation to maintain a continuous flow of the whole production line. The standard work deployed at the case study company followed the research areas shown in Figure 7.

What has to be noticed is the process at P_2 workstation including J-box side and bottom side. The aim of this study is to emphasise the implementation of standard work in solving the highly automated production problem. The following paragraphs describe the J-box side only.

Below section examines the proposed lean standard work implementation scheme in Section 2 to adopt the empirical illustrations.

3.2 *Analyse PQPR*

Company G produces several types of products, which are listed in Table 1. The focus of this VSM is on one product family. C_1, C_2 and C_3 products, which generated the greatest revenue contribution to the company, are defined as the target of this study.

3.3 *Determining the takt time*

The throughput required for the final products is an average of 576 panels to fulfil customers' daily demand. In this case study, the bottleneck of the laminator (P_3) workstation affects the whole value stream – both the pacemaker and the takt

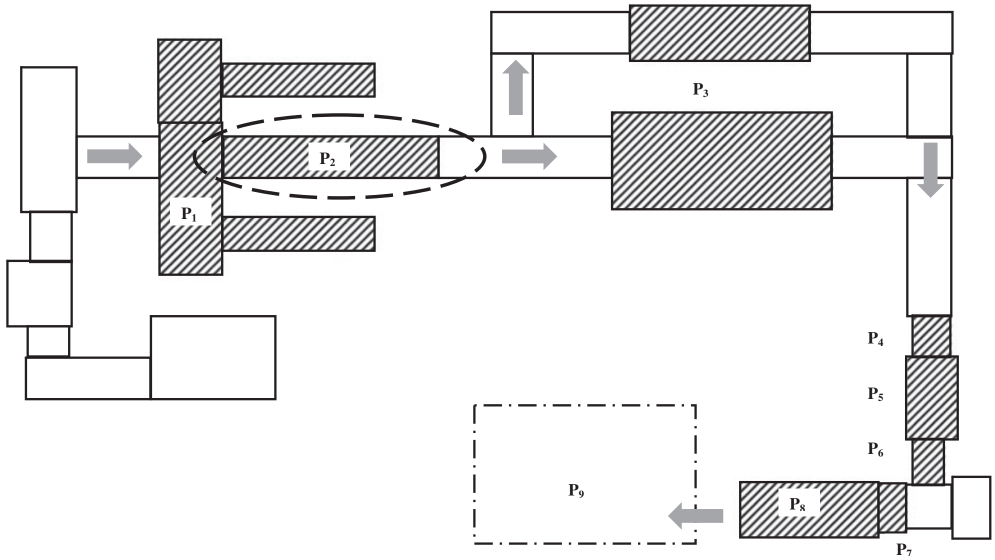


Figure 7. Illustration of the research area-P_2 J-Box side.

time. However, this workstation includes two machines, which are batch productions with four panels per batch such that the takt time requirement for the value stream is 20 min $\left(\left(\frac{24\times60}{576}\right)\times4\times2=20\right)$. Therefore, the upstream takt time of the inter-connect workstation is $\frac{20\times60}{4\times2}=150$ seconds per panel to keep the P_3 machines from starving. Furthermore, there are not enough WIP buffers ('supermarket') before the pacemaker to absorb this production variability. Hence, the proposed standard work needs to increase and smooth the arrival rate of the P_2 workstation that forms the capacity buffer as a substitute for the WIP buffer to maintain the P_3 machines' high utilisation.

3.4 *Measure the operation time based on the work elements*

The P_2 workstation of the J-box side needs four operators to finish part of the inter-connect process. We complete a time observation form by carefully and repeatedly observing the actual work, as shown in Appendix 1 Figure A1.

Before standard work implementation, the work sequences among different work shifts are quite different. A supervisor cannot use operators working overtime or from another shift because these operators need training time. Therefore, we eliminate the waste element work and re-arrange the work sequence after a discussion with operators by redesigning the element work and sequence.

A comparison of the before and after standard work implementations shows the following differences: (1) the element work numbers decrease from 31 to 25; (2) the average of the total cycle time decreases from 879 to 373.3; and (3) the standard deviation of the total cycle time decreases from 191 to 15. To sum up, the new time observation form shows that after standard work implementation, the process is much more predictable and easier to manage against the takt time and production requirement.

3.5 *Determining the cycle time*

Based on a takt time 150 s, we must confirm that all work elements have a sufficient capacity for each labour. The key is to remember that the effective cycle time of each machine should be considerably less than the takt time if continuous flow is to be achieved. This work carefully allocates the element work to each operator and reduces the labour from 4 to 3, as shown in Appendix 2 Table A1.

3.6 *Determining the standard operation routine by an SWCS*

An SWCS is prepared as follows. Firstly, draw the takt time with a vertical red line as the upper limit. Secondly, list the operator work elements in the order of the time observation form and number them by the 'adjusted element time' column. Thirdly, enter the operator, machine and walking times for each work element time that is recorded by the time

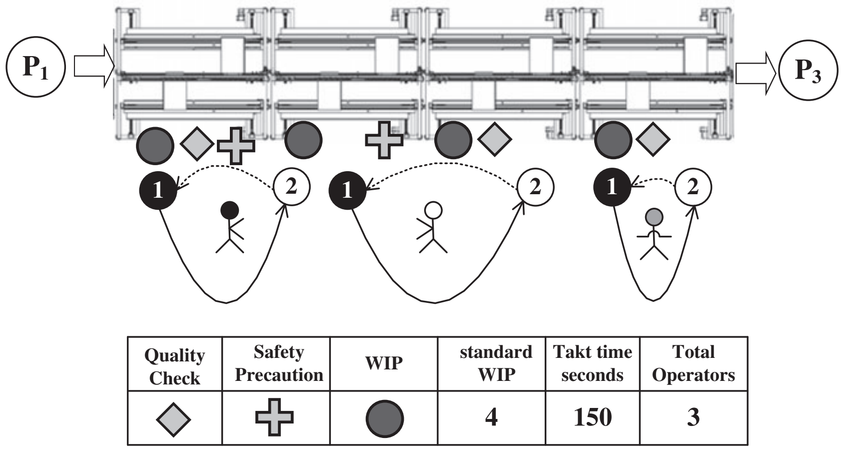


Figure 8. Standard work sheet-P_2 J-Box side.

observation form. Fourthly, draw the manual work time with a solid line, machine time with a dashed line and walking with wavy line, as shown in Appendix 3 Figure A3.

3.7 *Determining operation route by SWS*

Next step is to make the standard work sheet a visualised standard operation procedure for the operator as shown in Figure 8.

As shown in Figure 8, the standard work sheet shows the roles of each team member and concurrently documents the standard WIP, safety precautions, quality checks and safety concerns. It is the minimum required WIP that enables the operator to repeat the same predetermined sequential operation within the cycle time.

3.8 *Analyse the operation loading by an OLC*

With the SWCS in hand, we next create an OLC based on practical data. The operator loading chart is shown in Figure 9.

As shown in Figure 9, before standard work implementation, the job load of OP_1, OP_3 and OP_4 cannot meet the takt time requirement. Standard work implementation redistributes work to fully load every operator within the takt time. It must be noted that all wait times are loaded to the last operator and represent the opportunity for kaizen to be brought to the surface. Once the work is able to operate with one less production associate, the organisation saves costs.

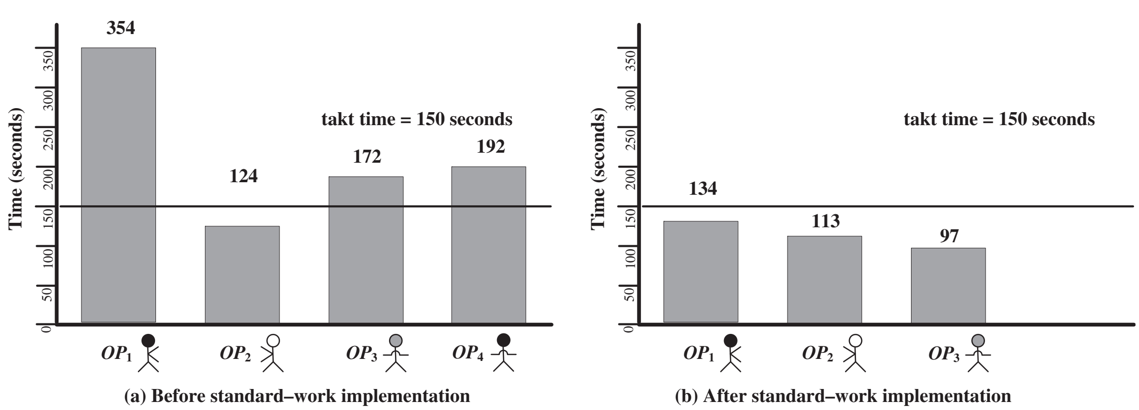


Figure 9. OLC; (a) before standard work implementation; and (b) after standard work implementation.

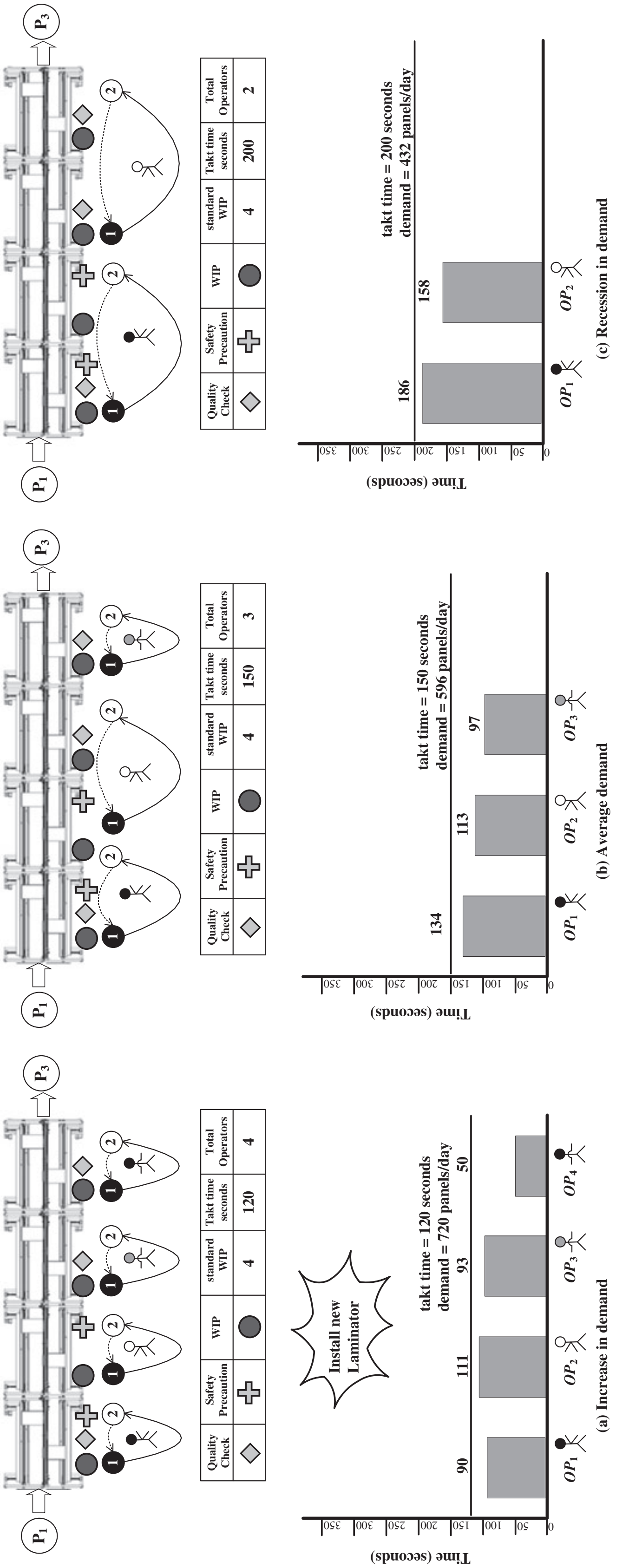


Figure 10. Playbook; (a) increase in demand; (b) average demand; and (c) recession in demand.

3.9 *Define playbook*

According to the demand, there is always uncertainty in the real world, and standard work must identify and make cycle times according to changes in the demand by reviewing any resource issues and essential changes in the takt time. If the takt time changes cannot be controlled completely through these processes, standard work playbooks are used to handle these large-scale takt time changes. This study develops three playbooks to respond to demand uncertainty as shown in Figure 10.

Figure 10(a) shows that when the demand increases to 720 panels per day, the takt time changes to 120 s and the operator increases to four operators. Moreover, the plant manager needs to install new laminator machines in advance. Figure 10(b) shows the condition of the average demand. Figure 10(c) shows that when the demand decreases to less than 432 panels per day, the takt time changes to 200 s and the operator decreases to two operators. After this step, the leader's role is to pick the appropriate playbook for the day based on changes in the takt time. The leader also has to make sure cross training is in place so reductions in the workload of the operators do not impact the ability to meet customer demand.

3.10 *Verify result and plan for the next step*

We demonstrate standard work implementation with Company G. Individual concerns about standard work were implemented at the P_2 workstation and are compared as shown in Table 2.

Table 3 shows the impact of the lean practice at the P_2 workstation as the calculated differences before and after implementation in the number of work elements, average cycle time, standard deviation of the cycle time, throughput, utilisation of bottleneck and number of operators per shift. The number of work elements after lean improvement is 19.4% by removing substantial operator effort. The improvement of the average and standard deviation of the cycle time is actually more significant, 57.6 and 92.1%, respectively, because the operators follow the same redesigned work step within the cycle time. This represents a valuable capacity increase of the P_2 workstation and a dramatic improvement of the downstream P_3 workstation. Both of their throughputs and utilisations increase by 304.7 and 236.2%, respectively. The number of operators per shift at both the J-box side and bottom side are 25 and 50%, respectively. Hence, the total operator reduction is 37.5%. Several lean techniques were adopted by Company G. It is too involved a subject to be treated here in detail.

The proposed system was launched in the production line beginning in October 2010. The implementation of the system at Company G significantly facilitated the mass production process by enhancing both the daily throughput and production yield. In addition, the system reduced the number of labours for both the training and process modifications through standard work. For a performance comparison before and after the implementation, the daily throughput data from August 2010 to Jun 2011 were collected from Company G's module production lines, as shown in Figure 11.

Figure 11 shows that the average daily throughputs before and after implementation are a maximum of 149 and 603, respectively. Furthermore, the implementation of the proposed lean production system significantly reduced defects related to the production downtime by continuously improving the quality at each workstation.

After implementing the lean standard work, the future-state VSM was presented as shown in Figure 12.

The results of the future-state map show that the cycle time of the P_2 workstation is 373 s by implementing standard work kaizen activity. The figure also shows that the daily throughput improves by 304.7% from 149 to 603. This is only a total of approximately 12 lots of inventories between the P_2 and P_3 workstations to maintain a continuous flow of the pacemaker by implementing standard work as a capacity buffer before the pacemaker, which significantly reduces both

Table 2. Comparing results between before and after standard work at the P_2 workstation.

Comparing items	Current-state	Future-state	Improvement ratio (%)
Numbers of work element (s)	31	25	19.4
Average cycle time (s)	879	373	57.6
Standard deviation of cycle time (s)	191.4	15.2	92.1
Throughput of P_3 workstation (pl/day)	149	603	304.7
Bottleneck machine utilisation (%)	25.7	86.4	236.2
Number of operators per shift (P_2-J-box side)	4	3	25
Number of operators per shift (P_2-bottom side)	4	2	50
Number of operators per shift (P_2)	8	5	37.5

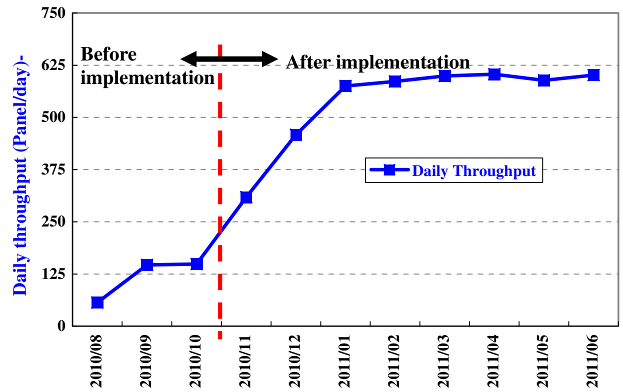


Figure 11. Daily throughput data from the case study company.

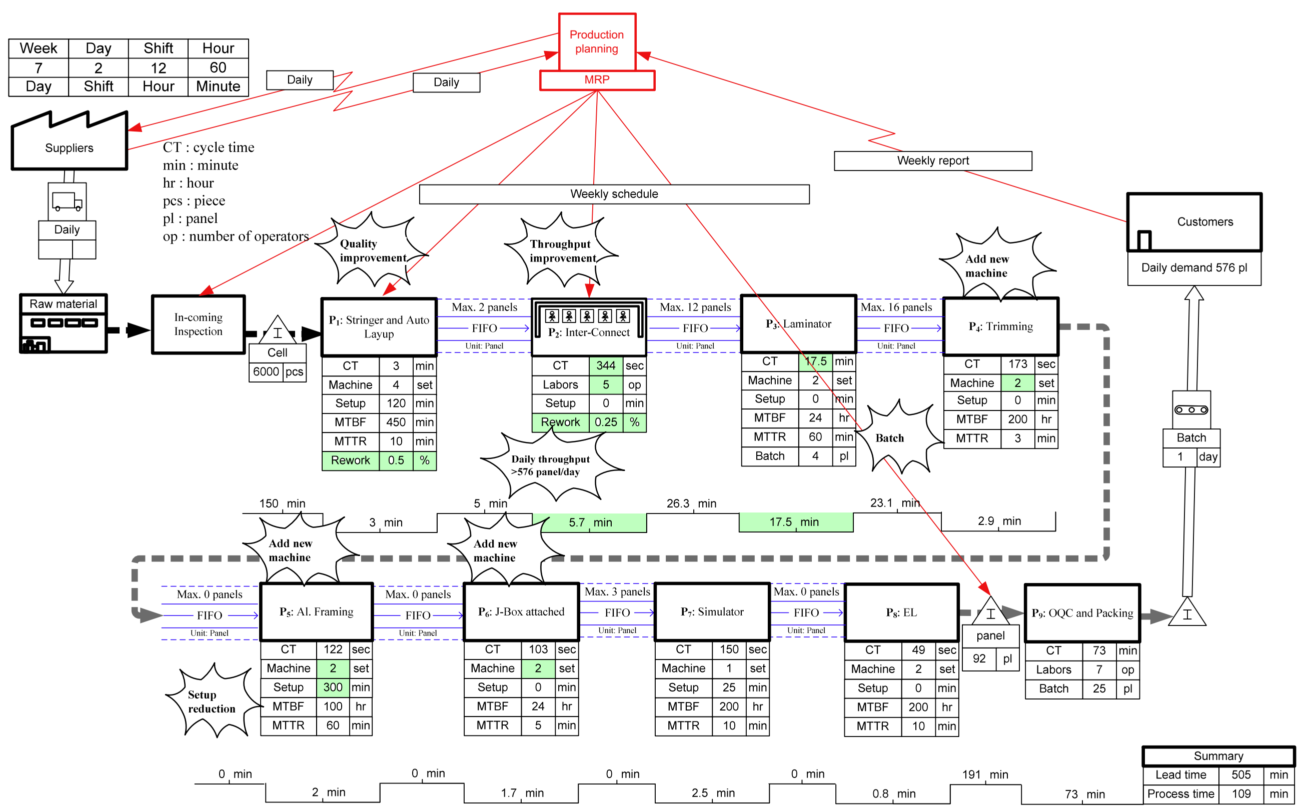


Figure 12. Future-state VSM.

the average and standard deviation of the cycle time. Figure 12 shows the enhanced throughput in the plant and the reduction in the rework ratio. The reliability of the production process increases, and the variability decreases. After lean tools implementation, the performance measures of the future-state VSM outperform the current-state VSM.

4. Conclusion

This paper proposed a lean kaizen tool by implementing standard work at a highly automated manufacturing environment: Set the assembly workstation before the pacemaker as a capacity buffer after implementing standard work improvement. Although the theoretical contribution is not significant, the practical application data before and after kaizen works gathered by this study provide reliable conclusion for a concrete technology scenario. Voss, Tsikriktsis, and Frohlich (2002) argued that case research has consistently been one of the most effective research methods in operations management, particularly in the development of new theory. In addition, case research gives insight in this idiosyncrasy and makes it possible to discuss the improvement measures and their effects in general terms (Pool, Wijngaard, and Van Der Zee 2011). Many of the breakthrough concepts and theories in operations management, from lean production to manufacturing strategy, have been developed through field case research (Serrano Lasa, Ochoa, and Castro 2008). That is what we have been trying to do here as well. Moreover, the proposed method implemented in highly automated production case study is rare. Thus, the actual throughput improvement proved in this study is meaningful to lean kaizen researcher and helpful to highly automated factory.

By analysing the results, a number of conclusions can be identified. First, adopting an ideal highly automated production line as the pull mechanism will induce low productivity when system variability is significant. Second, an upstream capacity buffer by implementing standard work will keep the whole system dominated by the pull mechanism from the pacemaker. Third, the study proposes an effective lean tool, standard work and its implementation procedure in a highly automated manufacturing environment. Fourth, this study solves the low WIP buffer problem before the pacemaker workstation. Finally, the proposed lean standard work can be simply extended to problems that have complex production variability. The study generates insights about the effective alignment of resources and labours, develops new procedures for manufacturing operations to respond to demand uncertainty, reveals manufacturing system variability that have been embedded in the production environment and challenges traditional lean implementation concepts in a highly automated manufacturing environment.

However, it is necessary to reflect on the main limitations of this research methodology from an implementation perspective. The first relates to the limitations of any single case study as lack of opportunity to compare events and data across cases. Second, whether the lean tool operating in a manufacturing or services industry may make some differences in applying the standard work. Third, this research assumed that the raw material supply is infinite; whereas, it is not. Fourth, the case study does not consider an automated material handling system (AMHS). Finally, and of significance, implementation of the lean concept could have been strengthened through an increased focus on the cultural aspects of lean, since the cultural dimension of change is a central element in the implementation of lean (Taylor, Taylor, and Mcsweeney 2013). These include existing performance management systems, employee mindsets and an underestimation of the level of senior management involvement (Fine, Hansen, and Roggenhofer 2008). Therefore, even when a lean system appears to be functioning well and delivering expected levels of performance, there are factors which can cause it to falter and even fail.

Suggested future research would, therefore, be the validation of the lean standard work in other manufacturing case and service industries. It would also be appropriate to examine whether this lean tool could be applicable or should be adapted to other levels of automated manufacturing environment with AMHS. Some topics remain unstudied, including the use of lean standard work based on a mass customisation production line, its implementation for different types of jobs and that its application to more complex product mix environments would imply searching in bigger solution spaces.

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Appendix 1. Time observation data

The P_2 workstation of the J-box side needs four operators to finish part of the inter-connect process. We complete a time observation form by carefully and repeatedly observing the actual work, as shown in Appendix 1 Figure A1.

Appendix 1 Figure A1 shows that there are many variations in the completion of a process, which takes place between 697 and 1224 s. In addition, the work sequences among different work shifts are quite different. A supervisor cannot use operators working overtime or from another shift because these operators need training time. Therefore, we eliminate the waste element work and re-arrange the work sequence after a discussion with operators by redesigning the element work and sequence. The time observation form after standard work implementation is shown in Appendix 1 Figure A2.

Time Observation Form Data - Top half is stopwatch reading; Bottom half is subtraction to get component time		Process Observed						Observation Date		2010/8/5	Operator Number	N/A
		Manual Layup (J-Box side)-DA						Observation Time		09:20 AM	Operator	DA
Step	**Element work**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Lowest element time**	**adjust**	**adjusted element time**
1	cell gap measurement	0:27	0:13	0:15	0:17	0:09	0:19	0:13	0:22	0:25	0:13	9	8	17
		27	13	15	17	9	19	13	22	25	13			
2	visual iinspection and clean	48	53	1:21	0:40	0:46	1:02	0:38	0:43	1:00	0:42	21	13	34
		21	40	66	23	37	43	25	21	35	29			
3	write measurement data	1:42	1:31	1:43	1:01	1:35	1:59	1:31	1:25	1:52	1:13	21	21	42
		54	38	22	21	49	57	53	42	52	31			
4	put tooling and jig*3	2:21	2:11	2:00	1:17	2:10	2:40	1:48	1:55	2:10	1:32	16	11	27
		39	40	17	16	35	41	17	30	18	19			
5	adjust position of Cell String	2:44	2:47	2:31	1:44	2:22	3:12	2:12	2:08	2:25	1:48	12	11	23
		23	36	31	27	12	32	24	13	15	16			
6	pull ribbon as the same direction	2:51	2:58	2:57	1:53	2:39	3:25	2:22	2:16	2:34	1:58	7	5	12
		7	11	26	9	17	13	10	8	9	10			
7	stick paster*10	3:21	3:47	3:35	2:22	3:17	3:55	2:52	2:55	3:57	2:47	29	13	42
		30	49	38	29	38	30	30	39	83	49			
8	cell gap measurement	3:47	5:34	4:00	2:41	3:45	4:08	3:12	3:12	4:11	3:05	13	16	29
		26	107	25	19	28	13	20	17	14	18			
9	put L-Ribbon	4:18	7:34	4:42	3:20	4:28	4:49	3:53	3:58	4:45	3:41	31	16	47
		31	120	42	39	43	41	41	46	34	36			
10	cut ribbon*12	4:58	8:17	6:33	4:06	5:05	5:38	5:27	4:48	5:25	4:27	37	19	56
		40	43	111	46	37	49	94	50	40	46			
11	clip L-Ribbon	5:21	8:47	7:08	4:24	5:25	6:01	5:48	5:20	5:48	4:45	18	6	24
		23	30	35	18	20	23	21	32	23	18			
12	move to table #2 (Auto)	5:23	8:49	7:09	4:27	5:27	6:03	5:49	5:22	5:50	4:46	1		1
		2	2	1	3	2	2	1	2	2	1			
13	ribbon soldering	6:28	11:37	8:08	5:41	7:01	6:50	6:50	6:27	8:49	5:37	47	39	86
		65	168	59	74	94	47	61	65	179	51			
14	cell gap measurement	6:49	11:55	8:20	5:55	7:15	7:05	7:10	6:40	9:02	5:51	12	3	15
		21	18	12	14	14	15	20	13	13	14			
15	visual iinspection and clean	7:03	12:37	8:55	6:15	7:32	7:29	7:24	6:57	9:21	6:08	14	8	22
		14	42	35	20	17	24	14	17	19	17			
16	move to table #3 (Auto)	7:05	12:38	8:56	6:17	7:34	7:30	7:25	6:58	9:23	6:10	1		1
		2	1	1	2	2	1	1	1	2	2			
17	cut ribbon*6	7:37	13:10	9:37	6:52	8:05	7:53	7:48	7:26	9:45	6:40	22	8	30
		32	32	41	35	31	23	23	28	22	30			
18	remove jig*3	8:11	13:40	10:10	7:17	8:32	8:26	8:18	7:55	10:33	7:08	25	7	32
		34	30	33	25	27	33	30	29	48	28			
19	put inner label	9:02	14:13	11:12	7:56	9:03	9:03	8:59	8:34	11:53	7:45	31	14	45
		51	33	62	39	31	37	41	39	80	37			
20	paste adhesive tape to fix inner label	9:39	16:11	11:42	8:23	9:29	9:38	9:35	9:13	12:39	8:12	26	16	42
		37	118	30	27	26	35	36	39	46	27			
21	visual inspection and clean	9:51	16:23	12:40	8:49	9:43	9:55	10:10	9:28	12:55	8:30	12	10	22
		12	12	58	26	14	17	35	15	16	18			
22	move to table #4 (Auto)	9:52	16:24	12:41	8:51	9:46	9:57	10:12	9:29	12:58	8:32	1		1
		1	1	1	2	3	2	2	1	3	2			
23	paste adhesive tape(type#2)	10:13	16:43	13:18	9:34	10:17	10:15	10:34	10:07	13:33	9:01	18	11	29
		21	19	37	43	31	18	22	38	35	29			
24	put EVA and adjust ribbon	10:41	17:02	13:37	9:51	10:38	10:33	10:59	10:27	13:57	9:28	17	5	22
		28	19	19	17	21	18	25	20	24	27			
25	put backsheet	11:07	17:30	14:20	10:31	11:04	10:52	11:27	10:56	14:49	9:50	19	12	31
		26	28	43	40	26	19	28	29	52	22			
26	check serial number	11:12	18:33	18:53	10:48	11:12	11:01	11:34	11:03	15:00	9:58	5	4	9
		5	63	273	17	8	9	7	7	11	8			
27	paste adhesive tape(type#3)	11:38	18:44	19:01	11:03	11:24	11:26	11:46	11:14	15:18	10:15	8	8	16
		26	11	8	15	12	25	12	11	18	17			
28	Voltage measurement	12:21	19:13	19:33	11:22	11:56	12:11	12:19	11:48	15:52	10:44	19	14	33
		43	29	32	19	32	45	33	34	34	29			
29	write runcard(Offline)	12:36	19:27	19:57	11:47	12:15	12:31	12:36	12:03	16:11	11:05	14	5	19
		15	14	24	25	19	20	17	15	19	21			
30	visual inspection and clean	13:42	19:44	20:23	12:55	12:35	12:58	13:06	12:22	16:55	11:35	17	15	32
		66	17	26	68	20	27	30	19	44	30			
31	move to Laminator (Auto)	13:44	19:45	20:24	12:58	12:37	13:00	13:07	12:24	16:58	11:37	1		1
		2	1	1	3	2	2	1	2	3	2			
Time for 1 Cycle		824	1185	1224	778	757	780	787	744	1018	697	524	318	842

Figure A1. Example of a time observation form before standard work.

Time Observation Form					Process Observed					Observation Date		2010/12/20	Operator Number	N/A
Data - Top half is stopwatch reading; Bottom half is subtraction to get component time					Manual Layup (J-Box side)					Observation Time		10:25 AM	Operator	N/A
Step	**Component Task**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Lowest element time**	**adjust**	**adjusted element time**
1	**visual inspection and clean**	5	6	7	8	9	7	7	5	10	5	**5**	**1**	**6**
2	**cell gap measurement**	10	10	11	10	12	10	11	11	15	10	**10**		**10**
3	**put tooling and jig*3**	11	11	12	11	14	12	11	14	13	12	**11**		**11**
4	**adjust position of Cell String**	11	12	11	9	9	10	9	13	12	9	**9**	**1**	**10**
5	**stick paster*10**	22	23	24	20	21	26	22	21	22	22	**20**	**2**	**22**
6	**put and clip L-Ribbon**	33	32	34	30	31	31	30	32	29	33	**29**		**29**
7	**move to table #2 (Auto)**	1	1	2	1	2	2	1	2	1	2	**1**	**1**	**2**
8	**ribbon soldering**	41	42	43	48	46	47	44	44	43	45	**41**	**3**	**44**
9	**cut ribbon*18**	31	30	31	36	41	41	37	32	37	31	**30**	**1**	**31**
10	**remove jig*3**	18	29	27	26	27	32	18	18	23	25	**18**	**3**	**21**
11	**move to table #3 (Auto)**	1	1	1	2	2	3	1	1	2	2	**1**	**1**	**2**
12	**Put inner label**	16	13	14	14	14	15	14	14	15	15	**13**		**13**
13	**paste adhesive tape/fix inner label**	20	16	19	24	25	24	24	21	18	21	**16**	**3**	**19**
14	**paste adhesive tape(type#2)**	6	5	5	5	5	9	6	5	6	5	**5**		**5**
15	**Voltage measurement**	22	18	21	20	22	20	23	21	19	20	**18**	**2**	**20**
16	**move to table #4 (Auto)**	1	1	2	3	1	2	1	2	2	2	**1**	**1**	**2**
17	**write runcard(Offline)**	13	13	9	11	12	12	12	11	11	14	**9**	**1**	**10**
18	**cell gap measurement**	9	16	15	18	18	16	17	11	10	8	**8**	**4**	**12**
19	**visual inspection and clean**	9	8	8	10	9	12	12	11	9	9	**8**		**8**
20	**put EVA and adjust ribbon**	19	20	15	19	17	17	17	20	19	18	**15**	**2**	**17**
21	**put backsheet**	21	22	21	23	22	23	23	23	26	24	**21**		**21**
22	**check serial number**	5	7	5	7	8	7	7	6	7	6	**5**		**5**
23	**paste adhesive tape(type#3)**	8	7	7	8	8	6	6	9	10	7	**6**		**6**
24	**visual inspection and clean**	18	14	19	15	14	17	17	15	18	18	**14**	**2**	**16**
25	**move to Laminator (Auto)**	2	2	3	1	1	2	1	1	1	1	**1**	**1**	**2**
TIME FOR 1 CYCLE		**353**	**359**	**366**	**379**	**390**	**403**	**371**	**363**	**378**	**364**	**315**	**29**	**344**

Figure A2. Time observation form after standard work.

Appendix 2. Element work allocation

Appendix 2 Table A1 shows that distribution of the element works in OP_1, OP_2 and OP_3 is from 1 to 8, from 9 to 16 and from 17 to 25, respectively. The criteria are that each time measurement in Table 2 cannot be over the takt time limit. Notably, the column of 'adjust element time' is our training target and will be used for the SWCS.

Table A1. Element work allocation for a standard work combination sheet.

	Time measurement										
Step	1	2	3	4	5	6	7	8	9	10	Adjusted element time
1	5	6	7	8	9	7	7	5	10	5	6
2	10	10	11	10	12	10	11	11	15	10	10
3	11	11	12	11	14	12	11	14	13	12	11
4	11	12	11	9	9	10	9	13	12	9	10
5	22	23	24	20	21	26	22	21	22	22	22
6	33	32	34	30	31	31	30	32	29	33	29
7	1	1	2	1	2	2	1	2	1	2	2
8	41	42	43	48	46	47	44	44	43	45	44
$\boldsymbol{OP_1}$	**134**	**137**	**144**	**137**	**144**	**145**	**135**	**142**	**145**	**138**	**134**
9	31	30	31	36	41	41	37	32	37	31	31
10	18	29	27	26	27	32	18	18	23	25	21
11	1	1	1	2	2	3	1	1	2	2	2
12	16	13	14	14	14	15	14	14	15	15	13
13	20	16	19	24	25	24	24	21	18	21	19
14	6	5	5	5	5	9	6	5	6	5	5
15	22	18	21	20	22	20	23	21	19	20	20
16	1	1	2	3	1	2	1	2	2	2	2
$\boldsymbol{OP_2}$	**115**	**113**	**120**	**130**	**137**	**146**	**124**	**114**	**122**	**121**	**113**
17	13	13	9	11	12	12	12	11	11	14	10
18	9	16	15	18	18	16	17	11	10	8	12
19	9	8	8	10	9	12	12	11	9	9	8
20	19	20	15	19	17	17	17	20	19	18	17
21	21	22	21	23	22	23	23	23	26	24	21
22	5	7	5	7	8	7	7	6	7	6	5
23	8	7	7	8	8	6	6	9	10	7	6
24	18	14	19	15	14	17	17	15	18	18	16
25	2	2	3	1	1	2	1	1	1	1	2
$\boldsymbol{OP_3}$	**104**	**109**	**102**	**112**	**109**	**112**	**112**	**107**	**111**	**105**	**97**
Total	**353**	**359**	**366**	**379**	**390**	**403**	**371**	**363**	**378**	**364**	**344**

Appendix 3. Standard work combination sheet

Step	Description of operation	Time (seconds)			Operation time (seconds)				
		Manual	Auto	Walk	30	60	90	120	150
1	visual inspection and clean	6							
2	cell gap measurement	10							
3	put tooling and jig*3	11							
4	adjust position of Cell String	10							
5	stick paster*10	22							
6	put and clip L-Ribbon	29							
7	move to table #2 (Auto)		2	2					
8	ribbon soldering	44							
***OP*₁**		**134**							
9	cut ribbon*18	31							
10	remove jig*3	21							
11	move to table #3 (Auto)		2	2					
12	Put inner label	13							
13	paste adhesive tape/fix inner label	19							
14	paste adhesive tape(type#2)	5							
15	Voltage measurement	20							
16	move to table #4 (Auto)		2	2					
***OP*₂**		**113**							
17	write runcard (Offline)	10							
18	cell gap measurement	12							
19	visual inspection and clean	8							
20	put EVA and adjust ribbon	17							
21	put backsheet	21							
22	check serial number	5							
23	paste adhesive tape(type#3)	6							
24	visual inspection and clean	16							
25	move to Laminator (Auto)		2	2					
***OP*₃**		**97**							
Total	**344 seconds**								

Figure A3. Standard work combination sheet-P_2 J-box side.