GRADUATE SCHOOL OF ADVANCED TECHNOLOGY AND SCIENCE

TOKUSHIMA UNIVERSITY

Application for Doctoral Degree Thesis

Doctoral Degree Thesis:

Overall performance effectiveness with customer demand and environmental consideration

Prepared by:

TEOH YONG SIANG

Intelligent Structures & Mechanics Systems Engineering

Collaborative Engineering Laboratory (CELab)

Student Number: 5014420061

Date: 17th March 2019

ABSTRACT

Overall equipment effectiveness (OEE) comprises of three elements called availability, performance ratio and quality ratio are mainly used to quantify downtime losses, speed losses and defects respectively. In ideal case, it encourages machine to operate all the time at the ideal speed and to produce no quality defect. In this study, it is implemented by an aerospace part manufacturing company which comprises of five workstations， namely layup process, autoclave, de-mold process, CNC trimming and NDT inspection, in its production system. Based on the observation, effectiveness of one workstation and transportation efficiency would affect the performance of other workstation they connect with. However, there is lack of integration between workstations and transporting activities under the implementation of OEE. This could be seen from the fluctuation of output at each workstation and inconsistent utilization of workstation whenever the transporting activities are not performed well whenever they are needed. Besides, other problems include the deviation of production from customer demand, and also the imbalanced capacity among processes which were are not quantified by OEE either. Consequently, this leads to inefficient material flow, over-production and excessive inventory level, as well as lack of interaction between workstations because the case company does not know where to initiate any corresponding improvement without the measure. First objective of this study is to study and quantify the impact of varying transportation efficiency onto the workstations in term of throughput and lead time of products. Besides, it aims to synchronize

capacity available within production system and also to monitor the fulfillment of customer demand in terms of delivery time and production amount. The target of these objectives are shorter lead time and wait time, less throughput, minimal equipment utilization and less capacity incurred in achieving and fulfilling customer demand. Simulation approach is applied because it enables the study of system behavior under various parameters and scenarios without interfering the daily production of the company. The results prove that both transportation efficiency and performance of Autoclave workstation affect material flow and throughput rate of other workstations. Consequently, the performance of workstations they connect with are also affected. Besides, simulation also proves different production rate and imbalanced capacity throughout production system as sighted in site observation. Therefore, Overall Performance Effectiveness (OPE) which comprises of availability, performance ratio and delivery performance is proposed in this study. It considers customer demand, historical equipment utilization and Takt time of each workstation to promote reasonable utilization of resource. It prevents both over processing and overproduction issues which are invisible in existing OEE. In particular, availability promotes smooth material turnaround, reduces consumption of materials and minimizes deviation between production amount and customer demand. Performance ratio, on the other hand, ensures reasonable utilization and production pace by considering historical utilization and also customer demand required. Furthermore, delay propagation throughout production system and the aforementioned interrelationship between processes could be quantified by delivery performance (DP) of the OPE. The waiting time and lead time spent in each workstation are monitored under the DP. Responsibility of all workstations and transportation process in delivering demand on timely basis are encouraged. Last but not least, transportation process which serves as the connectors of manufacturing workstations is also quantified and monitored via the proposed Transportation Measure (TM).

TM aims to reduce the queue length at destination and the corresponding waiting time with reasonable utilization of forklift. It also promotes less capacity investment in transportation and prioritizes its scheduling according to queue length or urgency of destination workstation. This is useful for the assignment of shared transporting capacity and also monitoring the impact of transporting activities onto the manufacturing processes. In short, all objectives are achieved and fulfilled. The newly proposed Overall Performance Effectiveness (OPE) and the quantification of Transportation Measure (TM) which affect each other help in promoting better delivery performance in terms of production amount and lead time. The effectiveness of entire production line is examined as a unity with joint responsibility under varying transportation efficiency and cycle time of each workstation. Both OPE and TM could be implemented together to optimize the production system. All of these are not quantified and provided by the OEE implemented by the case company. The proposed OPE and TM have resolved the issues which was invisible under the OEE implemented by the case company.

ACKNOWLEDGEMENT

First and foremost, I would like to express my gratitude to my supervisor, Teruaki Ito Sensei from the University of Tokushima and Associate Professor Ir. Dr. Puvanasvaran from Universiti Teknikal Malaysia Melaka (UTeM) for their support and encouragement towards the completion of study and thesis. Technical supports, experience and consultant offered and shared by them are valuable and important elements of my thesis.

I would also like to take this opportunity to acknowledge my co-supervisor Associate Professor Dr. Mohd Syaiful Rizal from Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, consultant and advice towards the completion of this thesis.

Last but not least, I would like to thank my parents for their support throughout the research and study. Their support and understanding mean very much for the completion of my study because it enables the focus and emphasis onto the study.

TABLE OF CONTENT

	Page
ABSTRACT	**2**
ACKNOWLEDGEMENT	**5**
TABLE OF CONTENTS	**6**
LIST OF TABLES	**8**
LIST OF FIGURES	**10**
CHAPTER	
1. INTRODUCTION	**11**
1.1 Background	11
1.2 Background of Case Company	14
1.3 Problem Statement	16
1.4 Objectives	17
1.5 Scope of Study	18
2. LITERATURE REVIEW	**20**
2.1 Job Shop Problem	20
2.2 Concept and Application of Overall Equipment Effectiveness	25
2.3 Additional Performance Metric and Consideration Required besides OEE	29
2.4 Incorporation of Metrics and Modification on OEE	32
2.5 Quantification of Environmental Factors in OEE and Integration with Other Tools.	40
2.6 Summary of Literatures	42
3. METHODOLOGY AND PRIMARY RESULTS	**48**
3.1 Development of Simulation Model	52
3.1.1 Experiment 1	54
3.1.2 Experiment 2	59

3.1.3 Experiment 3	62
3.1.4 Summary of the Results from Experiments	66
4. PROPOSED MEASURES AND DISCUSSIONS	**68**
4.1 Quantification of Transportation Process	68
4.1.1 Proposed Availability Ratio of Transportation Measure	68
4.1.2 Proposed Performance Ratio of Transportation Measure	73
4.1.3 Transportation Measure of the Case Company	76
4.2 Quantification of Workstations	78
4.2.1 Proposed Availability Ratio of Overall Performance Effectiveness (OPE)	78
4.2.2 Proposed Performance Ratio of Overall Performance Effectiveness	83
4.2.3 Proposed Delivery Performance of Overall Performance Effectiveness	87
4.2.4 Comparison of implemented Overall Equipment Effectiveness (OEE) with Proposed Overall Performance Effectiveness (OPE)	91
5. CONCLUSION AND RECOMMENDATION FOR FUTURE STUDY	**96**
5.1 Conclusion	96
5.2 Recommendation for Future Study	97
REFERENCES	**100**

LIST OF TABLES

TABLE	Page
1.1 The Capacity Available in Each Job Shop of the Production System	15
2.1 Description of Losses Propagation in the System According to OEE Metrics	34
2.2 Seven Lean Wastes in Transportation Operation	38
2.3 Improvement Timeline and Gap of Study Related to Overall Equipment Effectiveness (OEE)	44
3.1 Measures and Key Performance Index (KPIs) for Analysis of Interruption	51
3.2 Cycle Time of Transportation Process Under Different Efficiency of Transportation	55
3.3 Total Lead Time and Output of Processes under Different Transportation Efficiency	56
3.4 Different Cycle Time of Autoclave Curing Process (Experimental Factor) in Experiment 2	61
3.5 Lead Time and Output under Varying Cycle Time of Autoclave Process	61
3.6 Variation in Cycle Time as the Experimental Factor in Determining Difference in Throughput of each Process	64
3.7 Throughput at Each Process After the Arrival Rate is Doubled	65
4.1 Contribution to Continuity of Operation, CCOO and Throughput Rate for Transportation Process to Each Workstation in Experiment 1	70
4.2 Availability Ratio of Transportation Process to Each Workstation in Experiment 1	71
4.3 Forklift Utilization, Total Duration of Transportation per Product to All Workstations, and Uptme Ratio in Experiment 1	74
4.4 Performance Ratio of Transportation Process in Experiment 1	75
4.5 Availability, Performance Ratio and Transportation Measure of Case Company in Experiment 1	76
4.6 Operational Ratio and Productivity of Proposed Availability Ratio	81
4.7 Equipment Utilization of Each Workstation in the Production System	82
4.8 Capacity Available and Takt Time of Each Workstation	85
4.9 Comparison between Takt Time and Cycle Time in Performance Ratio	86

4.10 Delivery Performance of Each Workstation	89
4.11 Delivery Performance of Each Workstation in Experiment 2	90
4.12 Availability Ratio of Workstation in Experiment 2 under OEE Implemented	92
4.13 Performance Ratio of Workstation in Experiment 2 under OEE Implemented	93
4.14 Comparison on OEE and OPE of Workstations in Experiment 2	94

LIST OF FIGURES

FIGURE	Page
1.1 Process Flow of the Main Processes in Company under Study	14
2.1 Six Big Losses and Calculation of OEE (Eswaramurthi and Mohanram, 2013)	26
2.2 Comparison of the Backlog and Filled Order Rate with Target Delivery Delay in Overall Service Level, OSL (Ali and Deif, 2016)	33
2.3 The Model for Overall Resource Effectiveness (Eswaramurthi and Mohanram, 2013)	35
2.4 The Concept of OEE_MB and the Relationship between Elements (Anvari, Edwards, and Starr, 2010)	37
2.5 Triangular Efficiency, Effectiveness and Performance Model for Logistics Firms (Wong et al, 2015)	41
3.1 Overall Procedure of Modeling Overall Performance Effectiveness	49
3.2 Conceptual Model of the General Activity Flow of Job	52
3.3 Operational Model in Arena Simulation for the General Activity Flow of Job	53
3.4 Overall Procedures to Conduct Experiment 1	54
3.5 Composition of Waiting Time in the Lead Time per Entity for Actual Cycle Time of Transportation	57
3.6 Composition of Waiting Time in the Lead Time per Entity for Half Cycle Time of Transportation	58
3.7 Composition of Waiting Time in the Lead Time per Entity for 25% Cycle Time of Transportation	58
3.8 Overall Procedures to Conduct Experiment 2	60
3.9 Overall Procedures to Conduct Experiment 3	63

CHAPTER 1

INTRODUCTION

Chapter 1 is mainly describing the introduction of the entire study. It starts by introducing the background of manufacturing industry and also some corresponding concerns in daily operations. Different considerations and issues in manufacturing factory are briefly introduced to justify the objectives of the study which are also included in this section. In prior to that, the background of case company where data will be collected and studied is introduced so that the problems faced could be understood easily. The following problem statement elaborates the issues and problem encountered by that particular company. Last but not least, scope of study is included in the section so that the focus and coverage of the study could be clearly conveyed.

1.1 Background

There are different kind of data available in manufacturing industry nowadays for improvement of production system. Performance measurement is the fundamental principle of management that it identifies the gap between current performance and desired performance and enables company to initiate progress towards closing the gaps (Samad, Hossain, and Major, 2012). However, manufacturing company faces difficulty to utilize and process the data in such a way that could provide context and meaning, such as insight into future performance and estimation of the time to failures, so that the right personnel could respond accordingly (Lee et al, 2013). Inability in selecting the appropriate measures which adapt and suit the nature of manufacturing process would cause lean wastes in production not being quantified and monitored.

Customer demand, for instance, should be considered at the very first step to ensure smooth flow of production. Production plans should be carefully prepared and executed on a shop floor where performance indicators are measured and used for parameter optimization, minimization of the impact from uncertainties and proactive implementation of solution to prevent performance loss (Lee et al, 2013; Mugwindiri et al, 2013; Gansterer, Almeder, and Hartl, 2014). Therefore, every part of the operations within manufacturing environment should be synchronized with respect to customer demand.

Mass production which is preferable by most of the manufacturing companies due to the economies of scale and this would lead to overproduction if the customer demand is not taken into consideration carefully. Besides, utilization of the manufacturing facilities has been selected as the Key Performance Index (KPI) to be considered at most of the time to attain optimum operation of plant (Gansterer, Almeder, and Hartl, 2014; Ponsignon, and Mönch, 2014; Helo, 2000). Management concentrates on the important data generated such as the available capacity and fulfillment of customer demand and excel to the benefits of company (Mugwindiri et al, 2013).

It is understandable that companies emphasize on the capacity of their manufacturing facility which is available to fulfill customer demand. Examination on the measures helps to reduce the buffer inventories which are normally required to protect its downstream production from any possible breakdown. Utilization of manufacturing facility and fulfillment of customer demand, therefore, are related to each other. On the other hand, shorter waiting time of jobs in queues results from the shortage of buffer inventories and its corresponding shorter lead time will increase the competitiveness of company in term of flexibility and delivery (Afefy, 2013). This is one of the examples demonstrating the trade-off exists between buffer inventory and the performance of demand fulfilment because shorter lead time and waiting time do not exist in the production system with high level of inventories.

Therefore, big picture of the information flow and importance of focusing on the overall performance and availability of capacity are required especially when the market is full with fluctuation of demand on multiple version of product. Focus on the environment of manufacturing is necessary so that rightful decision could be made accordingly for lean improvement. Simulation method is also extensively used by industry to test different scenarios, model any abnormal situation and drive recommendation based on the results once the desired target is attained in the model (De Carlo, Arleo, and Tucci, 2014; Zhou et al, 2009). It is a common practice to emphasize solely on the manufacturing environment which is controllable and internal within a company in order to minimize the error of estimation

Besides, simulation tool is also used as the analytical tool, for the uncontrollable aspects such as the variation of customer demand, because of its capability of predicting the possible future events and identifying the area that would have gone wrong during a certain period of time (Mugwindiri et al, 2013). Besides, simulation-based framework is used to model the market behavior and production system so that demand and execution uncertainty could be considered as well as for the identification of production waste such as waiting, work in progress, inventories and transportation (Badiger and Gandhinathan, 2008; Heilala et al, 2008, Ponsignon and Mönch, 2014).

1.2 Background of Case Company

An aerospace part-manufacturing company located in Malaysia is selected as the subject of study. It is part of global supply chain for major aircraft manufacturers and also in the composite industry. There are five main manufacturing processes within the company namely layup, autoclave curing, demolding, CNC trimming and NDT inspection processes as illustrated in Figure 1.1 below:

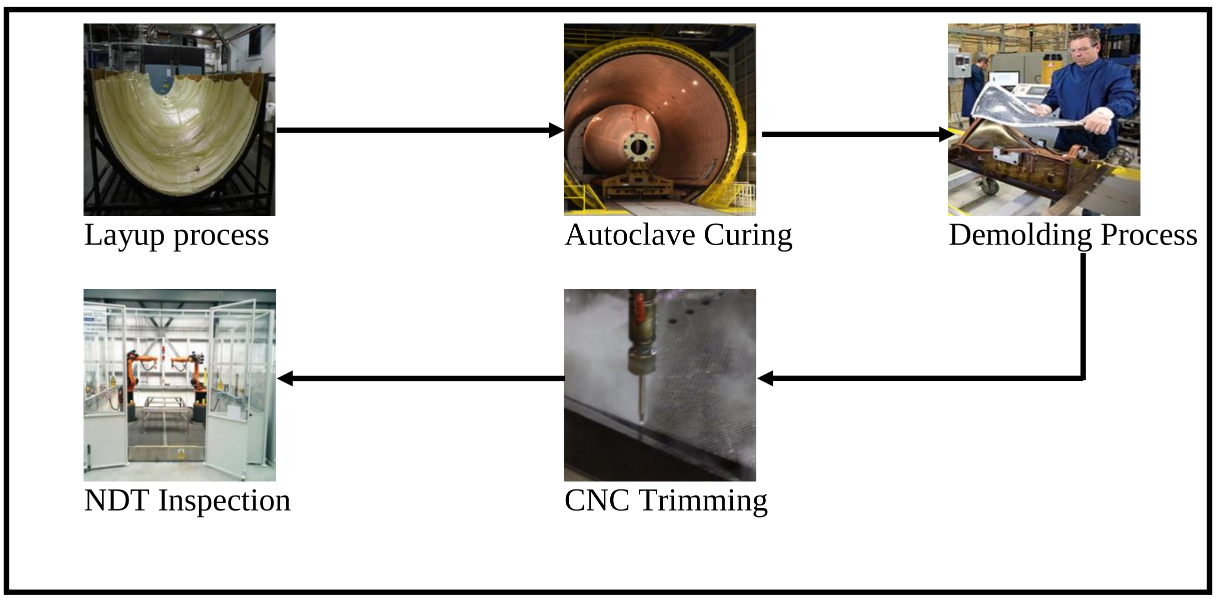

Figure 1.1: Process Flow of the Main Processes in Company under Study

Production system of the company under study starts from layup process which is to stack the ply materials layer by layer manually. The ply materials after the stacking process will be cured and hardened in autoclave curing process by mean of autoclave. The harden materials or the composite part will then be separated from its mold and so that it could be transferred into suitable trimming mold during demold process. The composite materials on the trimming mold is then trimmed in CNC process to remove excessive portion. It is followed by Non Destructive Testing (NDT) section where inspection is carried out to ensure that there is no void and crack within the product. In addition to 5 main processes as shown in Figure 1.1, there are transporting activities carried out within the production system, from origin workstation to destination workstation, to ensure smooth material flow.

Among the aforementioned job shops, layup and demold are manual process whereas the other three are automated process. Each job shop consists of varying number of man power, which are the operators to operate several machine available in automated process, and also the technicians to perform manual process. The capacity of each job shop are shown in Table 1.1 below:

Table 1.1: The Capacity available in each Job Shop of The Production System

Process	**Capacity and Nature**			**Cycle Time (Hour)**		
	Process type	**Unit Available**	**Capacity Type**	**Min**	**Mod**	**Max**
Layup	Manual	20	Man power	14.0	16.0	18.0
Autoclave	Automated	2	Fixed Capacity	9.0	14.0	28.0
Demolding	Manual	12	Man power	0.5	1.0	1.5
CNC Trimming	Automated	2	Fixed Capacity	18.0	20.0	21.0
NDT Inspection	Automated	1	Fixed Capacity	16.0	24.0	32.0
Transportation	Manual	5	Forklift	0.75	1.30	2.00

The production system of the company produces 27 sets of aerospace part per month with fixed routine since the process flow is constant and unchanged as per specification. The variation of cycle time for each process are shown in Table 1.1. The cycle time is plotted in upper and lower limit with the mod value because the data collection is time consuming and there is lack of operator to collect the data at the meanwhile performing operation during daily production. Note that in addition to the 5 main processes as shown in Figure 1.1, transporting activities within production system is supported by 5 forklift available. The company strives to achieve better delivery performance via shorter lead time and less consumption of materials in demand fulfillment.

1.3 Problem Statement

Due to the simplicity and efficiency, Overall Equipment Effectiveness (OEE) has been chosen as the measure by the case company to monitor its production system. However, company focuses on individual equipment and process separately rather than integrating and improving the performance of the entire production system. Consequence of that, issues such as unreliable downstream capacity and inefficient flow of Work In Progress (WIP) within production system have been neglected. This leads to excessive consumption of materials and delayed delivery of product to customer site even though the operation of machine in each process completes within the standard duration without any delay.

In addition, interaction between workstations and joint responsibility are not emphasized by the company under study due to absence of appropriate measure. There is no measure to pin point any individual process in the case company. The focal point which contributes to delayed delivery is invisible since the coverage of the implemented measure is too broad and general. Most of the processes and workstations in the production system are running at their optimal speed but the final output of the entire production system could not fulfil the customer demand.

In addition, the inventory level or work in progress is high between processes. The measures implemented should be able to pinpoint and quantify individual process so that improvement could be performed onto specific process. Besides, the measures should also be able to quantify the relation between processes or operational factors via examination of variation between measures.

From the observation, supportive activities such as transporting activities within the production system are not quantified and improved by company. There are five forklift shared among processes at the meanwhile only four forklift are required for transportation of each set of product. However, demolding process has to wait for incoming materials whereas other processes such as curing and inspection process are having long queue. Company wishes to resolve it via quantification and improvement on the transportation process.

Moreover, the company always experiences high level of inventory at certain processes with respect to the customer demand required because the company prefers high equipment utilization at most of the workstations to obtain higher OEE value. In contrast to the demold process which is always at idle status, NDT inspection process experiences time pressure in achieving the customer demand due to its tight capacity. It can be said that the company is lack of the emphasis on the behavior of line and also synchronization of capacity. Company could not quantify the impact of deviation in production pace in each process onto the effectiveness of the entire production system.

1.4 Objectives

The objectives of the study are as below:

i) To study and measure the impact of transportation within production system onto the throughput and lead time at each workstation.

ii) To quantify and synchronize capacity and the relations between processes for better effectiveness of entire production system.

iii) To promote the awareness in fulfilling customer demand at shorter lead time and minimal equipment utilization.

1.5 Scope of study

The study is to examine the effectiveness from the perspective of both equipment and product of the aerospace part manufacturing company. Therefore, the quality issue is not quantified within the proposed Overall Performance Effectiveness (OPE) because the defects are not the by-products of any inefficiency of production plan. Consequence of that, the demand used within the study is the one from external customer with the consideration of historical rejection rate at the end process of entire production system. The amount of demand is used throughout the entire production line to empower the joint responsibility of all processes in hitting the ultimate target of satisfying customer.

In addition, focus of the study is to propose suitable measurement to incorporate issue of overproduction results from the fluctuation of demand and also the hidden waste not quantified by the company using Overall Equipment Effectiveness (OEE). This includes the inefficiency exists between any two consecutive processes throughout the entire environment of manufacturing. At the meanwhile of promoting a more thorough and detailed analysis on the entire production system, the proposed measurement aims to improve the responsiveness of the production planning both at strategical capacity planning and tactical production scheduling.

Nevertheless, the fluctuation of external demand which occurs outside the environment of production system is not under the scope of study. The proposed measures in this study is to quantify the performance and effectiveness of production system amidst the fluctuation of external factors such as the fluctuation of demand and unavailability of materials. This is to promote the flexibility of the strategic and tactical planning instead of controlling the aforementioned factors. Besides, it is not possible to control the uncertainties beyond the manufacturing environment and even it is hard to be accurately predicted. The approach in this study is to enable a manufacturing company respond in agile and Lean way to survive under the condition.

Last but not least, the entire condition where corresponding operations are carried out internally within the manufacturing company is considered and quantified. The operations includes main manufacturing processes and also transporting activities which refer to the movement of work in progress and material from preceding supplier process to the following customer process.

CHAPTER 2

LITERATURE REVIEW

This section summarizes the review of literatures which are related to the title of this study. Since the case company under study is of job shop factory, papers and research on similar industry have been referred and studied to know more about the issue encountered by job shop factories and how other researchers resolve those issues. It is followed by the review of Overall Equipment Effectiveness (OEE) in term of concept and applications. Besides, the performance metrics or key performance index (KPI) in daily operations of manufacturing factories which are critical but not covered in the OEE are highlighted in this section. Subsequently, modification and incorporation of new metrics by other researchers are studied and summarized. This has shown the flexibility and adaptability of OEE into various natures of manufacturing industry. Before the summary of all the literatures are presented, the quantification of environmental factor in OEE and also its integration with other tools are reviewed and summarized. All of these help to facilitate the study and the way of conducting the experiment.

2.1 Job Shop Problem

The relations between work in progress (WIP), manufacturing lead time and operational variables such as performance time of each workstation, manufacturing lot size, setup time and transfer batch size is not the new topic of study (Cuatrecasas-Arbós et. al, 2015). Quantitative results show that increase of WIP would lead to increase in lead time and vice versa. In order to achieve shorter lead time and fewer inventories, Cuatrecasas-Arbós et al (2015) suggested conditions such as smaller lot size, reduced setup time and production run, as well as making the first workstation to wait for some duration and balancing of process to synchronize the process. The understanding of relations such as this would promote better design, implementation and control of manufacturing processes.

Benttaleb et al (2016) aimed to minimize the makespan of a two machine job shop with availability constraint on one machine. The unavailable period of the machine is known in advance and fixed under the deterministic case. The experimental results show that two mixed integer programming (MIP) models are not able to find the optimal solution for large instances of size up to 100 jobs within 1 hour of runtime limit. The Jackson's algorithm (Jackson, 1956) gives optimal solution only when the in-availability period is located at the beginning or end of horizon. On the other hand, branch and bound (B&B) algorithm is more efficient because it is capable of finding solution for problem of size up to 100 jobs optimally within reasonable time. However, the problem with non-deterministic unavailable period and multiple un-availabilities on same machine is not covered in the study.

One of the examples of job shop is the hospital. Chiarini (2013) had aimed at reduction of patient transportation inside a large hospital using Lean thinking tools and logistic solutions. In the study, spaghetti chart, value stream mapping (VSM) and activity worksheet have been used to deal with the distance covered and costs related to hospital staff. Distances from the perspective of layout issue is considered and it is resolved via smarter solutions based on different flows. They are all about moving offices and doctors to another place nearer to the place it is needed. The results include the reduced average lead time per patient and costs related to patient transportation, which includes annual saving of about 237.5 thousand Europe dollar, and other kinds of wastes. Nevertheless, the priority of transportation to different workstation is not discussed in the study.

On the other hand, tardiness and earliness are considered in a study by Huang et. al. (2013) to reduce the storage cost. Proper operation of each scheduling sequence is highlighted for a more flexible job shop environment. It seeks for best route and memorize the nodes to solve the scheduling problem faster at the same time minimize the sum of weighted earliness and tardiness. It has proven that good scheduling approach can lead to cost reduction due to shorter completion time, reduction in storage space requirement and increase in equipment utilization.

Salegna and Park (1996), on the other hand, found that pulling jobs in a job shop forwards every time the loading of shop falls below minimal load to avoid idle resources. Arriving jobs are accumulated in buffer. Due dates and routes of jobs are determined before the jobs are released to smooth the workload on weekly basis. It is better to bear with higher levels of finished goods inventories so that tardiness and percentage of jobs tardy could be reduced. Besides, the work released based on capacity could lower the workload of shop in following period.

Customer demand is vital in influencing the utilization of manufacturing facilities. Approach of demand division is sometimes implemented in industry nowadays by dividing the demands into segments to make them more predictable for reduced volatility or fluctuation. This enables company to adjust their lot sizes and safety stock level with respect to the demand and seasonal cycle of that particular demand. Besides that, several initiatives had also been done by suppliers to customers so that they could confirm and place their order in advance for the better production planning (Colares, n.d.). All these require some incentives to ensure large amount of reservation of demand so that stability in term of the economies of scale could be achieved, at the same time its amount does not create any discomfort to the supplier itself in case of cancellation.

Moreover, assessment method as the guidelines has been proposed by Rawabdeh (2005) in job shop environment for the search and identification of waste problem and elimination. Waste matrix which quantifies the relationships among wastes and the weight of wastes affecting each other as well as assessment questionnaire which allocates the source of waste are included in the assessment method. This is to resolve the situation that interventions of wastes elimination would result in other waste types being negatively affected. In short, it is to rank the existing wastes in a job shop and also highlights the relations between wastes. This has been done by defining the overlapping areas of seven wastes and quantifying their strength of direct relationship in waste matrix.

Job release to shop floor without review and planning activity is practiced in most of the companies. Visibility for the future load is not ensured because shop's workload is determined randomly (Salegna and Park, 1996). In addition, job shop is usually related with the release methods and workload control especially in high-variety flow and job shops with bottlenecks (Thürer et al, 2017). The scheduling mechanism controls and subordinates the release of jobs to the system based on the bottleneck or constraint. This is similar to the concept where a non-linear optimization model is formulated and implemented by Yuan and Graves (2016) to set optimal production lot sizes and lead time is planned as the tactical decision in make-to-stock job stock. Performance measures such as lead time, percentage tardy and mean tardiness against the throughput time are compared most of the time regardless of the severity of bottleneck.

Besides, make span, machine load balance and mean waiting time of jobs are evaluated to investigate the interaction between flexibility and scheduling performance of manufacturing job shops (Baykasoğlu and Özbakır, 2008). Nine test problems with different process plan and machine flexibility levels are generated. Most effective parameters are then determined and used for the design of full factorial experiment to obtain and analyze the results. The findings state that make span would decrease with the increment of flexibility level. Moreover, machine flexibility is more critical than the process plan flexibility in terms of the impact onto the job shop performance.

In addition, investigation of relationship between workload and performance has been performed (Bruggen, 2015). Productivity and complaints received are used as the quantitative and qualitative examination respectively to measure the effect of workload on the job performance. The results show an inverted U-shaped relationship between workload and performance because output and quality of performance are highest under moderate levels of workload. Investigation on such kind of relationship as this makes sure the capacity decision is improved and the workload is balanced at certain level to stimulate optimal performance of employees.

Gan and Chong (2014) had selected two bottleneck candidates in a high precision component manufacturer based on the criteria of highest utilization and longest wait time in buffer. Overtime and shift pattern are then simulated in the study by adding additional capacity in each bottleneck candidate to reduce the mean total wait time in buffer and to manage the mean total utilization of machines and technicians. Results prove that more overtime cost does not necessarily lead to improvement in total mean output.

Moreover, quantitative analysis is not the only method in detecting the shop floor bottleneck. There is a reliable approach as by Roser et al (2014) proposed that by observing the status of process and inventories in a flow lines, the direction of bottleneck could be detected in a dynamic system. The principle of the study is that a waiting process could not be a bottleneck process. On the other hand, bottleneck must be upstream when a process is starved or waiting for part whereas blocking phenomena indicates that the bottleneck must be downstream. Same goes to the inventories observation that downstream bottleneck occurs when the buffer between two processes is full or rather full whereas empty or rather empty inventory indicates upstream bottleneck. This is useful to understand the causes of the bottlenecks and improve overall manufacturing capacity.

2.2 Concept and Application of Overall Equipment Effectiveness

Lean production aims at waste elimination in every area including customer relations, supplier networks and factory management. It pursues for less human effort, reduced cycle time, inventory, defects, waste and cost to develop products as well as less space to be highly responsive to customer demand with top quality product and customer service and development of workers to company (Adanna and Shantharam, 2013; Hill, 2012). This is aligning with the objective of OEE implementation which quantifies six big losses in the measure including pursuit of ideal cycle time, minimal quality defect as well as less idle capacity and serves as an indicator to monitor, minimize and improve any detected wastes.

Overall Equipment Effectiveness (OEE) is a hierarchy of metric serves as driver of improvement and focuses on inefficiencies in manufacturing process such as wasted time when machine is not in operation, and is usually used to measure effectiveness of Total Productive Maintenance (TPM) via comparison with the world standard of OEE (Nakajima, 1988; Bamber et al., 2003; Chong, Ng and Goh, 2015; Ramlan et al., 2015). TPM was introduced by Nakajima to maximize the effectiveness of plant equipment and promote autonomous maintenance among operators. With the multiplication of availability, performance rate and quality rate, OEE tends to reduce six major production losses as shown in Figure 2.1 and also to serve as an indicator of process improvement activities (Dal, Tugwell and Greatbanks, 2000; Zammori, Braglia and Frosolini, 2011).

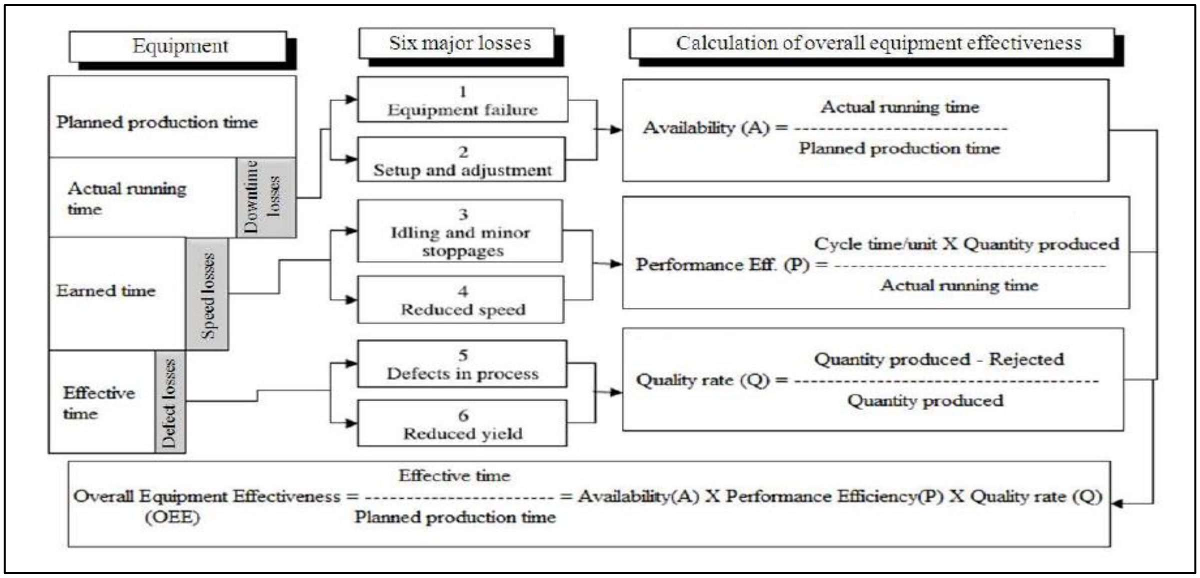

Figure 2.1: Six big losses and calculation of OEE (Eswaramurthi and Mohanram, 2013)

Formulation of OEE is suggested to be implemented in systematic way which starts from the analytical definition of OEE (Cesarotti, Giuiusa, and Introna, 2013). It is followed by the investigation of relation between OEE of single equipment with that of the production system from where they connect with. From that, the effects of different time losses categories make on single equipment and entire product system could be analyzed and this enables the OEE to be considered from different perspectives in terms of different factors. Performance measurement is important in management since it identifies the gap between current performance and the desired performance and also provides indication of progress towards closing the gaps (Samad, Hossain, and Major, 2012).

In contrast to the individual product based assignment methods, consideration of the portfolio-wise correlations among processes should be taken into account to determine the system configuration to obtain lower overall costs if it is applied on rolling horizon basis, revised and updated periodically (Gyulai and Monostori, 2017). Similar concept could be applied onto the system-wise OEE approach. Quantification and measure of effectiveness has to be implemented throughout the production system rather than focusing on single equipment because there are several wastes exist between processes. This could be done either by consolidating the measures of different processes and workstations, or by establishing a linkage of measure especially in the area between two or more processes.

Relations between processes could be illustrated from the fact that improvement in availability rate reduces the buffer inventories required to protect downstream production from breakdowns. This leads to decreased lead times since jobs are not waiting long in the queues due to less Work in Progress (WIP) and consequently this increases the competitiveness of company in terms of flexibility and delivery. Shorter lead time, quality and productivity of production system enable company to grab market opportunity and deliver multiple versions of product (Samad, Hossain, and Major, 2012; Afefy, 2013).

Time-based performance is usually used to evaluate the customer delivery performance due to importance of the time element (Dröge et al., 2004; Iyer et al., 2004). This is true that time-element should be used not only to evaluate not only performance of equipment but also to measure that of entity or material to highlight the aforementioned correlations among process. Despite that the measure of inventory or WIP has been monitored to minimize the potential issue arise from the correlations between processes, however, it is not practical to maximize the buffer size between processes in order to lessen the losses propagation due to several considerations like logistic and economic issues such as the space unavailability, plant layout and cost or interest on buffer (Cesarotti, Giuiusa, and Introna, 2013).

In general, availability measures the portion of lost production due to downtime losses over the amount of time a machine which is available for production. Downtime comprises of planned and unplanned downtime. Another factor named performance rate compares real production output to the theoretical output. It considers the speed loss and any causes that contributes to slower operation speed than the maximum possible speed. On the other hand, quality factor considers the rate of rejected item due to quality defect, the produced pieces that do not meet quality standard and wastages which require rework (Ramlan et al., 2015).

Most of the companies and studies identify potential inefficiencies in process using OEE to determine the initial performance in terms of productivity. This is then compared with ideal OEE values as indicators to help in monitoring and managing machine improvement (Ramlan et al., 2015). There is other study identifies those machines which work individually using OEE so that the machine with lowest OEE value signifies the place where TPM resources should focus on (Zammori, 2015). This is similar to the study conducted by Adanna and Shantharam (2013) which selects the process with most amount of time consumed for the experimentation and implementation of SMED to improve the setup process. Besides, it is recommended to carry out observation to identify the losses or inefficiency within the process to be studied, and sort out the significant few using Pareto chart so that the focal point of improvement could be on the step where most of the speed losses occur (Benjamin, Marathamuthu, and Murugaiah, 2015). In short, bottleneck with the worst performance could be tracked out using OEE measure and prioritized to improve the effectiveness of the entire line with least resources.

On the other hand, Overall Equipment Effectiveness-Market based (OEE-MB) as introduced by Anvari, Edwards, and Starr (2010) provides a tool not only for monitoring but also for managing improvement by taking into consideration all losses within market time for meeting both internal and external demands. Market time refers to the time duration for the production to satisfy both internal (ID) and external demand (ED). It considers the time consumed for the time spent on defects (D), breakdown losses (BD), setup and adjustment losses

(SA) and minor stoppage (MS). The manufacturing rate is evaluated by unit per hour (UPH) and the actual unit per hour (AUPH) is the actual speed of machine. The merit of the study is that it is not only evaluated in time unit, but also the fulfilment of customer demand has been considered within the OEE implementation. All of these studies suggest that the improvement could be implemented after the losses in time unit or from perspective of material with respect to demand are measured. However, none of them has highlighted the correlations between processes or any origin of the wastes from the perspective of correlations.

2.3 Additional Performance Metric and Consideration required besides OEE

Customer demand could fluctuate on daily basis that an effective system nowadays could be an outdated production line in future. In addition to the time-element measure (Dröge et al., 2004; Iyer et al., 2004), more customer-related metrics (Teoh, Ito and Perumal, 2017a; Ali and Deif, 2016) should be included into the Lean measurement because the objective of lean systems is to create value which is defined by customers. In fact, fluctuation of demand and its resulting deviation from the production rate are critical and vital because usually production rate is less likely to be flexible enough and it depends on net operating time (Ali and Deif, 2016).

Therefore, efficient planning approach is required to cope with varying order stream (Gyulai and Monostori, 2017). Effect of demand uncertainties on the supplier, internal and customer integration onto the customer delivery performance should be clarified to provide practical guidance for logistic and supply chain management (Sakun and Chee, 2011). In addition, the flexibility of production, full utilization of men and machines, and also the coordination between men and machines are deemed to be related with problems in scheduling (Mugwindiri et. al., 2013).

Feasible plan on strategic level and also tactical level should consider the forecast volume in the future to maintain the desired production rate which is verified in terms of manufacturing settings and demand environment (Gyulai and Monostori, 2017; Ali and Deif, 2016). Each and every operation of equipment should be necessary and based on the fulfillment of demand required. Customer demand and planning approach are related to each other in affecting the effectiveness of the production system (Teoh, ito, and Perumal, 2017b). A planner will face issues in term of flexibility if the OEE is referred as the only guideline in planning production.

Colares (n.d) states that there is tradeoff exists between the capacity utilization and service level. It is recommended to have tolerance on overtime and idle resources although it sometimes leads to high cost. Company should monitor the normal capacity utilization which is the average utilization in the last 3-5 years for short-term or tactical decision. Theoretical capacity utilization which is the equipment or system capacity working all the time, on the other hand, should be referred to for long term decision. This will keep the level of utilization controlled at the same time no service level is compromised.

Besides, the degree of leanness on a system under dynamic demand condition could be measured in terms of efficiency, work in progress and also service level (Ali and Deif, 2016). Responsiveness, capability to deliver world class products as per diverse customer demand, as well as the flexibility to adapt to changes from its surrounding and to handle products from all phases of life cycle efficiently are hardly implemented in conventional production system especially for the company with diverse production portfolio (Eswaramurthi and Mohanram, 2013; Váncza et al, 2011). This is intolerable because time effectiveness, delivery, inventory and resources are among the quantitative performance metrics required for the assessment of Leanness as per Pakdil and Leonard (2014).

Furthermore, the relationship between supply chain integration with customer delivery performance could be affected by the demand uncertainties (Sakun and Chee, 2011). According to Gansterer, Almeder and Hartl (2014), it is favorable to tackle uncertainties of demand by the increased safety stocks and lot sizes rather than by the premature production should there be free capacity on the production line.

Lack of effective internal and external supply chain integration would contribute to parts shortages, delivery and quality problems, and cost increases (Rosenzweig et al., 2003). This is particularly critical because one of the requirements to meet customer demand at the lowest total system cost is via integration of all internal functions from materials management to production, sales, and distribution (Morash and Clinton, 1998). Moreover, small process or secondary process is more likely to be the bottleneck process which is not studied in details. Among the bottlenecks, 30% to 50% of them are in secondary transport related processes (Roser et al, 2014). Likewise, OEE tolerates hidden wastes such as unnecessary motions, lengthy and inappropriate methods (Perumal et al, 2016)

Dhand and Singla (2016) focuses on the optimal production amount for each product type from the perspective of production cost, and optimizes the production of different items with varying cost in a cable manufacturing firm via dual-phase simplex method. Besides, sensitivity analysis has been used and proves that any potential breakdown of machine or equipment has no impact on the proposed production rate at the meanwhile the demand and target sales could be achieved. Again, the controllable lot sizes and its resulting flexibility are to compensate any stochastic events like breakdown of equipment and fluctuation of demand (Gansterer, Almeder and Hartl, 2014). This has proven that priority should go to the flexibility rather than the emphasis of minimizing any changeover or set up time as well as the minor stoppage at certain circumstance.

Last but not least, there is no separate metric or method in OEE to monitor the losses caused by non-availability of manpower and material likes components, sub-assemblies and WIP, which are also extremely important for effectiveness and smooth operation of a manufacturing system. Existing OEE is not sufficient to assess the losses associated with manufacturing resources with separate metrics (Eswaramurthi and Mohanram, 2013). The non-availability will further contribute to the idle time and waiting between processes or delayed delivery of product which only happens to affect performance of products but not that of equipment. This contributes to invisibility of the affected performance of products such as lengthy waiting between processes and delay delivery of product under the approach of conventional OEE. Therefore, corresponding quantification is required so that corrective actions could be initiated immediately and specifically on that particular delayed or suboptimal products.

2.4 Incorporation of Metrics and Modification on OEE

Positive impacts of both supplier integration and internal integration onto customer delivery performance became less significant under high level of demand uncertainties (Sakun and Chee, 2011). Companies should be equipped with integrated and balanced performance measure to have a better performance and availability of the production facilities (Kennerley and Neely, 2003; Fleischer, Weismann, and Niggeschmidt, 2006). It is important to select and convert the relevant, reliable, interpretable and valid performance measures into the timely instructions or provide insight into future performance of equipment so that the most effective activities could be done at right time to prevent performance losses of manufacturing system and yield highest payback with reduced overall workload (Al-Turki and Duffuaa, 2003; Lee et. al., 2013; Zeller, 2014).

Therefore, plan should be prepared carefully to utilize the manufacturing facilities fully and effectively for optimum operation of plant (Mugwindiri et. al., 2013). Besides, improvement of production effectiveness depends on the inputs of the production process such as man, machine, material and methods and the way to identify and eliminate the losses associated with each for outputs maximization (Eswaramurthi and Mohanram, 2013).

Besides that, the service level has been quantified to incorporate the customer demand and delivery performance into the measure called Overall Service Level (OSL). It is a measure to reflect the level of customer demand is filled on time by measuring the ratio of target delivery delay over the delivery delay (Ali and Deif, 2016). The measure highlights that target delivery is the portion of initial backlog in the system over the demand rate whereas the actual delivery delay is the quantification of backlog in system over the filled order rate. The illustration of OSL is demonstrated in the following Figure 2.2 below:

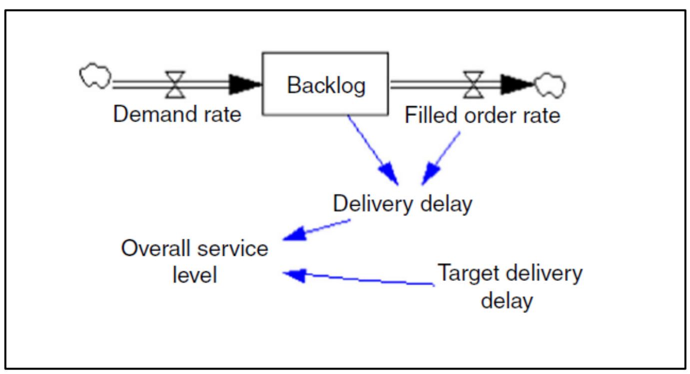

Figure 2.2: Comparison of the backlog and filled order rate with target delivery delay in Overall Service Level, OSL (Ali and Deif, 2016)

Ali and Deif (2016) in assessing the leanness level of a multi-stage production system with novel integrated metric which combines Overall Work-In-Progress Efficiency (OWE), OEE and Overall Service Level (OSL). Three metrics capture three fundamental Lean outcomes in term of stability or leveling as reflected in WIP level, production efficiency as measured by quality and availability, and also the responsiveness to market as reflected in service level respectively have same weight ratio and their average serves as the leanness score.

In the OSL, the calculation of actual WIP level which simply divides accumulated WIP throughout production system with total amount of workstation represents the entire production system as a unity and average out the WIP (Ali and Deif, 2016). In order to highlight the aforementioned synchronization between inputs and operational factors of production system, the concept of OEE has been extended up to factory level to reach at the measure called Overall Throughput Effectiveness, OTE or System OEE. (Huang et. al., 2003; Oechsner et. al., 2002; Razzak, Daley, and Dismukes, 2002). The modified version of it is to measure the performance of production system within factory level as shown in Table 2.1 below:

Table 2.1: Description of losses propagation in the system according to OEE metrics

	Single Subsystem/ Equipment	Entire System/ Production
Availability	Breakdown Losses Set-up and Adjustment	Without fair buffer, production rate of downstream is slowed down by downtimes losses of upstream processes, and vice versa
Performance	Idling and Minor Stoppages Reduced Speed	These could affect production rate of all processes without buffer.
Quality	Quality Defects and Rework Yield Losses	These are losses of entire process depends on the spot they are identified, rejected or reworked.

(Adapted by Oechsner et al, 2002)

In addition to the effectiveness of equipment, either at individual process or factory level, other evaluation of other resources such as man power has been presented by Chen and Sarker (2015) and it shows that employee training, combination of individual and organizational learning, continuous improvement as well as reduction of forgetting effect are keys to reduce production cost and improve flexibility of production planning. Besides, Overall Resource Effectiveness (ORE) has been introduced to address various kind of losses in manufacturing system (Eswaramurthi and Mohanram, 2013). It includes the factors known as readiness, changeover efficiency, availability of material and availability of man power to address the losses associated with the resources like man, machine, material and method individually as shown in following Figure 2.3.

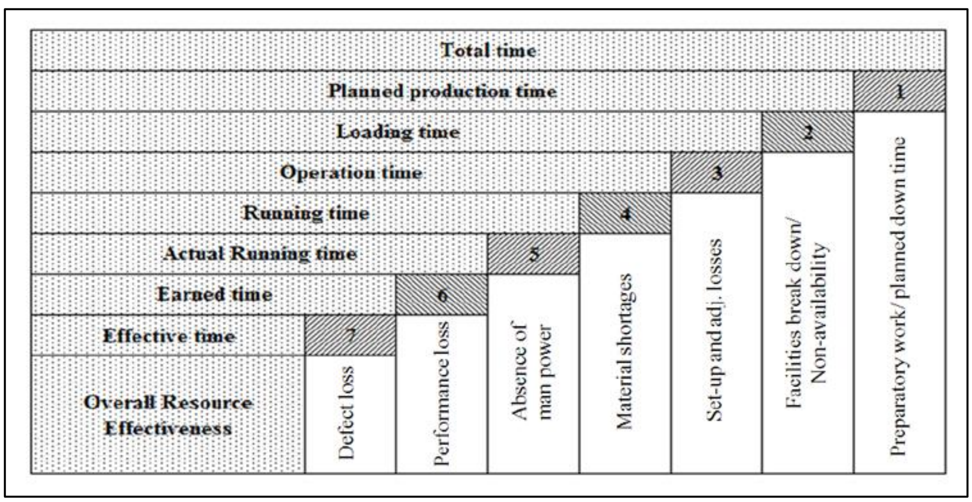

Figure 2.3: The model for Overall Resource Effectiveness (Eswaramurthi and Mohanram, 2013)

It can be seen from Figure 2.3 that the non-availability of resources are all quantified using separate metrics under ORE. Examples include the breakdown of facility which contributes loss within planned production time, shortage of material which contributes loss within operation time and absence of man power leads to loss within running time. They are quantified by availability of facility, material and man power respectively. The ORE, as the multiplication of all factors mentioned, helps decision makers to further analyze and continually improve the performance of resources accordingly. This is how the individual measures within the ORE facilitate the improvement done by pin pointing directly to the sub-optimal area.

There is a need for the OEE implementation to have the function of not only monitoring but also for managing improvement. Managerial implication on improvement of production planning and productivity could be obtained from the establishment of aggregate production planning model with numerical sample and data (Chen and Sarker, 2015). Besides, the losses exist within market time of satisfying the needs of internal and external markets should be taken into consideration (Anvari, Edwards, and Starr, 2010). Market time here includes the time before the loading and setup of the operation. It also considers the time spent on defects (D), breakdown losses (BD), setup and adjustment losses (SA) and minor stoppage (MS). The time losses before the loading time or within the market time is not classified as losses until the operation time of machine could not meet the market demand from either internal or external. The concept of the Overall Equipment Effectiveness-Market based (OEE-MB) is illustrated as in Figure 2.4 below:

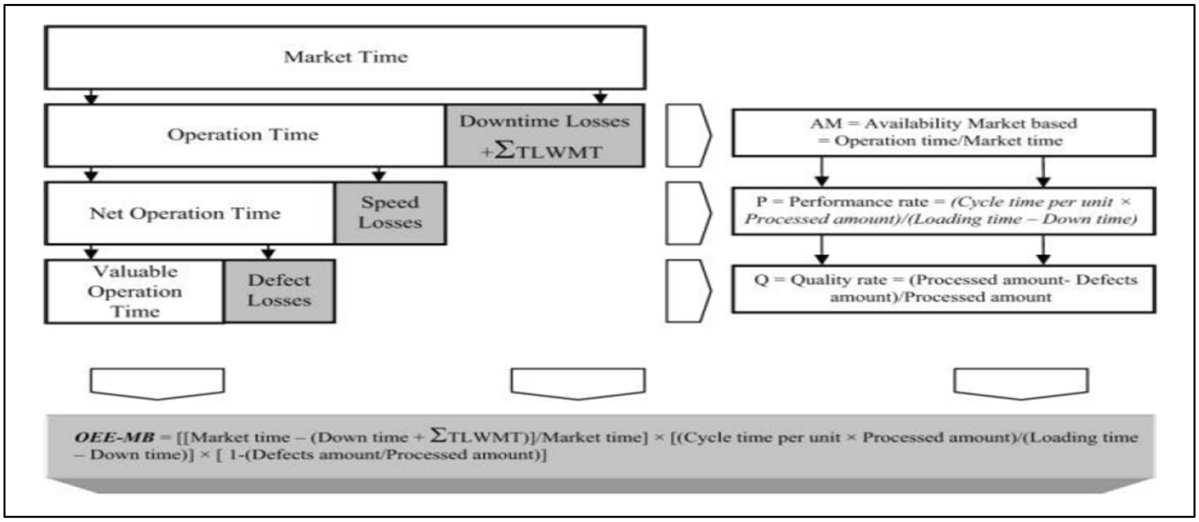

Figure 2.4: The concept of OEE-MB and the relationship between elements (Anvari, Edwards, and Starr, 2010)

From the Figure 2.4, the availability of the OEE-MB measures the portion of operation time after deducting all downtime losses as well as the total Time Loss within Market Time (TLWMT) which depends on the demand from market. This is a useful concept because the OEE-MB will change accordingly with the fluctuation of demand and hence promoting management to look into any existence of time loss before the loading time especially when the production is not able to meet market need. Examples of the time loss before loading time include time spent on any disruption to the production schedule, time spent on carrying out current orders, shortage of labor due to daily shop floor meetings, and training, as well as all non-operational time due to lack of material, electricity and utilities such as water (Anvari, Edwards, and Starr, 2010).

Transportation as the connecting part of two or more consecutive processes should be quantified and monitored from time to time. Poor delivery capability is the by-product from the failure to adopt integration between operation and logistic function (Fawcett et al., 1997). From the perspective of internal integration, the logistics operation itself could be the transportation activities which are carried out within production system from one process to another.

Last but not least, transportation could be considered as a transformation of position from one station to another, of which its service vehicles affect and are affected by the equipment losses or losses propagation from other processes (Cesarotti, Giuiusa, and Introna, 2013). Overall Vehicle Effectiveness (OVE) and also Transportation Overall Vehicle Effectiveness (TOVE) which is modified version of OVE, have been introduced to measure the vehicle performance and operating availability (Simons, Mason, and Gardner, 2004; Villarreal, 2012). In order to effectively track out wastes which contribute to losses in the TOVE, it is recommended to elaborate the operation using Transportation Value Stream Mapping (TVSM). The map enables explanation of the operation and the identification of all relevant wastes along with its causes (Villarreal et. al., 2012; Villarreal, 2012).

Villarreal, Garza-Reyes, and Kumar (2016) have in a study demonstrated the usage of Transportation Overall Vehicles Effectiveness (TOVE), which is a modification on OEE emphasizing on routing operation, and the wastes have been defined as in Table 2.2.

Table 2.2: Seven Lean wastes in Transportation operation

Waste	Description
Overproduction	Writing redundant report, Make extra copies of documents, Store same information at different places and ineffective meetings

Table 2.2: Seven Lean wastes in Transportation operation (Continued)

Waste	Description
Waiting	Idle employee due to the lack of demand Waiting for next process, processing delays, equipment downtime and tight capacity of process.
Incorrect Processing	Inefficient routing or driving causes excessive consumption of resource to transport goods to customer.
Unnecessary Movement	Any wasted motion of employees for preparation of operation. Walking and extra movement due to sequencing errors.
Defects	Damages on the transported goods or the equipment and their corresponding repairs, redelivery and scrapping.
Resource utilization (New)	Excessive equipment (investment) and bad resource planning.
Uncovered Assignment (New)	Carrying out unprofitable transport work due lack of information or planning.

Adapted from Sternberg et al. (2012) and Villarreal, Garza-Reyes, and Kumar (2016)

Cross-functional communication and joint efforts require strategic collaboration within supply chain integration because internal integration breaks down functional barriers and engenders cooperation, which forms the basis for the coordination of information flow across functions (Flynn et al., 2010). Accordingly, the satisfaction of multiple clients or fulfillment of customer demand, inventory level as well as variable processing time which could contribute to lack of synchronization between processes are some of the process parameters to be deliberately handled to retain production objectives (Graves, 1981).

2.5 Quantification of Environmental Factors in OEE and Integration with Other Tools

Eswaramurthi and Mohanram (2013) opine that the stratified lost time of set-up and adjustment under ORE could be improved by using SMED concept. SMED is useful in promoting flexibility of production with smaller lots size for diverse customer demand nowadays. In other study, flexibility of production could be tackled via adjustment on lot sizes and level of safety stock (Váncza et al, 2011; Gansterer, Almeder and Hartl, 2014). This shares the same point of view with the concept of calculating volume flexibility of production to investigate the manufacturing strategy of a firm amidst the dynamic market environment (Arafa and ElMaraghy, 2011) and also to incorporate both customer demand and learning effect into aggregate production planning (APP) model in favor of reduced production cost and improved flexibility of APP (Chen and Sarker, 2015).

Wong et al (2015) access the performance of several logistics firms listed in both Malaysia and Singapore. Not only has it presented the process parameters and operational factors in logistics firms or transportation process, it also introduces suitable measure which addresses performance of transportation via efficiency and effectiveness to understand the intermediate measures or linkage of activities. Performance measure of transportation process could actually be in various terms as shown in Figure 2.5. The important matter is to relate the final output to the raw input as in the study.

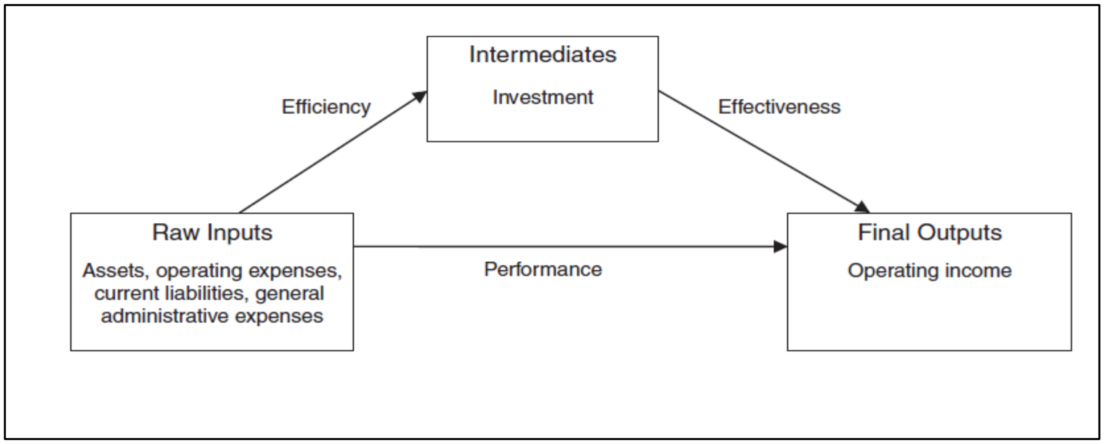

Figure 2.5: Triangular efficiency, effectiveness and performance model for logistics firms (Wong et al, 2015)

Under the measure of efficiency, internal capability and effective usage of resources have been emphasized. Maximization of final output from input factor such as investment, on the other hand, has been monitored by effectiveness which measures the external capability of generating revenue. Similarly, incorporation of transportation process in OEE is studied in order to yield optimal results. Villarreal, Garza-Reyes, and Kumar (2016) have shown that proposed distribution of goods via different route design is recommended to be simulated before they are implemented. In the study, lean thinking has been applied to improve the efficiency of warehousing and routing operations by classifying wastes into those relevant to transportation operations. The feasibility of transportation is assessed from the perspective of routing activities, transporting and customer serves per route.

The estimation of performance measure specifically for transportation activities named Transportation Overall Vehicle Effectiveness, TOVE is used to elaborate the transportation activities after the identification of wastes departing from the seven wastes using Transportation Value Stream Mapping, TVSM so that the contribution of loss from each waste could be quantified before and after implementation of loss elimination strategy (Stenberg et al, 2012; Villarreal, 2012). Different distribution scenarios from the routing activities, transporting and customer serving are simulated. Subsequence of that, the improvement initiative with the best impact on customer service has been chosen and the results shows that number of routes had been reduced from 30 to 22 and the distance travelled shorten by 32 percent. Therefore, the quantification of transportation include the dynamic of route design, the customer frequency, capacity or usage of service vehicle as well as the size of basket within the service vehicle (Villarreal, Garza-Reyes, and Kumar, 2016) are requied. Material flow and process sequence are fixed for the production and the demand is stochastic in nature (Ak and Erera, 2007) to be fulfilled from time to time.

2.6 Summary of Literatures

From the review of literatures, workload issues and imbalanced capacity especially at bottleneck in production system are common in job shops production system. Equipment utilization is the measure to be examined and studied for the prevention of excessive capacity or excessive workload. Besides, time-based performance metrics such as lead time, wait time as well as production unit such as throughput rate, transfer batch size, work in progress and inventory level are frequently used to evaluate the customer delivery performance. Therefore, these are the Key Performance Index (KPI) to be used in the site observation and data collection.

Among them, good scheduling based on the capacity is critical for equipment utilization and to reduce tardiness and percentage of jobs tardy. Concept is that higher workload does not necessarily lead to better improvement and higher output. Moreover, relations between the KPIs has been emphasized. Increased flexibility, improvement on production efficiency, shorter distance travelled and fewer inventories, for instances, would reduce the lead time and make span.

Even though the blocking or starvation within a production system would lead to losses in OEE, however, the so-called interrelations between processes or configurations could not be quantified by OEE at equipment level. Importance of performance measurement at system level has been justified by the modification on OEE. Among them, Overall Throughput Effectiveness (OTE) or System OEE is demonstrated to measure performance of system. Overall Throughput Effectiveness (OTE) is to measure performance, detect bottleneck, identify hidden capacity and find out the areas that constrain factory productivity. Following Table 2.3 has summarized other modifications which have been done on the OEE according to varying requirements and nature of manufacturing industry:

Table 2.3: Improvement timeline and gap of study related to Overall Equipment Effectiveness (OEE)

Author (s)/ Year of publication	**Anvari, F., Edwards, R., & Starr, A/ 2010**	**Ali, R., and Deif, A./ 2016**	**Eswaramurthi, K. G., and Mohanram, P. V/ 2013**	**Villarreal, Garza-Reyes, and Kumar/ 2016 Villarreal/ 2012**
Concept	OEE-Market Based (OEE-MB) is introduced to monitor all losses within duration of satisfying internal and external market needs. Change of market demand can be reflected under OEE-MB according to the time required.	Degree of leanness on a system is measured under dynamic demand conditions in term of efficiency, work in progress (WIP) and service level. They are quantified using OEE, Overall WIP Efficiency (OWE) and Overall Service level (OSL) at their own value of importance.	Overall Resource Effectiveness (ORE) is presented to measure overall effective time of manufacturing system or resources. Losses associated to resources like man, machine, material and method are addressed.	Transportation Overall Vehicle Effectiveness (TOVE) is presented to elaborate a transportation value stream mapping (TVSM) and improve efficiency of warehousing and routing operations.

Table 2.3: Improvement timeline and gap of study related to Overall Equipment Effectiveness (OEE) (Continued)

Author (s)/ Year of publication	**Anvari, F., Edwards, R., & Starr, A/ 2010**	**Ali, R., and Deif, A./ 2016**	**Eswaramurthi, K. G., and Mohanram, P. V/ 2013**	**Villarreal, Garza-Reyes, and Kumar/ 2016 Villarreal/ 2012**
Area of implementation	Focus is the non-scheduled time within market time related to production, personnel, organization and management. Only time unit and amount of defects are measured.	Stability or leveling as reflected in WIP level, production efficiency as measured by quality and availability, as well as responsiveness to market as reflected in service level are emphasized.	Whole facility of manufacturing system like machines, tools, jigs and fixtures and others are considered to target the losses created by the resources.	Focus on the classification of wastes which are related to the routing and transporting activities. Concern is to minimize number of clients not served and frequency of transportation.

Table 2.3: Improvement timeline and gap of study related to Overall Equipment Effectiveness (OEE) (Continued)

Author (s)/ Year of publication	**Anvari, F., Edwards, R., & Starr, A/ 2010**	**Ali, R., and Deif, A./ 2016**	**Eswaramurthi, K. G., and Mohanram, P. V/ 2013**	**Villarreal, Garza-Reyes, and Kumar/ 2016 Villarreal/ 2012**
Limitation	Delivery performance is not considered. Besides, over-production is not quantified.	Only demand variability and volumes are studied. Impact of one process onto leanness of other process is not covered.	Even though it considers whole facility, however, relationship and connection between processes are not covered. Besides, delivery performance and demand are not quantified either.	Mostly focus on routing operation which is external to the production system. Interaction between manufacturing and transportation process is absent.

In OEE- Market Based (OEE-MB), all losses during within the duration of satisfying internal and external market needs are monitored to cover the efficiency losses that results from rework and yield losses. Moreover, the level of customer demand is filled on time has been monitored under Overall Service Level (OSL) in term of delivery delay. Overall Resource Effectiveness (ORE), on the other hand, addresses various kind of losses in manufacturing system which associated with the resources such as man, machine, material and method individually. Moreover, transportation process has been monitored and quantified in many studies. Overall Vehicle Effectiveness (OVE) and also Transportation Overall Vehicle

Effectiveness (TOVE) are the examples to monitor vehicle performance and operating availability. Each of them has their area of application at the same time comes with limitations as shown in Table 2.3.

Other modification on the OEE includes Overall Fab Efficiency to cover financial parameters. Total Equipment Effectiveness Performance (TEEP) is demonstrated to highlight equipment utilization for more effective capacity planning. Overall Plant Efficiency covers capacity usage and labor operating efficiency includes availability, accumulated knowledge depth and quality of workforce, into the OEE. Overall Equipment Effectiveness of a Manufacturing Line (OEEML) highlights the progressive degradation of ideal cycle time and measures performance of entire production line. However, there is no study which covers all the delivery performance, issue of over-production, impact of one process onto leanness of other process as well as interaction between manufacturing and transportation process into single measure.

In short, more customer-related metrics, low inventory and waste are the keys for effective equipment utilization for consideration into OEE. The degree of leanness on a system in terms of efficiency, work in progress and also service level as well as time effectiveness, delivery, inventory and resources need to be assessed. The performance metrics as mentioned in previous section could also be incorporated into proposed OEE measure in this study. As described in Section 2.4 and 2.5, OEE is flexible and versatile to incorporate critical indicators as performed by similar studies.

CHAPTER 3

METHODOLOGY AND PRIMARY RESULTS

The study starts with site observation in an aerospace part manufacturing company which focuses on the operational procedures. Time data of automated processes is obtained from the computerized system whereas that of 2 manual processes are collected via time study. Besides, the number of operators, level of inventory and finished goods between processes are acquired at this stage so that a complete picture of the production could be obtained. All related non-value added activities (NVAs) as mentioned in previous section and operational factors are collected as the Key Performance Index (KPIs) of each workstation. Every portion of production, which consists of supplier and customer workstation as well as the process in between such as transportation activities, are studied for the data collection. The overall procedures of the study is shown in following Figure 3.1:

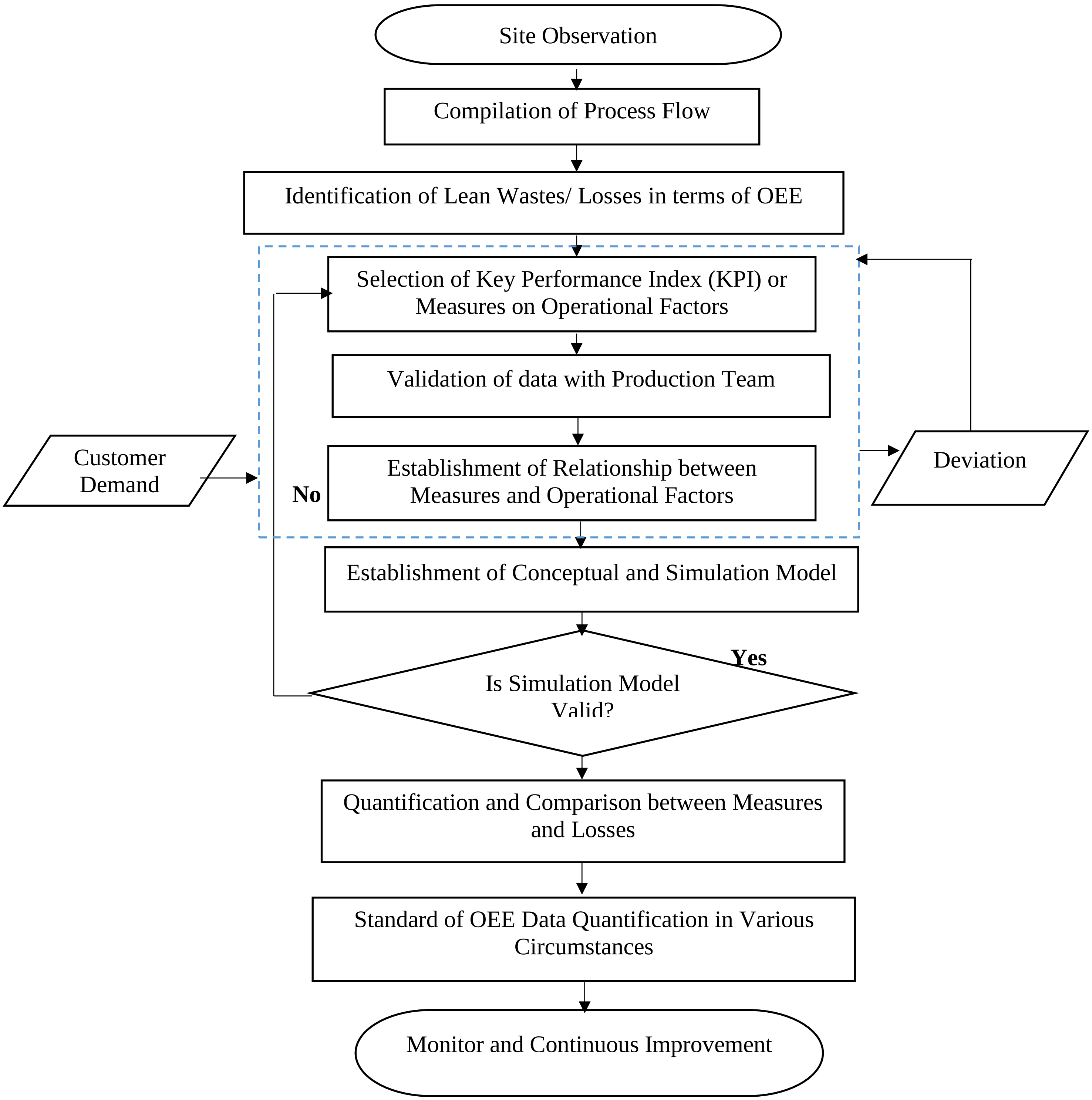

Figure 3.1: Overall Procedure of Modeling Overall Performance Effectiveness

The selection of KPIs as listed in Figure 3.1 is critical to ensure the measures to adequately represent the operational factors and to define the relations between them. Besides, they are related and compared with customer demand so that its deviation could be tracked out and corresponding Lean wastes could be identified. Therefore, it is essential to understand the processes in the production line of the case company thoroughly. The study of the process flow could be tabulated in table to summarize the details of production system.

The following steps as shown in Figure 3.1 is the identification of lean wastes from the perspective of OEE. In prior to that, extensive reference and review on related literatures are required to enhance the comprehension and facilitate the application of Overall Equipment Effectiveness (OEE). As for the selection of KPIs, two types of units used for the measurement in this study are either related to customer demand rate or corresponding time unit in achieving customer demand.

Comparison with demand is proposed to company in the study so that its deviation from production amount could be kept minimal but its amount is adequate to ensure continuity of next process with controllable level of buffer. It is a necessity to establish a linkage at both strategic and tactical level so that the decisions made for long term and short term are synchronized to achieve the objective of waste elimination

KPIs or metrics in following Table 3.1 is to monitor the losses caused by either the non-availability of manpower or material such as components, sub-assemblies and WIP. Besides, relationship between processes or internal integration could be quantified by some of the individual measures named waiting time of product, Takt time set and transportation time. They are also extremely important for effectiveness and smooth operation of a manufacturing system.

Table 3.1: Measures and Key Performance Index (KPIs) for analysis of interruption

Location of Data Collection	**Unit of KPIs and Measures**	
	Time Unit	**Resources Unit**
Preceding (Supplier) Process	i) Cycle time ii) Waiting time in queue iii) Production duration iv) Takt time	i) Number of Operator ii) Amount of product completed iii) Deviation between production and demand
Between Processes (Mostly transportation)	i) Waiting duration for forklift ii) Idle time of forklift iii) Transportation time	i) Utilization rate of the forklift per transportation ii) Availability of forklift. iii) Number of forklift iv) Size or capacity of forklift
Following (Customer) Process	i) Waiting time for availability of resource ii) Takt Time iii) Cycle time iv) Duration of production	i) Number of operator available ii) Ratio of unit transported to amount of buffer iii) Length of queue. iv) Deviation between production and customer demand

The relationship between workstations and interaction of KPIs are examined via development of simulation model. Production system under varying circumstances such as efficiency of transportation, cycle time of workstation, as well as fluctuation of customer demand is studied. The measures and KPIs under different scenarios are collected to examine their relations so that quantification and formula could be established. This ensures the causes of the aforementioned problems and issues in the company could be monitored and improved from time to time. Formula and measures are proposed to quantify the wastes and demonstration on its usage is presented afterwards.

3.1 Development of Simulation Model

Assumptions and hypothesis about the behavior of system and also the relations between processes are incorporated at the stage of constructing the conceptual model. Iterative procedures of verifying and validating both model are carried out with production personnel since the assumptions and hypothesis about the real system could be biased or inappropriate without the thorough understanding. The conceptual model of the production system before translated into Arena simulation software to represent the production system in the case company is as shown below:

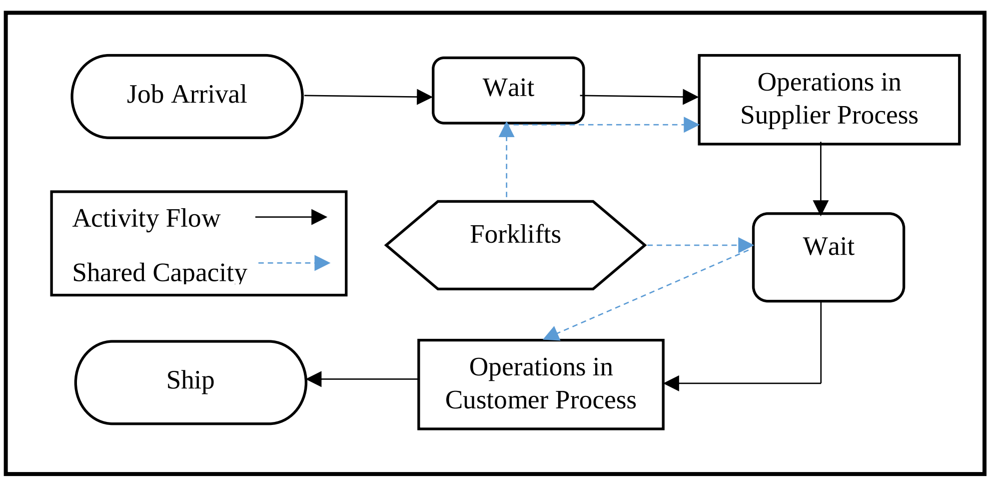

Figure 3.2: Conceptual Model of the General Activity Flow of Job

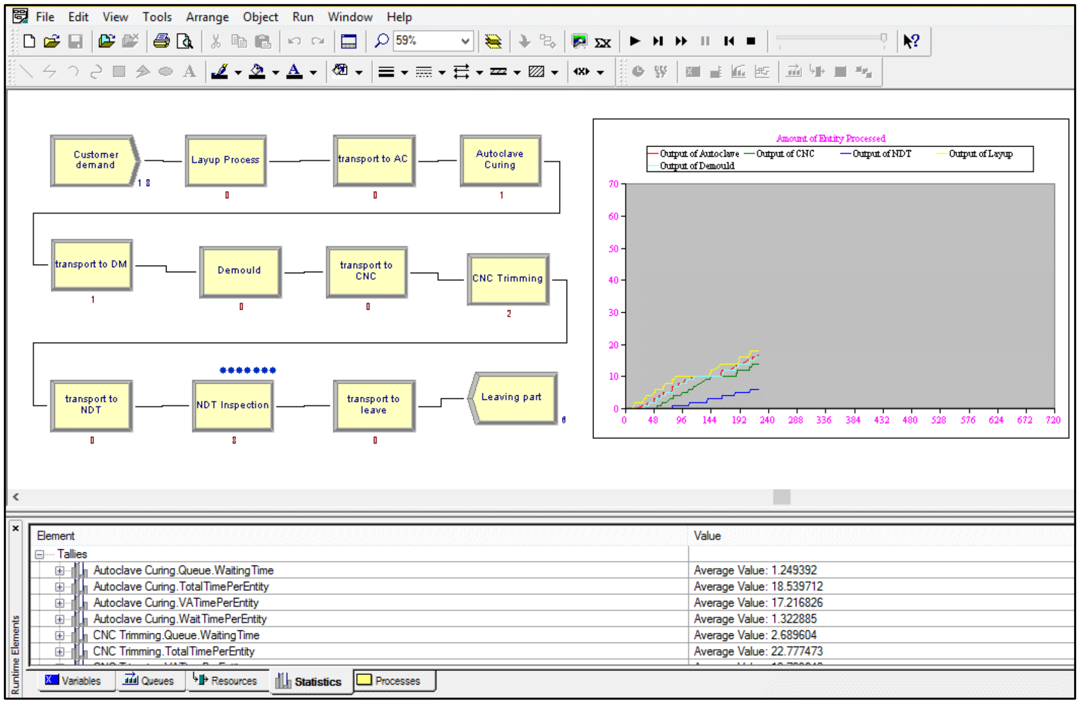

Figure 3.3: Operational Model in Arena Simulation for the General Activity Flow of Job

Entity or job arrives at process, seizes the required amount of resource which could be machine or technician depends on the nature of process. It will delay for certain period of time unit according to the cycle time of each process in triangular distribution before release and move on to next process. There are transporting activities carried out between the aforementioned five processes to facilitate the movement. Cycle time of each workstation and transportation are all the same as in Table 1.1 in the base simulation model developed. The base model is then simulated at different operational factors in 3 separate experiments as described in following sections.

3.1.1 Experiment 1

Transportation between processes is considered as an individual process or an operation although it usually is categorized as a non-value adding activity. The similar concept has been presented by Cesarotti, Giuiusa, and Introna (2013) which treats transportation as a transformation of position. In the concept, service vehicles could be quantified in term of OEE and Overall Throughput Effectiveness (OTE) to measure equipment losses categorization and their propagation throughout the system respectively. On the other hand, the transportation process considered in this study refers to the internal transporting activities which are carried out within the production system. All the external logistics activities outside of the manufacturing company is out of the scope of this study. The overall procedures of conducting experiment 1 is as shown below:

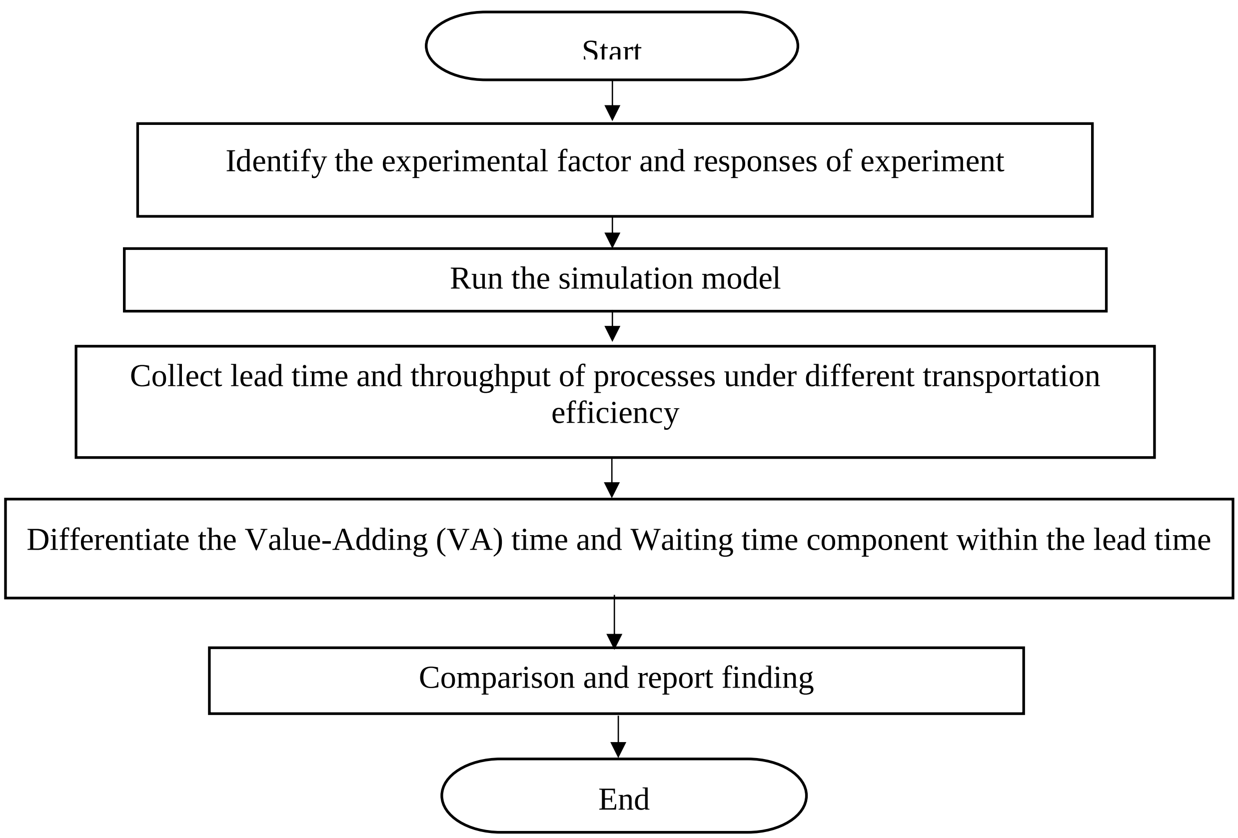

Figure 3.4: Overall Procedures to Conduct Experiment 1

Based on the site observation in the case company, it has been noticed that the output of each workstation and manufacturing process could fluctuate from time to time even though their cycle time remains the same. The potential cause of the situation, after the discussion with team of experts in the company, is hypothesized to be the secondary process carried out between the primary manufacturing processes or workstations. Therefore, the objective of experiment 1 is to study the impact of transportation process onto the effectiveness of manufacturing process and workstation it connects with. Shorter cycle time of transportation in Table 3.2 means better efficiency. Note should be taken that the cycle time of other workstations remain the same as in the model developed. From the base simulation model as shown in Figure 3.3, the transportation process between workstations are simulated in Experiment 1 under different efficiency as shown in following Table 3.2.

Table 3.2: Cycle Time of Transportation Process under Different Efficiency of Transportation

Scenario	Unit Available	Capacity Type	Cycle Time (Hour)		
			Min	Mod	Max
Actual Cycle Time (CT)	5	Forklift	0.75	1.25	2
Half Cycle Time (CT)	5	Forklift	0.37	0.65	1
25% Cycle Time (CT)	5	Forklift	0.19	0.31	0.5

Output in each process has been selected as one of the responses of Experiment 1 to justify the condition observed in the production system. The yield or output of each process could also provide the trend of output fluctuation between workstations and processes. On the other hand, lead time which is defined as the total duration elapsed by each set of output in each workstation or process, is also selected as the response of Experiment 1. The longer the lead time elapsed by each set of output, the lower the amount of output could be produced by that particular process or workstation due to slower turnaround of material or WIP. It could be said that both of the responses are related to each other because slower turnaround of WIP leads to longer wait time and therefore the lead time. The lead time and throughput of each workstation under these scenarios are collected and summarized as below.

Table 3.3: Total Lead Time and Output of Processes under Different Transportation Efficiency

Process	**Lead Time (Hour)**			**VA Time (Hour)**			**Output (Set)**		
	Actual CT	**Half CT**	**25% CT**	**Actual CT**	**Half CT**	**25% CT**	**Actual CT**	**Half CT**	**25% CT**
Layup	28.96	27.63	28.11	15.99	15.97	15.97	58.4	58.25	59.18
Autoclave	21.76	21.51	21.23	16.87	17.02	17.03	56.48	56.13	57.10
Demold	1.00	1.01	1.02	0.99	0.99	0.99	56.15	55.88	57.03
CNC	30.13	28.56	28.1	19.68	19.67	19.66	53.18	52.93	54.25
NDT	167.47	164.41	176.42	24.03	23.97	24.04	26.95	27.23	27.3
Total	249.32	243.12	254.88	77.56	77.62	77.69	-	-	-

Both the lead time and VA time in Table 3.3 reduce whenever the transportation efficiency improves from actual cycle time (CT) to half CT because better transportation efficiency or faster turnaround of materials would enable less input without worry on the interruption of production. This is supported by the reduction of throughput. However, the trend reverses in the scenario of 25% CT at some extent where WIPs reach destination processes at faster pace and incoming materials have to wait at the queue because the workstation or process could not afford to process them any faster due to the constant cycle time. The composition of wait time and value adding time within the lead time under varying transportation efficiency scenarios are summarized as below:

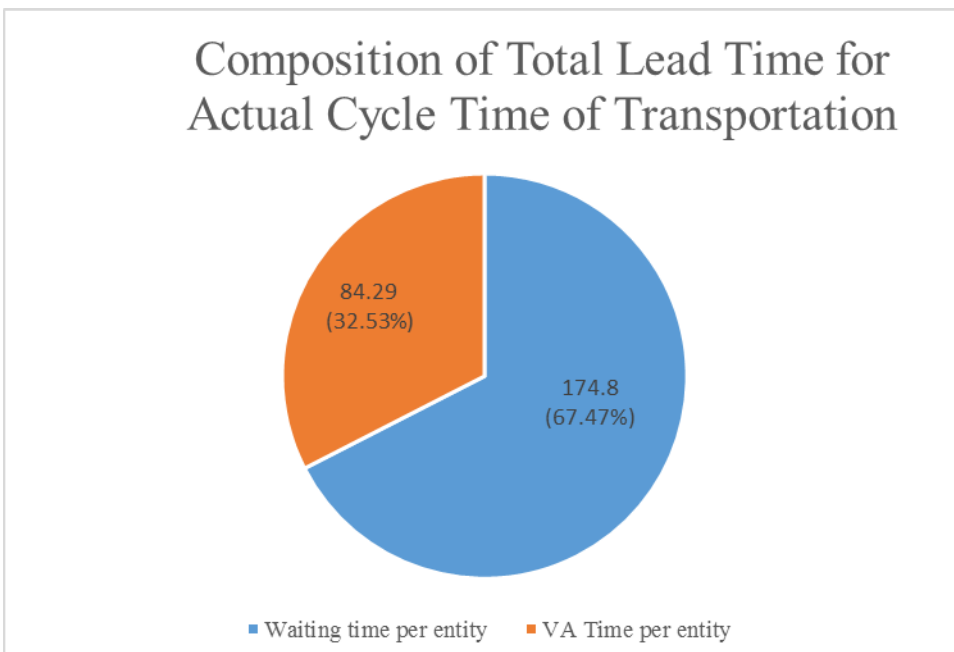

Figure 3.5: Composition of waiting time in the lead time per entity for actual cycle time of transportation

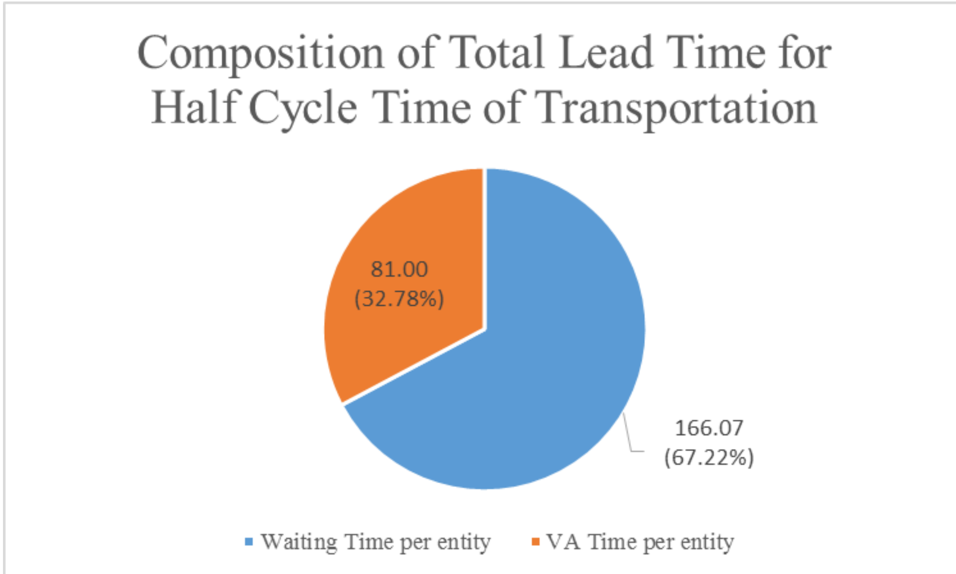

Figure 3.6: Composition of waiting time in the lead time per entity for half cycle time of transportation

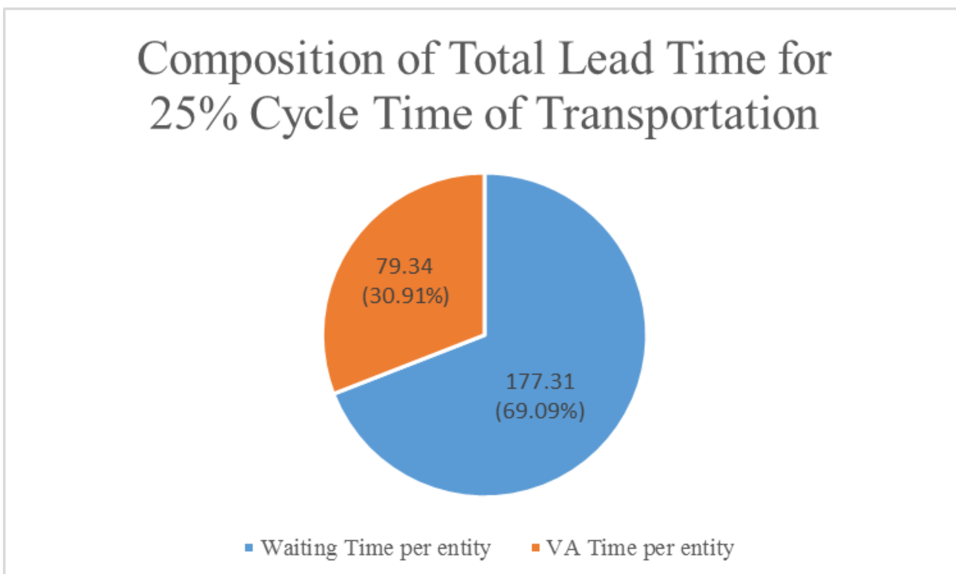

Figure 3.7: Composition of waiting time in the lead time per entity for 25% cycle time of transportation

Results in Figure 3.5 to Figure 3.7 prove that the composition of waiting time per entity has been reduced whenever the transportation efficiency is improved from actual cycle time to half cycle time but increased in the 25% of transportation cycle time. This has justified the statement as explained previously. This is also supported by the highest amount of output as sighted in Table 3.3 for the scenario with fastest turnaround of WIPs within the company. In short, this signifies that the transporting activities within production system should be monitored and measured because it would affect the delivery performance of materials and also the value adding time or corresponding equipment utilization.

3.1.2 Experiment 2

Relations between transportation process within company and manufacturing processes has been revealed in Section 3.1.1 by proving that throughput and lead time of each workstation or process within production system could be affected by the transport process it connects with. In this section, the base model as constructed in Figure 3.3 is used to simulate impact of varying cycle time of Autoclave workstation in Experiment 2.

Objective of Experiment 2 is to study the change of cycle time of Autoclave curing process and its impact onto throughput of other processes in term of lead time and throughput. This is to examine the aforementioned relationship among workstations and processes so that to make sure management team is well prepared for the breakdown of equipment and during the period with peak demand. The overall procedures of conducting experiment 2 is as shown in Figure 3.8 below:

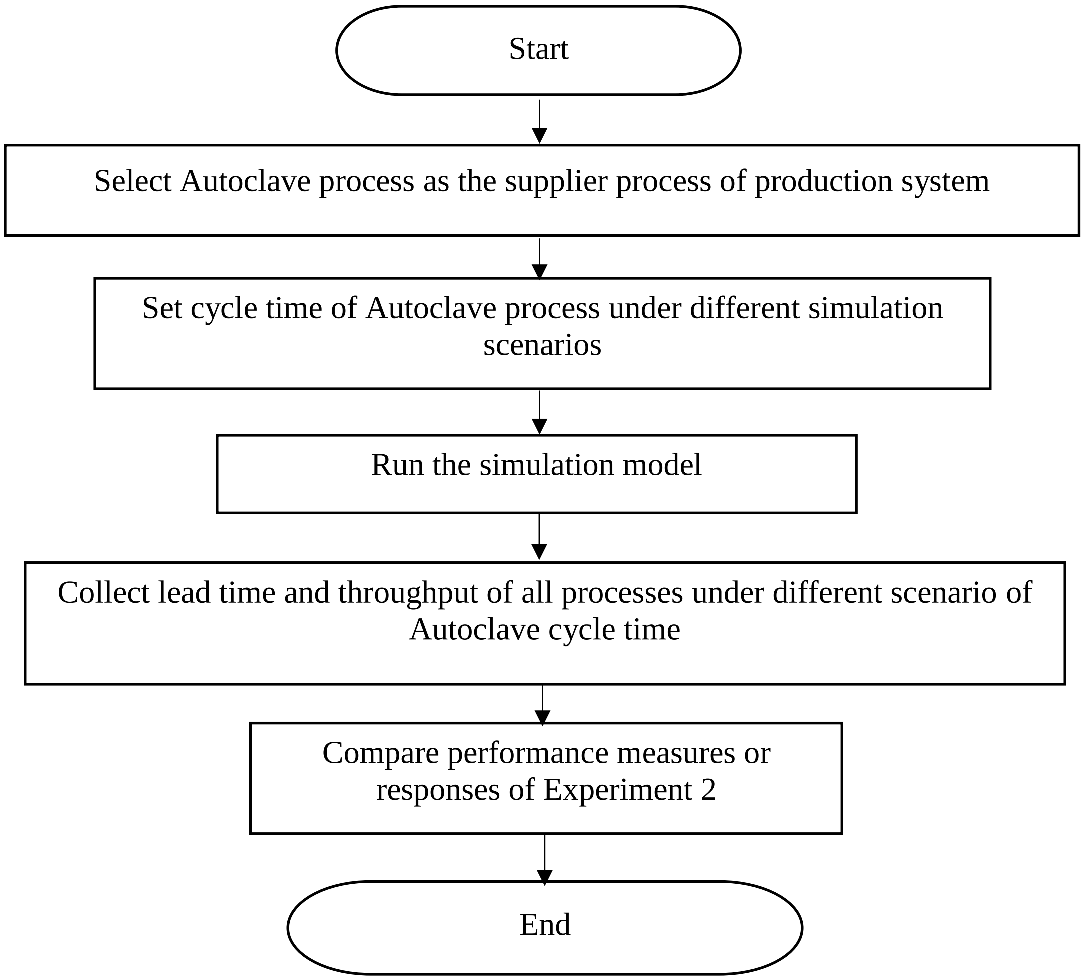

Figure 3.8: Overall Procedures to Conduct Experiment 2

Cycle time of Autoclave process is selected as the controllable variable because it is bottleneck process and also the supplier process of most of the workstations in the production system. In experiment 2, the cycle time (CT) of autoclave are simulated in 3 scenarios, which are double, actual and half of actual cycle time respectively, as listed in Table 3.4. On the other hand, wait time and output are selected as the responses of the experiment due to the same reason as explain in Experiment 1 and the results are shown in Table 3.5 as below:

Table 3.4: Different Cycle Time of Autoclave Curing Process (Experimental Factor) in Experiment 2

Scenario	Unit Available	Capacity Type	Cycle Time (Hour)		
			Min	Mod	Max
Double Scenario	2	Autoclave	18.00	28.00	56.00
Actual Scenario	2	Autoclave	9.00	14.00	28.00
Half Scenario	2	Autoclave	4.50	7.00	14.00

Table 3.5: Wait Time and Output under Varying Cycle Time of Autoclave Process

Process	**Wait Time (Hour)**			**Output (Set)**		
	Double CT	**Actual CT**	**Half CT**	**Double CT**	**Actual CT**	**Half CT**
Layup	13.69	12.97	12.86	62.03	58.4	59.78
Autoclave	100.67	4.89	0	39.43	56.48	58.98
Demold	0	0.01	0	39.28	56.15	58.73
CNC	0	10.45	13.05	37.98	53.18	55.13
NDT	84.20	143.44	146.74	26.53	26.95	27.25
Total	198.56	171.76	172.65	-	-	-

Simulation on cycle time of Autoclave workstation is to demonstrate the mutual responsibility of all processes in affecting delivery of product, which are represented by the wait time and amount of output. The KPIs or responses selected in experiment 2 are wait time and amount of output in each workstation and process so that the production pace and their effectiveness in fulfilling the right amount of customer demand are quantified and compared.

From Table 3.5, all scenarios produce almost the same amount of output by the end of NDT process regardless of the change in the cycle time of Autoclave curing process. However, total wait time elapsed by each entity all processes and workstations are shorter in the Actual CT and Half CT scenario than that in Double CT scenario even though the cycle time of each process and workstation except autoclave remain the same.

The blocking phenomena can be seen from lower throughput at autoclave process in Double CT scenario. On the other hand, both of the scenarios namely actual CT and half CT post lowest output in NDT workstation in contrast to autoclave process. In double CT scenario, blocking phenomena occurs on the autoclave process only whereas the situation is evenly distributed in both actual and half CT scenarios because of better line balancing practice. Besides, the waiting time of layup process are almost the same in all scenarios because the capacity of Autoclave (or blocking phenomena) does not affect its preceding process or supplier process. In short, this has proven the relations between processes. Delay delivery of company is not only because of effectiveness of any individual process but is also due to that of the overall system.

3.1.3 Experiment 3

The case company has highlighted that its capacity of workstations are not balanced and synchronized throughout the production system. Idle resources and tight capacity could be sighted in different workstations even though they manage to yield 27 sets of product per month. From site observation, tight capacity in NDT limits the production rate of entire product system even though most of other workstations have excessive capacity and are at idle status frequently throughout the site observation. The throughput produced by each workstation or process except

NDT workstation is relatively if compared to the customer demand. The overall procedures of experiment 3 are summarized as below:

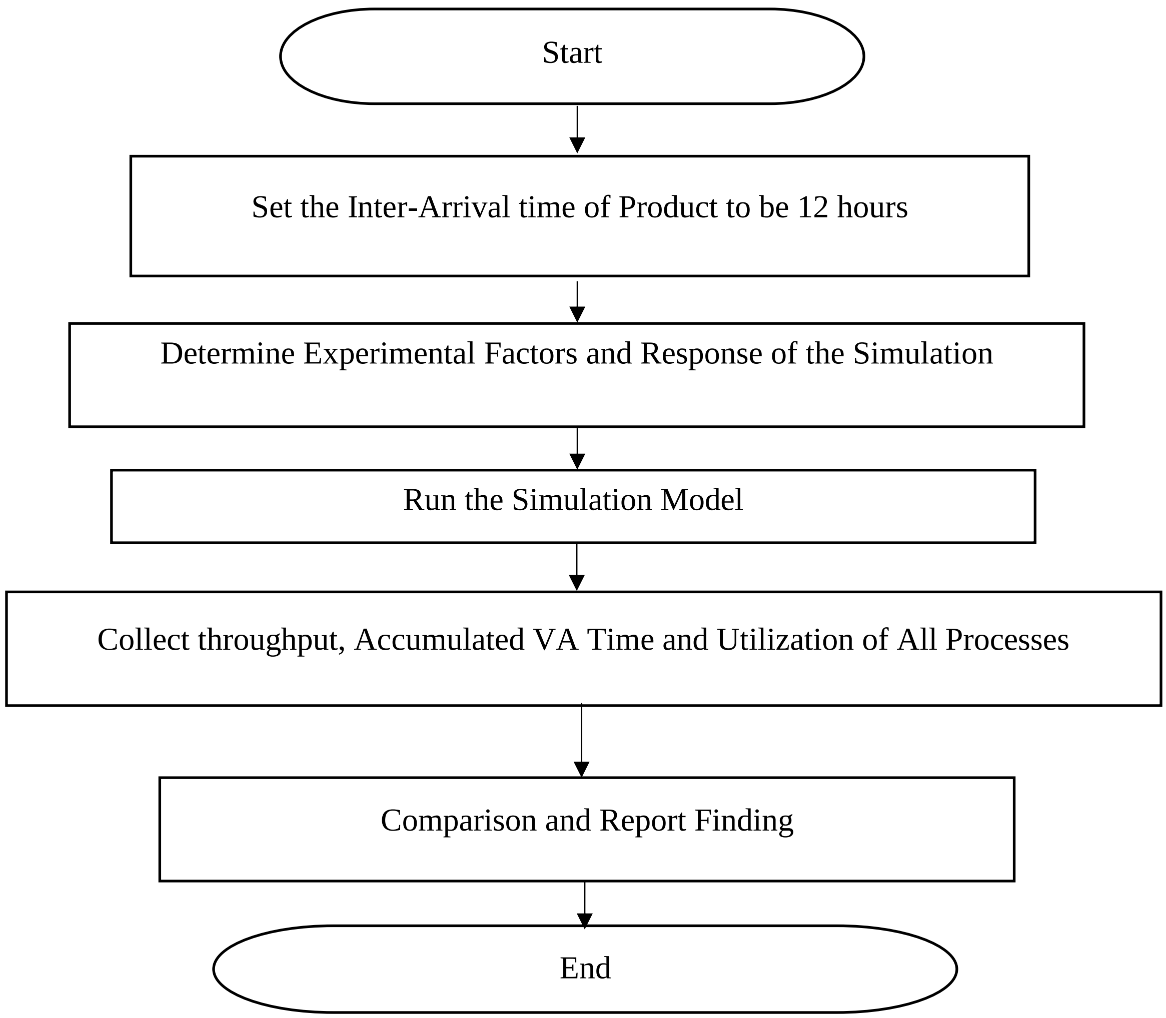

Figure 3.9: Overall Procedures to Conduct Experiment 3

The objective of Experiment 3 is to measure the difference of throughput rate at each process. Inter-arrival time of product is set to be 12 hours to represent more customer demand instead of 24 hours in the actual condition as developed in Figure 3.3. The experimental design is as shown in Table 3.6 below:

Table 3.6: Variation in cycle time as the experimental factor in determining difference in throughput of each process

Process	**Cycle time (Hour)**				
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Layup	Actual	0	0	0	0
Autoclave	0	Actual	0	0	0
Demold	0	0	Actual	0	0
CNC	0	0	0	Actual	0
NDT	0	0	0	0	Actual

The experimental factor is the varying cycle time of processes or workstation in each of the five simulation scenarios. As shown in Table 3.6, the cycle time of Layup process in Scenario 1 remains the same as the actual condition. All the other processes except Layup process are having zero cycle time in scenario 1. Similar setting is repeated in scenario 2, 3, 4 and 5 by fixing the cycle time of autoclave, demold, CNC and NDT as per actual condition in scenario 2, 3, 4, and 5 respectively but the cycle time of other workstation are set to be zero. The amount of throughput at each workstation is selected as the response of the simulation so that their output without the blocking phenomena from other workstation at the same time double up the demand could be examined. The response is summarized as in following table:

Table 3.7: Throughput at each process after the arrival rate is doubled

Process	Throughput (Set)				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Layup	87.65	121.45	124.80	121.75	121.45
Autoclave	87.43	82.45	116.40	118.65	117.58
Demold	87.13	82.00	109.00	116.08	113.93
CNC	86.95	81.65	102.13	71.00	110.05
NDT	86.80	81.28	94.35	69.40	28.18

The shaded values in Table 3.7 represents the throughput could be supported by each workstation under the condition where arrival rate of incoming material is doubled and all the other interconnecting workstations are having zero cycle time. Scenario 2 through Scenario 5 have more entry of input than that of scenario 1, which is above 120 sets in contrast to 87 sets. This is because layup process of the case company could only support 87.65 sets as in Scenario 1. Similar concept applies to other scenarios and the throughput could be supported is 82, 109, 71 and 28 sets for autoclave, demold, CNC and NDT workstation respectively, at doubled arrival rate.

This represents the production pace which is restricted by the capacity of each workstation based on their capacity. Among them, NDT posts lowest amount of throughput and it has restricted the output of the entire production system down to 28 sets. It could be said that NDT is the bottleneck process since its output is still the same as the actual condition from the site observation even though the arrival rate is doubled up. Last but not least, this has signified the imbalanced capacity among the workstations and processes.

3.1.4 Summary of the results from experiments

The results from Experiment 1 shows efficiency of transporting activities within the case company contributes to delay delivery of products. Results prove that shorter transporting duration of WIP helps to reduce the lead time and waiting time per entity within production system given the same cycle time of all manufacturing workstations. Therefore, appropriate measure for internal transportation should be proposed so that company could monitor and improve its transporting activities. This is not implemented by the company at current stage because it focuses on manufacturing processes only via OEE.

In addition, relations between manufacturing processes has been demonstrated in Experiment 2. The effectiveness of entire production system is proven to be due to the mutual responsibility of all workstations rather than because of any individual process. Shorter cycle time of Autoclave process contributes to better throughput rate throughout the production system. In other words, this has revealed the importance of measuring the joint responsibility of all processes in achieving timely delivery. This is not seen in the case company because measures of all processes are interpreted individually without interaction with each other.

Experiment 3 has demonstrated and measured the impact of imbalanced capacity throughout production system. Throughput rate could be supported by workstations are different from each other. The experiment has proven that high throughput rate in supplier processes are restricted by the unreliable downstream capacity of NDT curing process. Therefore, the company needs to balance the capacity of the production system.

All experiments have been performed to analyze the problems faced by the company under varying circumstances. The results have necessitated the quantifications of the responses into the daily measure so that company could monitor and improve the production system from time to time. In addition, the simulation model has provided the required values of the responses to demonstrate the implementation of the proposed quantification. They include the consideration of customer demand in term of delivery duration and production amount. Proposed quantification is to monitor the workstations individually and also as the unity so that the case company could fulfill the customer demand using less resources and more efficiently as shown in following chapter.

CHAPTER 4

PROPOSED MEASURES AND DISCUSSIONS

In this chapter, various measures are proposed to quantify the transportation process and manufacturing processes as well as the workstation. This is because the results obtained in the experiments have been proven to have impact on the performance of the entire production system as discussed in previous chapter 3. In addition to that, the relations between the results such as how they interact with or affect each other are examined and discussed. The aforementioned interaction is quantified via the proposed measure as described in following sections. The application of the proposed measures is discussed in this chapter.

4.1 Quantification of Transportation Process

4.1.1 Proposed Availability Ratio of Transportation Measure

Experiment 1 proves that transportation process within the production system could affect the effectiveness of the workstations it connects with. Therefore, it should be measured and improved from time to time to ensure better performance and collaboration of the entire production system, rather than eliminating or excluding the transportation from the production planning. Similar concept as the OEE and OPE has been applied onto the transportation process. The availability ratio for the transporting activities, A_T in the case company is proposed as in Formula 4.1 and Formula 4.2 below:

$$A_T = \frac{\text{Transported Output}}{\text{Transported Input}} \text{ x Contribution to Continuity of operation at destination}$$

(4.1)

Where,

$$\text{Contribution to Continuity of operation, CCOO} = \frac{1}{\text{Queue Length at Destination Process}}$$

(4.2)

Transportation process does not add value to the product or work in progress but promote fluid flow within the case company so that the lumpier arrivals of product or WIP to each work station could be reduced. Therefore, appropriate measure for improvement and monitoring purpose as defined above discourage the full utilization of the forklift and unnecessary transportation. Instead, the measures tend to reduce the frequency of the transporting activities and prioritize the usage or assignment of shared forklift based on the queue length at the destination process.

Contribution to continuity of operation as in Formula 4.1 and 4.2 is a measure to quantify the ability of transportation process in preventing any potential interruption at the destination process which results from the shortage in material or WIP. Basic concept of the measure is that operation of destination process will turn into idle status immediately right after the previous batch of operation is done, if and only if there is no awaiting WIP or incoming material in queue. The availability of transportation process to each workstation in Experiment 1 has been computed in Table 4.1 to demonstrate its usage:

Table 4.1: Contribution to continuity of operation, CCOO and throughput rate for transportation process to each workstation in Experiment 1

Destination workstation	**CCOO (%)**			**Transported output/ Transported input (%)**		
	Actual transport cycle time	**Half transport cycle time**	**25% transport cycle time**	**Actual transport cycle time**	**Half transport cycle time**	**25% transport cycle time**
Layup	7.71	8.58	8.24	99.74	99.91	99.92
Autoclave	20.45	22.27	23.81	99.68	99.91	99.88
Demold	100.00	100.00	100.00	99.64	100.00	100.00
CNC	9.57	11.25	11.85	99.85	99.91	100.00
NDT	0.70	0.71	0.66	99.74	99.82	99.93

Higher value of CCOO represents higher criticality and urgency of the transporting activities to that workstation in ensuring the operation at destination workstation. Basically, service vehicle or forklift should be prioritized for the transportation to the workstation with higher CCOO or otherwise that particular workstation will become idle without any incoming WIPs. For the workstation with the queue length number lies between 0 to 1 set, the CCOO computed is 100%. From here, the CCOO minimizes the queue length so that its impact onto the wait time per product could be reduced in the workstation too.

Besides, the amount it transports throughout the operation is not determined by the transportation process itself because it has to transfer all WIP from supplier workstation to customer workstation. Even though there is study which states that higher capacity of handling system in transportation will cause more item produced so that transportation cost per unit could be minimized (Rawabdeh, 2005), however, the case company does not consider the cost and efficiency of transportation during the production planning. Therefore, comparison of throughput with respect to customer demand is not required.

The ratio of transported output to the transported input is to promote rapid turnover of products or WIP through forklift. Amount of WIP stays inside the service vehicle could be kept as low as possible to ensure the readiness or availability of service vehicle for other workstations. In short, computation of the availability ratio of transporting activities within the case company is summarized in Table 4.2 below:

Table 4.2: Availability ratio of transportation process to each workstation in Experiment 1

Destination workstation	**Availability of transportation process (%)**		
	Actual transport cycle time	**Half transport cycle time**	**25% transport cycle time**
Layup	7.69	8.57	8.23
Autoclave	20.38	22.25	23.78
Demold	99.64	100.00	100.00
CNC	9.55	11.24	11.85
NDT	0.70	0.71	0.66

Availability ratio computed in Table 4.2 implies that shorter transportation time within the case company does not necessarily lead to higher availability ratio. This could be seen from the availability of layup and NDT workstation under the 25% of transportation cycle time and that of half transportation cycle time. Similar results are found in a study which shows that performance of employees is highest when workload is moderate (Bruggen, 2015).

From the perspective of internal integration, transporting activities is the internal logistic operation where its demand depends on the queue length at destination process. At some point, shorter transportation cycle time would lead to longer queue length at destination compared to the production system with longer transportation cycle time. Consequently, transportation of WIP to that workstation should not be promoted and but to assign the shared forklift to other workstations with higher CCOO values.

Even though Transportation Overall Vehicle Effectiveness (TOVE) had been introduced by Villarreal (2012) to improve efficiency of routing operation, however, it focuses on the delivery performance using time unit of equipment and total number of clients not served (Villarreal, 2012; Villarreal, Garza-Reyes, and Kumar, 2016). There is no emphasis on the responsibility of internal transportation in promoting operation and continuity of production system at the same time keep the forklift utilization to be low.

In short, the proposed availability of transportation A_T has emphasized the fulfillment of internal demand by its destination workstation to ensure continuity of production without interruption. Besides, this has promoted and facilitated in determining the priority of the transportation of material internally within manufacturing system based on their urgency which is not covered in the TOVE. Besides, equipment utilization of workstation determines the queue length which would further affect the priority of the transportation process. The inter-relations between transportation process and workstations it connects with are not measured by any quantification yet has been incorporated in the availability of transportation measure.

4.1.2 Proposed Performance Ratio of Transportation Measure

There are 5 similar forklifts with same capability to be shared throughout the production system, and each transportation could only be done after the previous transportation is completed. Therefore, equipment utilization of forklift is important to measure how well they are utilized to ensure the continuity of workstation in efficient way. The wellness of utilization here refers to not only the amount of utilization rate, it also focuses on the good time or quality service of the transportation which is really performing or moving towards its destination. It excludes those wait during along the service duration. Therefore, the performance ratio of transportation, P_T should quantify the uptime portion within the utilized capacity of service vehicle as shown in Formula 4.3:

$$P_T = \frac{\text{Total Transportation Uptime}}{\text{Total Service Duration of Forklift}} \text{ x Utilization of Forklift} \qquad (4.3)$$

The utilization of the forklift is incorporated in the performance ratio to prevent excessive investment in the service vehicle and large portion of idle capacity of forklift with respect to required demand. Instead of encouraging the higher frequency of transportation, the utilization of forklift in Formula 4.3 could be increased via reduction of investment in equipment or capacity expenditure. This is how it keeps the transporting activities in minimal level yet ensures the continuity of production. Summary of the forklift utilization, the total service duration of transportation to each workstation and the portion of transportation uptime within it in Experiment 1 is tabulated as following:

Table 4.3: Forklift utilization, total duration of transportation per product to all workstations, and uptime ratio in Experiment 1

Destination	Forklift Utilization (%)			Total Service Duration (Hour)			Uptime/ Total Service Duration (%)		
	Actual cycle time	Half cycle time	25% cycle time	Actual cycle time	Half cycle time	25% cycle time	Actual cycle time	Half cycle time	25% cycle time
Layup	37.50	18.66	9.42	2.11	0.85	0.37	63.98	80.00	89.19
Autoclave				1.86	0.78	0.35	72.58	87.18	94.29
Demold				2.04	0.78	0.35	65.69	85.90	94.29
CNC				1.89	0.78	0.35	71.43	87.18	94.29
NDT				1.87	0.76	0.35	71.66	88.16	94.29

Table 4.3 shows reduction in both utilization and total service duration of forklift whenever the transportation cycle time reduces because it depends on accumulated transportation cycle time. In addition, faster movement of WIP within production system would ensure the readiness of the shared forklift for other destination workstation. On the other hand, the ratio of uptime in transportation over the total service duration of forklift makes sure that the resource utilized is essential and to reduce the non-value added duration such as wait time and preparation duration within the utilized resource. It is higher when the transportation cycle time is reduced because task could be completed at faster pace. The total service duration of forklift in the transportation process consists of downtime and uptime of transportation. Downtime is the duration elapsed to wait for the readiness of forklift or the driver whereas the uptime is the portion which is really moving towards the destination process. The performance

ratio of transportation, P_T is computed from the data in Table 4.3 and is shown in Table 4.4 as below:

Table 4.4: Performance ratio of transportation process in Experiment 1

Destination	Performance ratio (%)		
	Actual cycle time	**Half cycle time**	**25% cycle time**
Layup	23.99	14.93	8.40
Autoclave	27.22	16.27	8.88
Demold	24.63	16.03	8.88
CNC	26.79	16.27	8.88
NDT	26.87	16.45	8.88

The performance ratio of transportation process to each workstation posts reduction whenever the transportation cycle time becomes shorter. This is because of the excessive investment in the forklift capacity. The forklift utilization in Table 4.3 has reduced from 37.5% to 9.42% when the transportation cycle time has been shortened, from actual cycle time, half cycle time to 25% of its actual cycle time. The excessive capacity of forklift has mitigated the reduction of wait time and the improvement on the portion of uptime. In short, this has implied that utilization should be improved by trimming down the excessive capacity or amount of forklift for a better performance ratio.

4.1.3 Transportation Measure of the Case Company

Availability ratio, Av and performance ratio, Pr for the transportation activities to each destination workstation are summarized in Table 4.5. The performance ratio and availability of forklift or transportation process are interpreted simultaneously to draw a much more precise conclusion for the improvement of entire production system. In addition to that, the transportation measure, TM of transporting activities is computed based on the definition as in Formula 4.4 below.

$$\text{Transportation Measure} = \text{Availability ratio}, A_T \text{ x Performance ratio}, P_T \qquad (4.4)$$

Table 4.5: Availability, performance ratio and transportation measure of case company in Experiment 1

Transportation Destination	Actual transport CT			Half transport CT			25% transport CT		
	Av. (%)	Pr. (%)	TM. (%)	Av. (%)	Pr. (%)	TM. (%)	Av. (%)	Pr. (%)	TM. (%)
Layup	7.69	23.99	1.85	8.57	14.93	1.28	8.23	8.40	0.69
Autoclave	20.38	27.22	5.55	22.25	16.27	3.62	23.78	8.88	2.11
Demold	99.64	24.63	24.54	100.0	16.03	16.03	100.0	8.88	8.88
CNC	9.55	26.79	2.56	11.24	16.27	1.83	11.85	8.88	1.05
NDT	0.70	26.87	0.19	0.71	16.45	0.12	0.66	8.88	0.06

In overall, the transportation measures reduce whenever the cycle time of transporting activities within case company is shortened. This is due to the reduction of performance ratio and forklift utilization in the scenario with shorter transportation cycle time as explained previously. The negative impact has mitigated the improvement of availability ratio and positive effect from better flow faster within case company.

Elements of transportation measure are compared to yield balance between better utilization and efficiency of forklift. Free capacity or utilization rate as well as the queue length at the destination process determine the priority of the service vehicle assigned to one workstation over the other. Note should be taken on NDT workstation that its transportation measures are relatively low in all scenarios. Blocking phenomena is critical in NDT workstation with lengthy queue due to its tight utilization. This leads to lower CCOO value and availability ratio than other workstations.

The delivery performance has been incorporated and measured using Overall Service Level (OSL) in the study carried out by Ali and Deif, (2016). However, the OSL measures the effectiveness of how the order is filled at the end of the production system instead of after every workstation. Consequence of that, it is difficult to pin point any individual process which contributes to delayed delivery for corresponding improvement, which is obviously the NDT workstation in the case company. Besides, the coverage of the aforementioned OSL is hard to pinpoint the responsibility of each workstation in ensuring the on-timely demand fulfilment.

Sometimes, additional incoming materials to this workstation are considered as a heavy burden because of their tighter capacity and consequently the materials have to wait in the queue. Overall Service Level is not suitable to be implemented in the case company because efficient assignment of shared forklift and area of improvement for shorter lead time is not available under the approach.

On the other hand, the quantification of transportation measure reduces unnecessary transportation within production system because it is one of the Lean wastes. Lower frequency of transportation is promoted to yield larger performance ratio because the wait time is reduced accordingly. In addition, reduction of the investment in capacity of forklift could obtain higher utilization rate of forklift. This is how the transportation measure take care of both tactical and strategical planning of capacity in the transportation process within the case company.

In short, the availability and performance ratio of transportation measure as defined in Formula 4.1 to Formula 4.4 establishes balance between utilization, excessive capacity of forklift and also the efficient assignment of forklift to the workstations which urgently need incoming materials for the continuity of production without starving phenomena. The quantification prefers less work or job in transportation process for high value in measure based on the necessity of transportation.

4.2 Quantification of Workstations

4.2.1 Proposed Availability Ratio of Overall Performance Effectiveness (OPE)

Experiment 1 show that efficiency of transportation within production system affects the departure and arrival of work in progress go and forth each workstation. This is one of the factors which contributes to wait time and lead time of work in progress and product. Therefore, the material flow and throughput at each workstation should be monitored closely. This is supported by the finding which states that increase of lot size would contribute to longer processing time, less fluid flow and lumpier arrivals at workstation (Yuan and Graves, 2016).

In addition, the case company tends to feed more inputs and raw material into the production system to mitigate the potential unavailability of raw materials which would cause interruption of production and idle equipment utilization in certain workstations such as autoclave and NDT. According to the case company, this intends to reduce the mismatch between workstations when the equipment is idle and available for operation but there is no incoming work in progress to be processed.

Therefore, the consideration of demand and its corresponding production rate are vital because case company experiences issue of overproduction and high level of work in progress. In this section, introduction of operational ratio with respect to customer demand, OPR_{cd} which is defined as below:

$$\mathrm{OPR_{cd}} = \frac{\text{No.of Output}}{\text{Customer demand}}, \text{ when production output is less than customer demand} \quad (4.5)$$

$$\mathrm{OPR_{cd}} = \frac{\text{Customer demand}}{\text{No.of Output}}, \text{ when production output is more than customer demand} \quad (4.6)$$

The OPR_{cd} compares the production rate with respect to the customer demand and to prevent the issue of both inability of fulfilling customer demand (Formula 4.5) and also the overproduction issue (Formula 4.6). In order to achieve that, deviation between output and customer demand should be kept as minimal as possible. Besides, the number of output is compared by each of the work stations to quantify their responsibility in promoting material flow of the production system. Note that the customer demand could be different from one workstation to another after incorporating their respective quality issue. This is to mitigate the effect of demand uncertainties on the supplier, internal and customer integration onto the customer delivery performance and to provide practical guidance for supply chain management (Sakun and Chee, 2011). However, it is not demonstrated here because of the assumption that there is no defect throughout the study for the simplicity of demonstration.

In addition, the difference between input and output of each workstation are incorporated in the proposed availability ratio. Similar concept has been applied to study the inputs of production process such as machine, material and methods as well as the losses associated with each of them to maximize the output and improve production effectiveness (Eswaramurthi and Mohanram, 2013). Therefore, productivity of each workstation, P_{ws} is introduced in the company to monitor the level of work in progress as defined below:

$$p_{ws} = \frac{\text{No. of Output}}{\text{No. of Input}} \tag{4.7}$$

$$\text{Availability} = \text{OPR}_{cd} \text{ x } P_{ws} \tag{4.8}$$

Large deviation between output and input is discouraged in order to obtain higher value of productivity. With the introduction of the productivity computation, high level of raw materials, inventory and finished parts within the production system could be prevented when the amount of output is same as the amount of input. This further leads to shorter lead time of material within that particular work station as proven by the results of experiment 1. The operational ratio, productivity, and availability ratio of the case company are summarized as in Table 4.6 given 29 sets of customer demand per month for all workstations:

Table 4.6: Operational ratio and productivity of proposed availability ratio

Process	Customer demand	Throughput		Components of availability ratio		Availability (%)
		Input (set)	Output (set)	P_{ws} (%)	OPR_{cd} (%)	
Layup	29	61.10	58.40	95.58	49.66	47.46
Autoclave	29	58.25	56.48	96.96	51.35	49.79
Demold	29	56.30	56.15	99.73	51.65	51.51
CNC	29	55.95	53.18	95.05	54.53	51.83
NDT	29	53.10	26.95	50.75	92.93	47.17

From Table 4.6, output is very much higher than the amount required by external customer in all work stations except NDT which yield only 26.95 sets of output due to its constraint of capacity. Results from the experiment 3 concludes that this is due to the lack of balance between workstations in term of capacity. This is supported by Cuatrecasas-Arbós et al (2015) which states that imbalance between workstation will cause higher amount of waiting parts in queue especially before the operation with higher processing time. From the results in Table 4.6, productivity of all workstations except NDT are higher than 90% which signifies that lower deviation between input and output or shorter queue. Since NDT has the highest processing time or cycle time, there are large amount of waiting part and this contributes to lowest productivity. The accumulated VA time and corresponding equipment utilization of each workstation are summarized in following Table 4.7:

Table 4.7: Equipment utilization of each workstation in the production system

Process	Accumulated VA time (Hour)	Equipment Utilization (%)
Layup	934.01	64.86
Autoclave	952.66	49.62
Demold	56.00	6.48
CNC	1046.14	72.65
NDT	647.12	67.41

According to the company, higher availability of Overall Equipment Effectiveness (OEE) implemented could be attainable with less downtime or higher equipment utilization if they minimize the duration of minor stoppage. In other words, although company achieves higher availability in total calendar approach, its production always faces higher inventory level especially most workstations with low productivity ratio of around 50%. Neither availability nor performance ratio in the OEE implemented by company could highlight the production amount with respect to the required demand by the external customer.

The equipment utilization of Table 4.7 could be equalized as the availability ratio of OEE in total calendar approach under the situation where minor stoppage is negligible. Without the consideration of customer demand, high equipment utilization would lead to over-production, excessive level of inventory and wastage of material especially during the season with low customer demand. Besides, large difference between the input of layup workstation (first workstation of the production system) and output of NDT (last workstation of the production system) in Table 4.6 has highlighted that the synchronization in term of capacity of workstations is not promoted. Therefore, the proposed availability ratio aim to monitor the level of inventory and consumption of raw materials which could represent the synchronization between workstations of the company. This is the area of improvement obtained by company using the proposed availability ratio.

4.2.2 Proposed Performance Ratio of Overall Performance Effectiveness (OPE)

Experiment 2 shows that performance of supplier process could affect the throughput of its customer process and total lead time of product in the company. Besides, the production system of the case company has been proven to be lack of balance and synchronization between workstations in term of capacity in Experiment 3. In fact, production leveling is one of the Lean techniques to reduce unevenness and wastes in industry (Chahal and Narwal, 2017). Therefore, the production pace should be critically monitored and measured so that workstations in the case company are running at same pace in fulfilling customer demand. The production pace with respect to customer demand is like the main heartbeat of the entire production system which all workstations should follow. This is to promote balance of workload among workstations and prevent blocking phenomena which has been proven in Table 3.5 and Table 4.6. Therefore, performance ratio is proposed to the company by incorporating the Takt time as shown in following Formula 4.9:

$$\text{Performance ratio (\%)} = 100\% - \frac{|\text{Takt time} - \text{Actual Cycle Time}|}{\text{Takt time}} \qquad (4.9)$$

Takt time in Formula 4.9 is useful for the production system of company to keep its production rate up to that level and as close to the demand-fulfilling pace as possible. There is no negative sign for the deviation between Takt time and cycle time of workstation because both inability of fulfilling customer demand and overproduction are equally important and need to be quantified under same weight. The quantification of Takt time in Formula 4.9 is defined as in following Formula 4.10:

$$\text{Takt time} = \frac{\text{Maximum Capacity x Historical Equipment Utilization}}{\text{Demand x Unit of resources required per production}} \quad (4.10)$$

Information about the capacity available in next production period is important. In addition, equipment utilization which is achievable based on historical utilization is considered in the quantification of Takt time as in Formula 4.10. It helps to avoid overestimation on the capacity available because it excludes the non-utilized portion of resource from the past record. Example could be seen from Table 4.7 where NDT could achieve less than 70% due to capability consideration even though it experiences blocking phenomena.

In fact, historical equipment utilization provides a reference of capacity available for the production. It raises the confidence in production planning because all the utilization and operation have been proven to be achievable. Therefore, capacity of each workstation should be improved in prior to acceptance of new demand via reduction of unplanned breakdown. Computation of Takt time for each workstation in the case company is performed based on 29 sets of customer demand as shown in Table 4.8 below:

Table 4.8: Capacity available and Takt time of each workstation

Workstation	Capacity and Takt Time for 29 sets							
	Process type	Unit	Working Hour/ Day	Working Day/ Month	Max. Capacity (Hour)	Historical Utilization (%)	Unit Required/ Operation	Takt Time (Hour)
Layup	Manual	20	16	24	7680	64.86	10	17.2
Autoclave	Automated	2	24	30	1440	49.62	0.75	32.9
Demold	Manual	12	16	24	4608	6.48	10	1.0
CNC	Automated	2	24	30	1440	72.65	1	36.1
NDT	Automated	1	24	30	720	67.41	0.75	22.3

Moreover, historical equipment utilization determines the production pace to prevent over-processing at any workstation which could be completed at shorter time. One of the examples is the demold process which sets the production pace based on 6.48% of utilization instead of full capacity of 12 men powers. The cycle time or value added time per each set of product is compared to the computed Takt time. The resulting performance ratio of each workstation is summarized in following Table 4.9:

Table 4.9: Comparison between Takt time and cycle time in performance ratio

Workstation	Cycle Time per Set (Hour)	Takt Time (Hour)	Performance Ratio (%)
Layup	15.99	17.2	93.11
Autoclave	16.87	32.9	51.35
Demold	0.99	1.0	96.84
CNC	19.68	36.1	54.53
NDT	24.03	22.3	92.39

In autoclave and CNC workstation, Takt time is much higher than the actual cycle time per set. This leads to lower performance ratio in these workstations compared to the others. Note that cycle time or the value added time per set is constant throughout time horizon because it is an established production system. Therefore, it can be said that the lower performance ratio is due to excessive equipment utilization at autoclave and CNC workstation with respect to customer demand. Equipment utilization at these workstations should be reduced to yield higher performance ratio and to prevent over-processing in the company.

One the other hand, performance ratio of demold workstation is relatively high even though its equipment utilization is low. Small deviation between cycle time and Takt time suggests that the over-processing is less likely to happen in demold workstation. Although NDT workstation experiences blocking phenomena, however, it posts high performance ratio because its production rate is close to the pace in fulfilling customer demand. In order to lessen time pressure in NDT, the unutilized capacity or unplanned should be reduced so that there is more production slot for the fulfillment of existing demand.

In contrast to the proposed performance ratio as defined in Formula 4.9, the OEE approach as implemented by the case company could not quantify the issue of overproduction. This is because it compares only the ideal cycle time of each workstation with their actual cycle time. None of these two measures is related customer demand and remain the same regardless of the demand required. Besides, the achievability of demand required is not examined in the OEE and most of the time, case company could not determine if the production pace is on right track in producing right amount of product.

Therefore, data in Table 4.9 provides a guidance about the responsibility of each workstation in fulfilling demand. All workstations but NDT could produce more than 29 sets of output because their cycle time per set is shorter than the Takt time. However, input of work should be aligned with output rate of bottleneck or production rate of each workstation could be adjusted based on amount of work in queue (Thürer et al, 2017; Yuan and Graves, 2016). For the case company, all workstation should not produce more than 27 sets because it is the maximum rate could be supported by NDT section. In short, production pace in the company could be monitored via proposed performance ratio to prevent over-processing and over production at the same time fulfilling customer demand.

4.2.3 Proposed Delivery Performance of Overall Performance Effectiveness (OPE)

Despite of constant cycle time of all workstations in the case company, experiment 1 shows that the wait time spent by each set of product is affected by the internal transportation process within production system. Besides, Experiment 2 shows that variation of cycle time in autoclave workstation could also contribute to change in wait time of product in other workstations without any change in their cycle time. Results of Experiment 1 and Experiment 2 imply that sometimes the performance of any particular workstation in the company could be due to the performance of the transportation process or supplier process it connects to.

Besides, performance metric from the perspective of product, such as the total lead time it spends before reaching to the customer site, is not quantified by the case company. This is important because most of customers request for on time delivery in addition to quality product. Even though the performance ratio of OEE is capable of monitoring the rapidness of the workstation with respect to its historical ideal or fastest duration, however, the cycle time refers to the duration of main operation and setup which start in each workstation. The wait time wasted, which is from the moment a product reaches to the workstation and before it is being processed, is not quantified by the implemented OEE.

Consequences of that, there is a necessity to introduce a measure to quantify the performance of product in each workstation from the perspective of wait time per set. The wait time spent by each product in the workstation is not only due to the performance of that particular workstation itself. From Experiment 1 and 2, it is also the result of impact from connected processes, be it transportation process or other workstations. The proposed measure named delivery performance, D_P in term of wait time per entity and lead time is as shown in Formula 4.11 below:

$$\text{Delivery performance}, D_P = \frac{(\text{Lead time per set} - \text{Wait time per set})}{\text{Lead time per set}} \qquad (4.11)$$

Formula 4.11 helps to measure the effect of synchronization between workstations. It is similar with the point of view from Fawcett and Closs (1993) as well as Noble (1997) which stated that the delivery performance of a logistics system can be measured in term of on-time delivery, delivery lead-time and delivery reliability and the wait time and queues would affect the process (Chiarini, 2013). The proposed higher delivery performance could be achieved by reducing the inventory, queue length and wait time of each workstation. According to Cuatrecasas-Arbós et al (2015), shortened manufacturing lead time will increase productivity and improve customer response time. The delivery performance of the case company is computed as shown in Table 4.10 below:

Table 4.10: Delivery performance of each workstation

Workstation	**Lead Time/ Set (Hour)**	**Wait Time/ Set (Hour)**	**Delivery Performance, D_p (%)**
Layup	28.96	12.97	55.21
Autoclave	21.76	4.89	77.53
Demold	1.00	0.01	99.00
CNC	30.13	10.45	65.32
NDT	167.47	143.44	14.35

Table 4.8 and Experiment 3 show that issue of synchronization exists between workstations because the production pace of workstations differ from each other throughout the production. From the site observation, the incoming materials have to wait for the readiness or availability of next workstation because its equipment or man power is currently processing other batch of WIP. The mismatch of the scheduling time happens in any workstation even though their equipment utilization is low.

Delivery performance is not the wait time elapsed by equipment or the so-called idle time of machine but the wait time of each set of WIP spends. It indicates that more inventories than needed at certain point (Rawabdeh, 2005). Therefore, measures of the wait time of materials is necessary in the proposed delivery performance to establish balance between idle capacity with over-processing and overproduction. From Table 4.10, the NDT workstation posts the least promising delivery performance of 14.35. In other words, there is more than 85% of total duration has been spent by each product which is entering NDT for waiting. Delivery performance of Experiment 2 is as shown in following Table 4.11:

Table 4.11: Delivery performance of each workstation in Experiment 2

Workstation	**Double Cycle Time of Autoclave**			**Half Cycle Time of Autoclave**		
	Lead Time/ Set (Hour)	**Wait Time/ Set (Hour)**	**Delivery Performance, D_p (%)**	**Lead Time/ Set (Hour)**	**Wait Time/ Set (Hour)**	**Delivery Performance, D_p (%)**
Layup	29.68	13.69	53.87	28.85	12.86	55.42
Autoclave	134.83	100.67	25.34	8.48	0.00	100.00
Demold	0.99	0	100.00	1.00	0.00	100.00
CNC	19.67	0	100.00	32.73	13.05	60.13
NDT	108.07	84.3	22.09	170.75	146.74	14.06

The result in Table 4.10 and Table 4.11 have proven that the proposed deliver performance could easily track out the blocking phenomena which result from the absence of synchronization between processes in the company. The delivery performance of almost all workstation posts improvement when the cycle time is reduced from double CT, Actual CT until the half CT scenario respectively. Note should be taken that the demold workstation which experiences starving phenomena in all scenarios post high value of delivery performance since there is no wait time before the workstation. This, on the other hand, has highlighted excessive capacity in demold workstation.

Table 4.10 and Table 4.11 shows that the workstation with blocking phenomena posts low delivery performance. The quantification of delivery performance is necessary in the case company to monitor the performance from the perspective of product and to promote the joint responsibility of workstation in ensuring timely delivery. Time-based performance is important and should be used to evaluate the customer delivery performance (Dröge et al., 2004; Iyer et al., 2004) especially when time effectiveness and delivery performance are equally crucial in addition to inventory and resources for Lean assessment (Pakdil and Leonard, 2014). In short, the computed delivery performance in Table 4.10 helps to improve the issue of lack of synchronization of capacity and the case company should aim to establish constant delivery performance throughout the production system.

4.2.4 Comparison of implemented Overall Equipment Effectiveness (OEE) with Proposed Overall Performance Effectiveness (OPE)

As mentioned in previous section, the case company experienced lengthy wait time spent by each set of output and high level of work in progress with respect to customer demand. Even though OEE is implemented to measure each of the individual workstation, however, the case company could not tell from which area and aspect should be improved. Given the same minor stoppage, the availability ratio of OEE in the case company is the portion of accumulated VA time, which inclusive of setup and loading time, or the so-called equipment utilization over the total calendar time as defined and computed as below:

$$\text{Availability Ratio} = \frac{\text{Accumulated Value Adding Time} - \text{Minor stoppage}}{\text{Total Duration in Calendar Approach}}$$

(4.12)

Table 4.12: Availability ratio of workstation in Experiment 2 under OEE implemented

Workstation	**Accumulated VA time (Hour)**			**Availability given no minor stoppage (%)**		
	Double AC cycle time	**Actual AC cycle time**	**Half AC cycle time**	**Double AC cycle time**	**Actual AC cycle time**	**Half AC cycle time**
Layup	991.64	934.01	955.63	68.86	64.86	66.36
Autoclave	1344.36	952.66	499.89	70.02	49.62	26.04
Demold	39.02	56.00	58.35	4.52	6.48	6.75
CNC	746.80	1046.14	1084.51	51.86	72.65	75.31
NDT	632.58	647.12	654.04	65.89	67.41	68.13

As mentioned in previously, change in the cycle time of autoclave (AC) leads to different extent of starving phenomena in its customer workstations such as demold and CNC. However, it is invisible in the computed availability ratio as shown in Table 4.12. In other words, the case company could not tell if the reduction of availability ratio in demold and CNC is due to their own utilization or because of the blocking phenomena at autoclave workstation. The proposed overall performance effectiveness is, on the other hand, able to track out the blocking phenomena via delivery performance and also productivity ratio. Besides, the performance ratio in OEE implemented by case company is defined and computed as below:

$$\text{Performance Ratio} = \frac{(\text{No.of output x Ideal Cycle Time})}{\text{Accumulated VA Time}} \quad (4.13)$$

Table 4.13: Performance ratio of workstation in Experiment 2 under OEE implemented

Workstation	Output (Set)			Performance ratio (%)		
	Double AC cycle time	Actual AC cycle time	Half AC cycle time	Double AC cycle time	Actual AC cycle time	Half AC cycle time
Layup	62.03	58.40	59.78	87.57	87.54	87.58
Autoclave	39.43	56.48	58.98	52.79	53.36	53.09
Demold	39.28	56.15	58.73	50.33	50.13	50.33
CNC	37.98	53.18	55.13	91.54	91.50	91.50
NDT	26.53	26.95	27.25	67.10	66.63	66.66

In contrast to the little fluctuation of availability ratio in demold and CNC workstation, the performance ratio of the case company is relatively flat regardless of the change in cycle time of autoclave in different scenarios of Experiment 2. This is because the cycle time is constant all the time for an established and stable production system. Therefore, the ratio of net operating time with respect to the accumulated VA time of each workstation is almost the same among three scenarios. On the other hand, even though autoclave has different cycle time, varying number of output and also the accumulated value added time in three scenarios, however, it also comes along with different ideal cycle time. This contributes to the same performance ratio of autoclave in the case company.

Quality ratio is not quantified in the study because it is all about the quality defects and the case company has no issue in measuring that. Definition of quality ratio is same in both of the implemented OEE and proposed OPE. Under the assumption of same quality ratio in both measures, the comparison between Overall Equipment Effectiveness (OEE) and Overall Performance Effectiveness (OPE) which are defined in Formula 4.14 and Formula 4.15 is summarized in Table 4.14:

Overall Performance Effectiveness (OPE) = Availability Ratio x Performance Ratio (4.14)

Overall Performance Effectiveness (OPE) = Availability Ratio x Performance Ratio x Delivery performance (4.15)

Table 4.14: Comparison on OEE and OPE of workstations in Experiment 2

Workstation	**Overall Performance Effectiveness, OPE (%)**			**Overall Equipment Effectiveness, OEE (%)**		
	Double AC cycle time	**Actual AC cycle time**	**Half AC cycle time**	**Double AC cycle time**	**Actual AC cycle time**	**Half AC cycle time**
Layup	21.28	24.40	23.26	60.31	56.78	58.12
Autoclave	8.72	19.82	23.92	36.97	26.48	13.82
Demold	45.38	49.38	45.64	2.27	3.25	3.40
CNC	56.52	18.46	15.67	47.48	66.48	68.91
NDT	12.83	6.25	6.13	44.22	44.92	45.42

There are few things could be interpreted from the results in Table 4.14. Firstly, regardless of the blocking phenomena in the double AC cycle time scenario, autoclave workstation posts relatively high level of OEE with respect to other workstations. Second, the blocking phenomena and wait time per output in the autoclave workstation have been improved and reduced in the actual and half autoclave cycle time scenario. However, this has not led to any improvement in the OEE value. Third, the OEE of NDT workstation are almost the same in three scenarios regardless of long wait time in half AC scenario. In contrast to that, OPE of NDT shows reduction when the cycle time of autoclave reduces and this necessitates the reduction of WIP and production rate since the beginning of the production system. Last but not least, lower OPE values in layup workstation represent the overproduction issues whereas lower OPE values in NDT workstation are due to lengthy wait time of output. On the other hand, OEE values could not quantify the aforementioned overproduction and long wait time. The interaction of workstations and how they affect each other could be drawn in bigger picture by putting the interpretation of OPE altogether.

In this section, Overall Performance Effectiveness (OPE) has been proven to promote the fulfilment of customer demand from the perspective of quantity and time unit. It equally quantifies the issue of overproduction and shortage of production with respect to customer demand, at the same time reducing the wait time spent by each product and ensuring timely delivery. This is important for the collaboration of functional departments, suppliers and customers are included in supply chain integration to link and coordinate information flow and processes to enable on-time delivery (Sakun and Chee, 2011). All of these are not emphasized by the OEE implemented in case company.

CHAPTER 5

CONCLUSION AND RECOMMENDATION FOR FUTURE STUDY

5.1 Conclusion

As a conclusion, all objectives are achieved. First of all, the impact of transporting activities within the production system has been proven to have impact on the effectiveness of workstations it connects with. Novelty in the study is that the rapid turnover of materials and priority of transportation have been quantified based on the demand at the destination workstation so that the lead time and wait time of product could be reduced. Besides, the frequency of transportation process has been monitored through the introduction of the performance ratio in transportation measure to reduce excessive capacity.

Moreover, this study focuses on the relationship between workstations and transporting activities. Delivery performance, the comparison of production amount to demand and Takt time in the proposed OPE ensure that the entire production system to work under the same pace to achieve the mutual target at better effectiveness and lower waste. Besides, capacity between workstation could be synchronized under the consideration of the historical equipment utilization in the Takt time computation. Variation of delivery performance which results from the unbalanced capacity between workstation is another useful measure to track out the issue of the case company.

Last but not least, the study promotes and encourages production with lean way. Shorter lead time and wait time are achieved via delivery performance and quantification of transportation activities. Besides, the production rate is always related to the customer demand to reduce the queue length and WIP level. Indirectly, this reduces the wait time and also equipment utilization in contrast to the OEE which promotes high equipment utilization.

Novelty in this study is the incorporation of historical utilization at each workstation as the reference. This prevents the over processing and excessive equipment utilization during the fulfillment of customer demand. In addition to that, hidden wastes in the OEE implementation has been revealed under varying manufacturing environment of the company such as efficiency of transporting activities and cycle time of certain workstation. Another significance in the study is that effectiveness from the perspective of equipment and material could be considered at the same time without compromising any one of them.

In short, relations between performance measures like equipment utilization and customer demand has been analyzed and tradeoff between them with inventory level is resolved via the introduction of Overall Performance Effectiveness. Besides, delivery performance of materials is taken care along with the effectiveness from the perspective of equipment. Synchronization of TPE for main processes with the TM for transportation processes has been demonstrated in the study for a better production system. They are proven to be useful as a new guidance and measure in improving the production system from both tactical production planning and strategical capacity planning.

5.2 Recommendation for future study

In order to promote minimal utilization of equipment, it is recommended to list down the duration per each production slot with its corresponding maximum production rate could be produced within the frequently planned duration. Note should be taken that the duration recorded should be adequate enough to avoid time pressure at the same time should be short enough to discourage slower than usual production speed. The duration along with the maximum allowable production rate serves as the reference for computation of Takt time and production planning in the future.

Moreover, implementation of aggregate production planning is suggested to compute and define the cycle time per each set of products from a diverse portfolio of products. Total operating time which is exclusive of any downtime could be obtained from previous production period. They are listed down and divided by the total amount of production to yield the average cycle time for the production rate. The average cycle time in aggregate unit has to be updated from time to time to ensure the production rate scheduled is on par with respect to the best record of time. However, the product mix has to be considered in the list of reference to cater the capability requirement of various product types.

In addition to the maximum production rate with respect to certain production period, the maximum limit of the equipment utilization or capacity at each process has to be considered. This serves as the maximum production hour could be offered by each equipment in each workstation and has to be respected to make sure that excessive customer demand is not accepted by company. It is important to be a guidance of capacity available in each workstation. The list of maximum production hours, again, has to be updated from time to time in order to take into account of capability and capacity constraint which should not be surpassed beyond during production planning.

In order to promote the synchronization of records, the list of maximum production hour could be offered by each equipment and the maximum production rate for certain product type have to be compared to determine the topline of company's production. The comparison could be performed via matrix to sort them by process and product type so that any fluctuation of demand on certain product type or improvement on process parameter could be responded immediately.

As the suggestion to further improve the versatility of simulation model, varying product mixes with different process route could be simulated in order to study the impact of transportation efficiency from complicated route onto the throughput rate of production system and lead time of all product types. In addition, quality issue for different product types could also be incorporated in each of the workstations. Beside, some of the setup time are sequential dependence or affected by the lot size. These are the variables or parameters could be incorporated in the simulation model to ensure its adaptability in wider range of manufacturing environment.

Last but not least, it is recommended to perform detailed study in the future to cater the fluctuation of demand from the external environment. Sensitivity analysis is proposed to so that the effectiveness of the entire production system with respect to the change of demand, unavailability of raw materials or any breakdown of upstream workstation without adequate level of buffer could be analyzed and that production planning could be well prepared for better responsiveness. The impact is suggested to be examined in term of inventory, throughput at each process as well as the delivery performance per each process.

REFERENCES

Adanna, I. W., & Shantharam, A., 2014. Improvement of setup time and production output with the use of single minute exchange of die principles (SMED). *Int. J. Eng. Res*, *2*, pp. 274-277.

Afefy, I. H., 2013. Implementation of total productive maintenance and overall equipment effectiveness evaluation. *International Journal of Mechanical & Mechatronics Engineering*, 13(01), pp. 69-75

Ak, A., & Erera, A. L., 2007. A paired-vehicle recourse strategy for the vehicle-routing problem with stochastic demands. Transportation Science, 41(2), pp. 222-237

Ali, R., & Deif, A., 2016. Assessing leanness level with demand dynamics in a multi-stage production system. *Journal of Manufacturing Technology Management*, 27(5), pp. 614-639.

Al-Turki, U., & Duffuaa, S., 2003. Performance measures for academic departments. *International Journal of Educational Management*, 17(7), pp. 330-338.

Anvari, F., Edwards, R., & Starr, A., 2010. Evaluation of overall equipment effectiveness based on market. *Journal of Quality in Maintenance Engineering*, 16(3), pp. 256-270

Arafa, A., & ElMaraghy, W. H., 2011. Manufacturing strategy and enterprise dynamic capability. *CIRP Annals-Manufacturing Technology*, 60(1), pp. 507-510.

Badiger, A. S., & Gandhinathan, R., 2008. A proposal: evaluation of OEE and impact of six big losses on equipment earning capacity. *International Journal of Process Management and Benchmarking*, 2(3), pp. 234-248.

Bamber, C. J., Castka, P., Sharp, J. M., & Motara, Y., 2003. Cross-functional team working for overall equipment effectiveness (OEE). *Journal of Quality in Maintenance Engineering*, *9*(3), pp. 223-238.

Baykasoğlu, A., & Özbakır, L. (2008). Analysing the effect of flexibility on manufacturing systems performance. *Journal of Manufacturing Technology Management*, *19*(2), 172-193

Benjamin, S. J., Marathamuthu, M. S., & Murugaiah, U., 2015. The use of 5-WHYs technique to eliminate OEE's speed loss in a manufacturing firm. *Journal of Quality in Maintenance Engineering*, *21*(4), pp. 419-435

Benttaleb, M., Hnaien, F., & Yalaoui, F., 2016. Two-machine job shop problem for makespan minimization under availability constraint. *IFAC-PapersOnLine*, *49*(28), 132-137

Bruggen, A., 2015. An empirical investigation of the relationship between workload and performance. *Management Decision*, *53*(10), 2377-2389

Cesarotti, V., Giuiusa, A., & Introna, V., 2013. *Using Overall Equipment Effectiveness for Manufacturing System Design*. INTECH Open Access Publisher

Chahal, V., & Narwal, M., 2017. An empirical review of lean manufacturing and their strategies. *Management Science Letters*, *7*(7), 321-336

Chen, Z., & Sarker, B. R., 2015. Aggregate production planning with learning effect and - uncertain demand: A case based study. *Journal of Modelling in Management*, *10*(3), pp. 296-324

Chiarini, A. 2013. Waste savings in patient transportation inside large hospitals using lean thinking tools and logistic solutions. *Leadership in Health Services*, *26*(4), 356-367

Chong, K. E., Ng, K. C., & Goh, G. G. G., 2015, December. Improving Overall Equipment Effectiveness (OEE) through integration of Maintenance Failure Mode and Effect Analysis (maintenance-FMEA) in a semiconductor manufacturer: A case study. In *Industrial Engineering and Engineering Management (IEEM), 2015 IEEE International Conference on*, pp. 1427-1431. IEEE.

Colares, E. M. T. How to solve the trade-off between capacity utilization and service level

Cuatrecasas-Arbós, L., Fortuny-Santos, J., Ruiz-de-Arbulo-López, P., & Vintró-Sanchez, C., 2015. Monitoring processes through inventory and manufacturing lead time. *Industrial Management & Data Systems*, *115*(5), 951-970.

Dal, B., Tugwell, P., & Greatbanks, R., 2000. Overall equipment effectiveness as a measure of operational improvement-A practical analysis.*International Journal of Operations & Production Management*, *20*(12), pp. 1488-1502.

De Carlo, F., Arleo, M. A., & Tucci, M., 2014. OEE Evaluation of a Paced Assembly Line Through Different Calculation and Simulation Methods: A Case Study in the Pharmaceutical Environment. *International Journal of Engineering Business Management*, *6*.

Dhand, S., & Singla, A., 2016. Sensitivity Analysis and Optimal Production Scheduling as a Dual Phase Simplex Model. *Indian Journal of Science and Technology*, *9*(39)

Dröge, C., Jayaram, J., & Vickery, S. K., 2004. The effects of internal versus external integration practices on time-based performance and overall firm performance. *Journal of operations management*, *22*(6), pp. 557-573

Eswaramurthi, K. G., & Mohanram, P. V., 2013. Improvement of manufacturing performance measurement system and evaluation of overall resource effectiveness. *American Journal of Applied Sciences*, *10*(2), p. 131.

Fawcett, S. E., Calantone, R., & Smith, S. R., 1997. Delivery capability and firm performance in international operations. *International Journal of Production Economics*, *51*(3), pp. 191-204

Fawcett, S. E., & Closs, D. J., 1993. Coordinated global manufacturing, the logistics/manufacturing interaction, and firm performance. *Journal of Business Logistics*, *14*(1), 1

Fleischer, J., Weismann, U., & Niggeschmidt, S., 2006. Calculation and optimisation model for costs and effects of availability relevant service elements. *Proceedings of LCE*, pp. 675-680.

Flynn, B. B., Huo, B., & Zhao, X., 2010. The impact of supply chain integration on performance: A contingency and configuration approach. *Journal of operations management*, *28*(1), pp. 58-71

Gan, S. Y., & Chong, K. E., 2014. Improving throughput and completion date estimation in high precision component manufacturer using simulation approach. *Journal of Advanced Manufacturing Technology (JAMT)*, *7*(1)

Gansterer, M., Almeder, C., and Hartl, R. F., 2014. Simulation-based optimization methods for setting production planning parameters. *International Journal of Production Economics*, 151, pp. 206-213

Graves, S. C., 1981. A review of production scheduling. *Operations research*, *29*(4), pp. 646-675

Gyulai, D., & Monostori, L., 2017. Capacity management of modular assembly systems. *Journal of Manufacturing Systems*, *43*, pp. 88-99

Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B., & Stahre, J., 2008, December. Simulation-based sustainable manufacturing system design. In *2008 Winter Simulation Conference,* pp. 1922-1930. IEEE.

Helo, P. T., 2000. Dynamic modelling of surge effect and capacity limitation in supply chains. *International Journal of Production Research*, *38*(17), pp. 4521-4533

Hill, A. V., 2012. *The encyclopedia of operations management: a field manual and glossary of operations management terms and concepts*. FT Press

Huang, R. H., Yang, C. L., & Cheng, W. C., 2013. Flexible job shop scheduling with due window- a two-pheromone ant colony approach. *International Journal of Production Economics*, *141*(2), 685-697

Huang, S. H., Dismukes, J. P., Shi, J., Su, Q. I., Razzak, M. A., Bodhale, R., & Robinson, D. E., 2003. Manufacturing productivity improvement using effectiveness metrics and simulation analysis. *International Journal of Production Research*, *41*(3), pp. 513-527

Iyer, K. N., Germain, R., & Frankwick, G. L., 2004. Supply chain B2B e-commerce and time-based delivery performance. *International Journal of Physical Distribution & Logistics Management*, *34*(8), pp. 645-661

Jackson, J. R., 1956. An extension of Johnson's results on job IDT scheduling. *Naval Research Logistics (NRL)*, *3*(3), 201-203

Kennerley, M., & Neely, A., 2003. Measuring performance in a changing business environment. *International Journal of Operations & Production Management*, *23*(2), pp. 213-229.

Lee, J., Lapira, E., Bagheri, B., & Kao, H. A., 2013. Recent advances and trends in predictive manufacturing systems in big data environment *Manufacturing Letters, 1*(1), pp. 38-41

Morash, E. A., & Clinton, S. R., 1998. Supply chain integration: customer value through collaborative closeness versus operational excellence. *Journal of Marketing Theory and Practice*, *6*(4), pp. 104-120.

Mugwindiri, K., Nyemba, W. R., Madanhire, I., & Mushonga, R., 2013. The Design of a Production Planning and Control System for a Food Manufacturing Company in a Developing Country , using Simulation ., 2(6), pp. 116–125

Nakajima, S., 1988. Introduction to TPM: Total Productive Maintenance.(Translation). *Productivity Press, Inc., 1988,*, p. 129.

Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., Müller, E., & Vonderstrass, T. 2002. From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE). *Materials Science in Semiconductor Processing,5*(4), 333-339

Pakdil, F., & Leonard, K. M., 2014. Criteria for a lean organisation: development of a lean assessment tool. *International Journal of Production Research*, *52*(15), pp. 4587-4607.

Ponsignon, T., & Mönch, L., 2014. Simulation-based performance assessment of master planning approaches in semiconductor manufacturing.*Omega*, *46*, pp. 21-35.

Ramlan, R., Ngadiman, Y., Omar, S. S., & Yassin, A. M., 2015, August. Quantification of machine performance through Overall Equipment Effectiveness. In *Technology Management and Emerging Technologies (ISTMET), 2015 International Symposium on* (pp. 407-411). IEEE.

Rawabdeh, I. A., 2005. A model for the assessment of waste in job shop environments. *International Journal of Operations & Production Management*, *25*(8), 800-822.

Razzak, M. A., Daley, G., & Dismukes, J. P., 2002. Factory Level Metrics: Basis for Productivity Improvement. In *Proceedings of the International Conference on Modeling and Analysis of Semiconductor Manufacturing (MASM2002),* pp. 158-162

Roser, C., Lorentzen, K., & Deuse, J., 2014. Reliable shop floor bottleneck detection for flow lines through process and inventory observations. *Procedia CIRP*, *19*, 63-68

Rosenzweig, E. D., Roth, A. V., & Dean, J. W., 2003. The influence of an integration strategy on competitive capabilities and business performance: an exploratory study of consumer products manufacturers. *Journal of operations management*, *21*(4), pp. 437-456

Puvanasvaran Perumal, Teruaki Ito, Teoh Yong Siang, and Yoong Sai Sieng, 2016, Examination of Overall Equipment Effectiveness (OEE) in term of Maynard's Operation Sequence Technique (MOST). *American Journal of Applied Science (AJAS)*, 13(11), pp.1214-1220

Sakun Boon-itt & Chee Yew Wong, 2011. The moderating effects of technological and demand uncertainties on the relationship between supply chain integration and customer delivery performance. *International Journal of Physical Distribution & Logistics Management*, *41*(3), pp. 253-276

Salegna, G. J., & Park, P. S., 1996. Workload smoothing in a bottleneck job shop. *International Journal of Operations & Production Management*, *16*(1), 91-110

Samad, M. A., Hossain, M. R., & Major, S., 2012. Analysis of Performance by Overall Equipment Effectiveness of the CNC Cutting Section of a Shipyard, *2*(11), pp. 1091–1096

Simons, D., Mason, R., & Gardner, B., 2004. Overall vehicle effectiveness. *International Journal of Logistics Research and Applications*, 7(2), pp. 119-135

Sternberg, H., Stefansson, G., Westernberg, E., Boije af Gennäs, R., Allenström, E., & Linger Nauska, M., 2012. Applying a lean approach to identify waste in motor carrier operations. *International Journal of Productivity and Performance Management*, 62(1), pp. 47-65

Teoh, Y. S., Ito, T., & Perumal, P. 2017a. Invisibility of impact from customer demand and relations between processes in Overall Equipment Effectiveness (OEE). *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, *11*(5), JAMDSM0065-JAMDSM0065.

Teoh Yong Siang, Teruaki Ito, and Puvanasvaran Perumal, 2017b, *Visibility of customer demand and its impact in Overall Equipment Effectiveness (OEE)*, In the proceedings of International Design and Concurrent Engineering Conference, September 2017, No. 41

Thürer, M., Stevenson, M., Silva, C., & Qu, T., 2017. Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation. *International Journal of Production Economics*, *188*, 116-127.

Váncza, J., Monostori, L., Lutters, D., Kumara, S. R., Tseng, M., Valckenaers, P., & Van Brussel, H., 2011. Cooperative and responsive manufacturing enterprises. *CIRP Annals-Manufacturing Technology*, *60*(2), pp. 797-820

Villarreal, B., Garza-Reyes, J. A., & Kumar, V., 2016. A lean thinking and simulation-based approach for the improvement of routing operations.*Industrial Management & Data Systems*, *116*(5), pp. 903-925

Villarreal, B., 2012. The transportation value stream map (TVSM). European Journal of Industrial Engineering, 6(2), pp. 216-233.

Villarreal, B., Sañudo, M., Vega, A., Macias, S., & Garza, E., 2012. A Lean Scheme for Improving Vehicle Routing Operations. In Proceedings of the 2012 International Conference on Industrial and Operations Management (IEOM), pp. 3-6.

Wong, W. P., Soh, K. L., Chong, C. L., & Karia, N., 2015. Logistics firms performance: efficiency and effectiveness perspectives. *International Journal of Productivity and Performance Management*, *64*(5), pp. 686-701

Yuan, R., & Graves, S. C., 2016. Setting optimal production lot sizes and planned lead times in a job shop. *International Journal of Production Research*, *54*(20), pp. 6105-6120

Zammori, F., Braglia, M., & Frosolini, M., 2011. Stochastic overall equipment effectiveness. *International Journal of Production Research*,*49*(21), pp. 6469-6490.

Zammori, F., 2015. Fuzzy Overall Equipment Effectiveness (FOEE): capturing performance fluctuations through LR Fuzzy numbers. *Production Planning & Control*, *26*(6), pp. 451-466.

Zeller, M., 2014, May. Convert operational data into maintenance savings. In *Rural Electric Power Conference (REPC), 2014 IEEE* (pp. B6-1). IEEE.

Zhou, J., Zhao, S., Li, P., Zhou, H., Zhang, Q., & Shang, Z., 2009, February. Research on processes simulation and reconfiguration for piston production lines. In *Computer Modeling and Simulation, 2009. ICCMS'09. International Conference on* (pp. 49-52). IEEE.