Engineering Journal issn: 0125-8281

Article

A Hierarchical Analytic Process Framework for Manufacturing System Improvement

Jongkon Sukjamnong[1,2], Paveena Chaovalitwongse[1,2], Siravit Swangnop[2,3,*], and Poom Luangjarmekorn[1,2]

1 Department of Industrial Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
2 Integrated Management System and Smart Technology Research Group, Chulalongkorn University, Bangkok, Thailand
3 Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand
E-mail: *siravit.s@eng.kmutnb.ac.th (Corresponding author)

Abstract. This paper proposes a hierarchical analytic process framework to facilitate practitioners to determine improvement directions for a manufacturing system efficiently and systematically. The proposed framework analyzes current state performances of a manufacturing system by applying the knowledge of science of manufacturing systems which describe relationship control factors, performance measures, and improvement objectives. Then, concrete directions for improvements are suggested. The analysis process embeds the concept of diagnostic tree which makes it an easy-to-handle framework. Under the diagnostic tree concept, it decomposes the high-level business goal into successively low-level activities to give more comprehensive areas of improvement. The proposed framework comprises of three key elements: Operation Performance Measures (OPMs), Diagnostic tree (D-Tree), and Action guidelines. The OPMs are used in the D-Tree to determine improvement objectives. Then the Action guidelines suggest how to adjust control factors in a manufacturing system according to each improvement objective. The proposed diagnostic framework is demonstrated by Promodel simulation of a case study. The simulation model includes physical resources, flow lines, WIP, and replenishment signals of the case. By following the analytic process in the framework, the performance measures have shown improvements according to action guidelines and the result of improvements meets the requirement of a factory in the case study.

Keywords: Manufacturing system analysis, operational performance measures, diagnostic tree, factory physics.

ENGINEERING JOURNAL Volume 27 Issue 9
Received 28 February 2023
Accepted 19 September 2023
Published 30 September 2023
Online at https://engj.org/
DOI:10.4186/ej.2023.27.9.55

DOI:10.4186/ej.2023.27.9.55

1. Introduction

Manufacturing system is defined as the process of arrangement and operation of resources to produce products [1]. 'Arrangement' is to prepare sufficient resources for production and 'Operation' is to manage resources to produce product efficiently.

Manufacturing sectors have faced several challenges to keep up with customer demands and expectations. The continual improvements of the manufacturing systems are necessary for a manufacturing company to be agile and competitive at a high level of responsiveness.

To improve manufacturing systems, direction for improvement is very important. There are many choices for improvement but because of limited resources and budget, all choices cannot be made at the same time. In addition, while improving, a production line is usually interrupted, and the production capacity is reduced so trial and error is not a good method. Another issue is the consequence of the improvement, which may be worse if choosing a wrong direction or may be raised a new problem instead.

Selecting the suitable direction for improvement is not easy because in real-world problem manufacturing system is usually complex and the complexity of the manufacturing system leads to be hard for analyzing and choosing what to be improved to meet the target. For example, mostly in the manufacturing process, there is more than one route for production. Each station has more than one machine with different efficiency. One production line usually produces more than one product, and some machines are dedicated for a specific group of products, and some are shared. Loads of each station are different according to demands. Production of each product is managed with difference setting such as different production lot sizes, different lot transfer, different priority, or different stock policy. When focusing on production activities, some factories can control loss time such as setup time or breakdown, but some cannot do so although they have the same products, machines, routes of product and rules of production, the result may be different. Assume the factory confronts the problem that they cannot satisfy demand on time. The cause of the problem may be the wrong setting of production policy, too many products being shared in some machines, being blocked by stations before or after the bottleneck station or insufficient machine at bottleneck station. There are many causes, and each cause has many choices for improvement. What is the right cause and what is the suitable choice. More importantly, when the manufacturing system is large and complex, an adjustment in some elements in manufacturing system may affect others and to meet the target, an improvement may be a continuous process more than one-time adjustment.

In practice, many manufacturers use their experiences to select the choice and analyze the problem, so the quality of the solution depends on the individual. In academic aspect, there is rarely an easy-to-use tool to navigate them to get a good direction of manufacturing improvement. Some tools are too broad and provide only the concept not methodology [1-4]. Some tools are too specific with problems and too hard for factory to understand and implement [5-7].

The objective of this research is to develop a hierarchical analytic process framework for manufacturers to analyze and improve their manufacturing system to meet requirements. The proposed framework comprises: Operation Performance Measures (OPMs), Diagnostic tree (D-Tree), and Action guidelines. OPMs and D-Tree are used to identify precise improvement objectives and then Action guidelines suggest how to improve manufacturing system.

This paper is organized as follows. Section 2 gives a review of relevant literature on manufacturing system analysis and methods. Section 3 describes the detail of the proposed problem. Section 4 presents the proposed diagnostic tree and guidelines for improvement in terms of reconfiguration of control factors respectively. Section 5 shows a case study analysis, and finally, the conclusion is presented in Section 6.

2. Literature Review

Various analysis processes that are related to improving production capability in manufacturing systems have been developed in different aspects, different methodologies, and different forms of results. We categorize strategies into two different levels including process level and system level. Improvement in process level deeply interprets process characteristics and provides improvement guidelines in terms of work-process improvement. For example, Zonga and Kongkaew [7] developed neighborhood search algorithm for improving the quality of the production plan in the precast production problem. A goal is to minimize makespan and total earliness and tardiness penalties. The proposed algorithm provides production schedules to facilitate managers in decision making on precast concrete production. Another example, convolutional approach that used to analyze laser manufacturing process for quality monitoring [8]. We found that the strategies provide clear guidelines. However, it is specific and needs a lot of detailed information about the case. It hardly performs with other types of industry.

On the other hand, strategies in system level view operations in the broad sense rather than as a specific function and avoids the need for detailed descriptions of the products or processes. Most of previous analysis processes in this level using simulation technique and science of manufacturing system. For example, Burduk et al. [6] proposed a simulation model to improve production effectiveness. They analyze production processes and evaluate alternative scenarios by dispensing with managerial decisions to increase utilization rate of operators and machines and decrease production cycle time. Supsomboon [5] applied simulation technique to reduce bottlenecks and increase productivity. Manufacturing systems were decomposed into crucial

DOI:10.4186/ej.2023.27.9.55

components for constructing simulation models and analyzing from those components based on science of manufacturing system to get better performance. It is found that analysis process at this level is easy to adapt with other industries if we can decompose manufacturing system into those components. Thus, improvement strategies in system view are more appropriate with improving general manufacturing system as well as components reconfiguration is interesting to use as form of results. However, simulation model is a tool for investigating the system behavior and recording performance measures. Applicability is greater when it is used to solve specific problems in tangible sectors. It still needs other methodologies to analyze or technicians to evaluate performance measures. To obtain effective improvement strategies, it requires understanding the relationship of components reconfiguration and effect to performance in a holistic view.

Improvement methods for suggesting components reconfiguration generally analyze in specific problems. For example, M. Filho et al.'s literatures who present improvement methods by using continuous improvement, system dynamics, and factory physics. They present effect of improvement as performance measures from simulation model by adjusting parameters or activities in manufacturing system, e.g., the relationship between lot sizes, cycle times, and shop floor parameter [10] and effect of lot sizes reduction to improving on WIP and utilization [11]. To recommend specific problem improvement, it hardly concerns about effects of whole system performances along with deficiency of the method to obtain crucial problems in the system. While some improvement methods are too generic and difficult to use, e.g., probability model, queueing model, petri nets, or algebraic models [12], it would be better to have easy-to-use guidelines.

Among analysis methods that provide clear guidelines to achieve crucial problems such as fault tree analysis, failure mode and effect analysis [13], and diagnostic reference model, the diagnostic reference model is an interesting concept to investigate crucial problems of manufacturing system. However, the diagnostic reference model is much used in medical research. It is rarely used in production research and usually provides just a concept and history of the model [14-15]. Diagnostic tree is another model that uses diagnostic reference model for improving production line [16]. They present that the diagnostic reference model is based on questionnaires. The model is made for investigating the current state of the system. Therefore, it means the method is no limitation of topic and it can be adapted by many different industries. Moreover, it enables a declarative representation of root cause analysis to capture cause and effect relationships that are relevant to current situation, to find the most effective improvement strategies as well as provides clear guidelines. Table 1 shows a summary of current analysis processes. They have limitations between improving the general manufacturing system and providing clear guidelines.

Table 1. Summary of current analysis process.

Types of analysis process	Information	Limitation
Science of manufacturing system (e.g. Queueing model, Probability model, Factory physics)	Describing the relationships between demand, capacity, inventory, response time and variability in quantitative model.	Deficiency of the method to obtain crucial problems in the system.
Simulation technique	A tool for investigating the system behaviours and recording performance measures.	Require technician to investigate the system.
Guideline method (e.g. Diagnostic tree, FTA, FMEA)	Based on questionnaires for investigating the current state of the system.	No standard for improving manufacturing system.

Analysis processes that improve general manufacturing system generally focus to improve in specific problem therefore, it difficult to realize effect of whole system performance. Moreover, it is required for some methods to obtain crucial problems in the system. In contrast, analysis processes that provide clear guidelines are usually presented as a concept and analyze in some specific case study. Therefore, we need to propose a new analysis process to reduce this limitation by analyzing in holistic approach and constructing easy-to-handle process. It must work with the nature of manufacturing system in a systematic view, improve systems performance, and provide improvement guidelines with possible consequences.

3. Problem Description

The objective of this research is to develop a hierarchical analytic process framework for manufacturing system improvement. The aim of the framework is to navigate manufacturers to systematically analyze their manufacturing systems and choose the right direction for improvement. In this section the component of the manufacturing system is described and then the scope of the diagnosis framework is presented.

A manufacturing system can be described by four components: physical resources, flow lines, WIP (entities move), and replenishment signals [17-18]. Figure 1 shows an example of a manufacturing system structured by its common components. Physical resources are machines, tools or operators who work in workstations. Flow lines are routes or paths of the material in a system. WIP is a stock point located before or after resources. Replenishment signals are the rule for triggering the production.

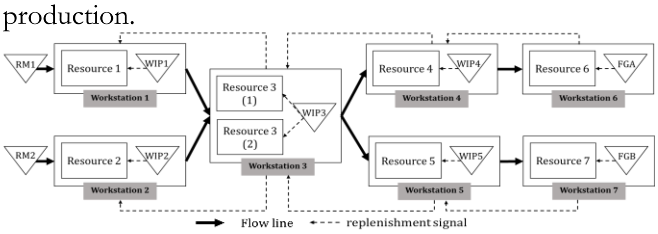

Fig. 1 A. manufacturing systems and its components.

The proposed framework suggests what components in the manufacturing system should be adjusted. However, there are too many aspects for adjustment in each component. To scope the area for adjustment in manufacturing system, the control factor is introduced. The control factor is the element in the component that the proposed framework can adjust. Table 2 shows the scope of control factors considered in this study.

Table 2. Control factors of each component.

System components	Control factors
Physical resources	Number of machines
Flow lines	Dedicated (simple flow line) or shared (complex flow line) resources
Entities (WIP)	Lot sizing
Replenishment signals	Reorder point (ROP)
	Product priority

Physical resources include machines, labor, and tools. The number of resources in the system is directly related to system capacity and investment. Thus, the number of machines is defined as a control factor.

Flow lines are a set of sequential operations established in manufacturing system where work-in-processes are put through a process to produce finished goods. Management of the flow line is very imperative, especially in systems with multi-machine workstations and/or multi-product workstations. Under multi-product manufacturing systems, the flow line can be viewed as resources sharing. Under shared flow line (complex flow line) or shared resource capacity means one resource can produce many products. It gives less investment and efficiency used of resources. However, product changeovers might cause machine downtime leading to poor throughput rate. Thus, dedicated flow line (simple flow line) may be more appropriate in some cases.

The level of *entities* or work-in-processes is controlled by lot size parameter. Large lot sizes may cause delayed demand response because of batching effects. On the other hand, small lot sizes may cause high traffic intensities from setting. Therefore, determining the right amount is important.

Replenishment signals are used to control the operation of manufacturing system when production of which product should start. These signals are represented by reorder point (ROP) and product priority respectively.

The analysis process can be divided into three consecutive phases: (1) Capturing operational performance measures, (2) Determining improvement objective/s, and (3) Suggesting guidelines for control factor reconfigurations. The operational performance measures show the current state of a manufacturing system, which is resulted from the configuration of components and is controlled by the control factors [22]. The operational efficiency and the effectiveness of manufacturing can be monitored through the operational performance measurements [23]. Once the quantitative data of performance measures are captured, there are two questions to be answered: (1) Are there improvements needed? and (2) What areas or directions for improvement should be considered? The first questions can be answered by benchmarking or comparing to the performance expectations. To answer the second question, the diagnostic tree is proposed to determine the direction/s or objective/s for improvements.

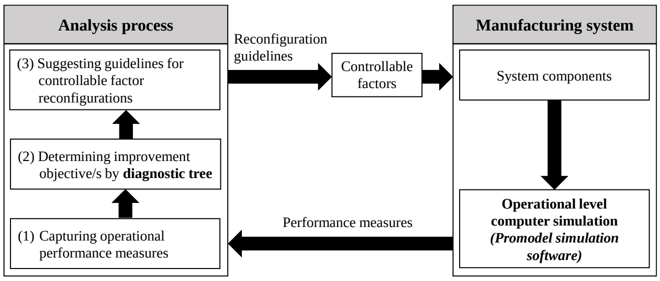

Fig. 2. A manufacturing systems improvement method.

4. Proposed Hierarchical Analytic Process Framework

The proposed framework aims to facilitate practitioners to systematically determine improvement direction for their manufacturing systems. It provides an easy-to-handle framework for practitioners to implement by using hierarchical diagnosis nodes which guide making decisions step-by-step. Moreover, this framework also helps practitioners to see a big picture of their manufacturing systems through suggested system components as well as the performance measures and their relationship with control factors. Finally, the framework also provides practical action guidelines for performance improvement.

To help identifying concrete directions for improvement, this framework comprises of three key elements: Operation Performance Measures (OPMs), Diagnostic tree (D-Tree), and Action guidelines. The OPMs are used to reflect the state of manufacturing system to take appropriate improvement decisions in a manufacturing system [2, 19]. Thus, OPMs are also used for aligning activities in manufacturing system and production capability goals accomplishment. The D-Tree is an analysis tool that decomposes the problem of improving performance of high-level goals into successively low-level activities that gives more clear and comprehensive improvement objectives. Usually, high-level goals concern cost and demand response, while low-level activities concern the operational level including operations of an individual workstation, a production line (a set of workstations), and a system (a set of production lines). Finally, the action guidelines are given to suggest how to adjust control factors to improve OPMs according to improvement objectives retrieved from the D-Tree. The adjustment of control factors can be seen as the ability to rearrange or adjust system components to change system behaviors [20-21]. For example, if the improvement objective is to reduce setup time loss with lot size as a control factor, thus an increase of lot size can reduce setup time between batch changes. Once the lot size is set to an appropriate level, the objective can be attained. Thus, the understanding of system behaviors is essential and crucial to relate control factor settings to attainable levels of performance measures. The details of each element of the framework are as follows.

4.1. Operation Performance Measures (OPMs)

Within the proposed framework, there are different types of analysis needed ranging from systems level to a single workstation or low-level activity analysis. At systems level, manufacturing systems performance and inventory performance are measured to diagnose whole system in generic level. The OPMs for manufacturing systems performance are service level (SL) and maximum throughput (Max TH) because they can represent both business requirements and ability of manufacturing system. The OPMs for inventory performance are amount of stock and inventory turnover rate because it represents manufacturing system management and economic analysis in financial terms [24]. At low-level activities, the state of resource performance is measured for diagnosis of activity level or workstation level. All states of resource performance represent how capacity at a workstation is distributed among activities [2, 25]. Each OPM in this category represents different states of resources including production time, waiting time, setup time, breakdown time, and idle time. The production time is the amount of time when the workstation or machine has been in production. The waiting time is the amount of time when the workstation or machine has a production order but unable to carry out production or having production blocking caused by inventory management. The production at a workstation can be blocked from either starving for WIP to feed into the workstation or having too much inventory at the downstream stock points. The setup time is the amount of time to set up the workstation or machine for production. The breakdown time is the amount of time the workstation or machine breaks down and cannot resume production. Finally, the idle time is the amount of time when there is no production order.

Table 3 summarizes three categories of performance measures: manufacturing system performance, inventory performance, and state of resource performance.

Table 3. Operation performance measures.

Manufacturing system performance	Inventory performance	State of resource performance
1. Service level 2. Maximum throughput	1. Average amount of stock 2. Inventory turnover rate	1. Percentage of production time 2. Percentage of waiting time 3. Percentage of setup time 4. Percentage of breakdown time 5. Percentage of idle time

The description of each OPM is as follows.

- Service Level (SL) represents the production capability to meet customer's product requirements in a timely manner. SL are assigned to measure and display the results separately in each product.

$$SL_i = \frac{Amount\ of\ product\ i\ that\ can\ respond\ within\ the\ time\ required}{Total\ requirements\ of\ product\ i\ within\ the\ time\ required} \times 100\%$$

- Maximum throughput (Max TH) is the amount of product that can be produced within a specified period when the system has the highest utilization.
- Average amount of stock measures the average inventory level within a specified period at the interested workstation.
- Inventory turnover rate represents how long will it take to run out of the stock if the amount of stock is not replenished. When inventory turnover rate is low, it indicates a high stock level compared to average demand.

$$inventory\ turnover\ rate = \frac{Amount\ of\ products\ required\ within\ the\ time\ required}{Average\ amount\ of\ stock}$$

- Each state of performance is calculated based on the total amount of time in that state and divided by the total time spent working and multiplied by 100.

$$\%State = \frac{Total\ \ time\ in\ that\ state}{Total\ time\ spent\ working} \times 100$$

The information regarding OPMs can also be captured from the simulation model with less cost and time because it is easier to operate and record all needed information [5].

4.2. Diagnostic Tree (D-Tree)

The D-tree represents the hierarchy of successive improvement objectives from system analysis based on high-level goal to low-level activity analysis based on its requirements. The D-tree comprises of diagnosis nodes (DN) and improvement objective nodes which is derived according to diagnostic reference model [16] and the concept of basic factory dynamics from Factory physic [17]. The basic factory dynamics gives understanding of the relationship among cycle time, work-in-process, and throughput of a production line or at a workstation which helps to conjecture the system behavior and its leverages when changing some parameters of the manufacturing systems.

For the proposed framework, the analysis is done at diagnosis nodes (DN) while improvement objective nodes are the outputs from DN. In addition, its inputs (e.g., OPMs, business requirement, manufacturing systems component information) can be varied depending on the purpose of the DN. Moreover, the diagnosis process should be done with only one product at a time because each product might have different values of input information. Therefore, in any manufacturing system, the D-tree may give outputs more than one potential improvement objective. These potential improvement objectives are carried out to the next step of improvement for action guideline of the control factors.

At high-level goal, the proposed D-tree focuses on cost reduction and improving demand response. Thus, it aims to improve service level by enhancing production capability to cope with uncertainty at efficient use of resource and investment. Both goals, cost reduction and demand response, are the main purposes in most businesses, so in the developed D-tree they are positioned at the highest level of the tree. In this paper, the scope of cost reduction includes cost of resources (e.g., machines, workstations, equipment, etc.) or fixed cost and inventory cost (holding cost). In the demand response aspect, it begins with improving service level objective. Consequently, this objective leads to subsequent objectives in hierarchy for low-level activities that enhance production capability following basic factory dynamics concept. These low-level activity objectives are more concrete to implement, e.g., increase buffer stocks, reduce set up time loss, increase utilization, etc.

Figure 3 represents the proposed D-tree. At the beginning of D-tree, there are two main branches, cost aspect branch and demand responding aspect branch. The cost aspect branch is fathomed at machine cost and inventory cost reduction, while the demand responding aspect branch extends to include systems analysis and operations analysis at low-level activities or at workstation. The connection DNs represents the analysis to identify potential workstation to improve. Finally, low-level activity analysis concerns productivity and loss at the workstation level.

The proposed D-tree clearly separates different level objectives by the means to achieve objectives. For example, if a high throughput is required in high-level goal, then machines should be working on production most of the time. In some undesirable cases like machine breakdown, preparing backup machine or having buffer stocks can be done to maintain the high-level goal [26].

From this concept, practitioners can follow step-by-step along the path in D-tree to get the right direction for improvement.

DN1. Improve high-level goal

As mentioned before, the high-level goal concerns demand response at reasonable cost. Since a high level of demand response brings in both profits and reliability for customers which is a priority of business. Thus, the key performance measure used at this node is service level (SL). If the acquired service level is less than target service level, it implies that demand is not yet satisfied thus the subordinate objective should focus on **improving service level**. When SL is low, it may result from either not enough capacity or poor management. Thus, the objective to improve SL concerns more in low-level activities. However, if the service level already meets the target, the objective shifts to **manufacturing cost reduction** since there might be excess cost from too much capacity.

DN2. Improve service level (SL)

This DN supports its root node, DN1, by considering the cause of poor service which can be either not enough capacity or poor management. Normally, there is variability in both demand and production environment. Thus, to guarantee demand response, the maximum throughput should be able to cover the average demand. The OPM used at this node is the maximum rate of production or maximum throughput (TH). When the maximum TH is less than an average demand, it indicates that the current production rate cannot cover the demand volume. Thus, the objective should be **increasing throughput (TH) at the bottleneck (BN)** station where the TH of the entire line is capacitated by it.

Besides TH, another key aspect to enhance SL is time. The usual dynamics production environment such as demand variability, machine breakdown, and reworks can contribute to the time used to satisfy demand (i.e., cycle time). Some literatures call them flexibility [27, 28]. Thus, reducing time to respond demand is also crucial to be considered for improvement objective. By reducing cycle time or response time to demand, it can increase SL or customer order fulfilment [29].

DN3. Reduce manufacturing cost

This DN supports its root node, DN1, by eliminating excess manufacturing cost which either from fixed cost (i.e., capacity cost) or operating cost (i.e., inventory cost). Sources of manufacturing cost are resource cost (e.g., machine cost, equipment cost, etc.) and inventory level. Thus, the OPM used at this DN are percentage of idle time at each station, inventory turnover rate, and average amount of stock. If percentage of idle time at each station is high, then the objective is "**reduce capacity cost.**" As for inventory cost, if inventory turnover rate is low or average amount of stock is high, then the objective is "**reduce inventory cost.**"

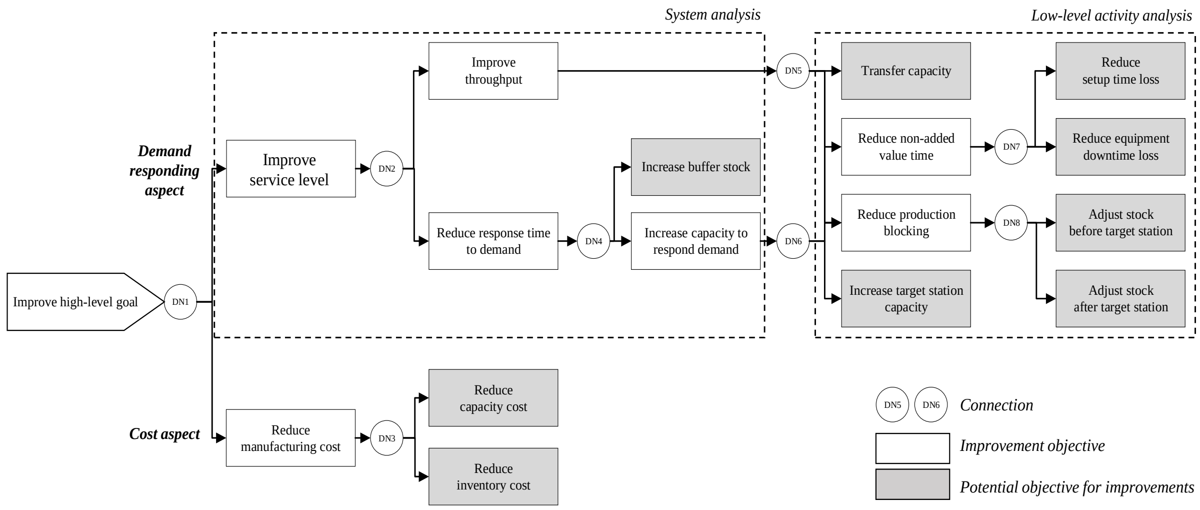

Fig. 3. D-Tree.

DN4. Reduce response time to demand

This DN supports its root node, DN2, by accelerating production time to respond demand. The stock buffering strategy is a widely used strategy to provide prompt response time and cope with variability [30]. Thus, **increasing buffer stock** should be stated as an improvement objective. The OPMs used at this DN are amount of stock and inventory turnover rate to check the possibility of increasing buffer stock by making careful analysis of cost and restrictions regarding inventory management. When buffering stock strategy is not justified, **increasing capacity to response demand** becomes a viable improvement objective. Usually, adding more capacity is a more complex and expensive objective compared to buffering stock objective. Increasing capacity in some workstations may not improve the whole performance system. Consequently, more diagnosis is needed to find root causes and significant workstation to improve.

DN5. Improve throughput at the bottleneck station

This DN supports its root node, DN2, by promoting productive time at the BN station to have enough TH to satisfy demand. The BN-station is the busiest station in the production line or having the largest preceding WIP. If simulation model is constructed, the bottleneck station can be detected by observing the point that limits production output [31]. The BN-station is always busy with both productive and unproductive times such as waiting time, setup time, and breakdown time. Thus, the enhancement of productive time at the BN-station can be achieved by eliminating unproductive time and/or adding more capacity.

The unproductive time is caused by non-value-added activities and waiting time. The unproductive activities include time for maintenance and setting up machines. The OPMs used to recognize this cause are the percentage of setup time and breakdown time. If they are greater than preset values, then the improvement objective is to **reduce non-value-added** activities. In case of waiting time, the BN-station may have to hold on to its production because either the BN-station is starving from lacking WIP at the preceding stock point and/or frequently having too much WIP at the proceeding stock point of the BN-station. It is also called production blocking. Thus, in both cases, the BN-station cannot work on any job but wait for incoming WIP or entity flow at the post-BN station to clear up. The percentage of waiting time is measured to identify production blocking. If the percentage of waiting time is greater than preset value, then the improvement objective is to **reduce production blocking**.

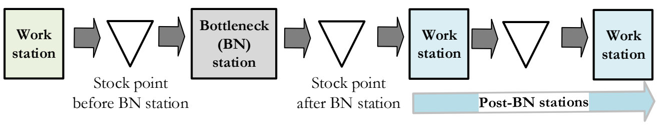

Fig. 4. Bottleneck station and stock point.

One of the reasons for poor TH is not having enough capacity. If the capacity among multi-products is not effectively allocated under shared resource environment, the unnecessary capacity can be allocated to some products. Thus, re-allocation of capacity among products should be considered to **transfer capacity** to the product that needs more. Finally, if no capacity can be transferred and the maximum throughput is still not adequate, then **increasing capacity** of workstation capacity should be an improvement objective.

DN6. Improve capacity to respond demand at post-bottleneck stations

Like DN5, this DN supports its root node, DN4, by promoting productive time to have enough TH to satisfy demand. However, DN6 focuses on the post-BN stations. Increasing capacity of pre-BN station does help the system to fill stock faster because jobs cannot go any faster than the production rate of the BN station. To get faster response to demand variety, it would be better to first consider improving the TH of the post-BN stations. In that case, the production cycle time can be reduced, and the manufacturing systems can respond to demands more rapidly. The performance measures and improvement objective are like DN5 except that it is done at the post-BN stations.

DN7. Reduce non-added value time

This DN supports its root node, DN5 and DN6, by retrieving more productive time to enhance station capacity. There are substantial reasons for capacity loss such as workstation downtime and setup time. The percentage of breakdown time is one measure to assess whether capacity loss due to inefficient maintenance process is more than necessary or not. Thus, the improvement objective is to **reduce breakdown time loss**. In case of capacity loss from setups, it includes workstation setups and product change setups. When the percentage of setup time is greater than expected, the improvement objective is to **reduce setup time loss**.

DN8. Reduce production blocking

This DN supports its root node, DN5 and DN6, by adjusting WIP level before and after the target station to eliminate unproductive time at the target station. The target station can be either the BN or post-BN stations. When the WIP level before the target station is frequently empty, the target station cannot start its production because of starving for WIP. Then the improvement objective is to **adjust stock before the target station** to have enough inventory. On the other hand, the target station may be blocked from its production because there is too much WIP at the stock point after it already. Then the improvement objective is to **adjust stock after the target station** to avoid production blocking. At this DN, the average amount of stock is used as an OPM. It should be assessed at both stock points to indicate where to adjust the stock level.

DOI:10.4186/ej.2023.27.9.55

Table 4. Details of D-Tree and OPMs.

Diagnosis nodes	Current node	Root node	INPUT: Related information and operational performance measures (OPMs)	OUTPUT: Subordinate objective nodes
DN1	**Improve high-level goal**	NONE	1. Target service level *2. Service level*	(a) Increase service level (b) Reduce manufacturing cost
DN2	**Improve service level**	Improve high-level goal (DN1)	1. *Maximum throughput* 2. Average demand	(a) Increase throughput (b) Reduce time to response demand
DN3	**Reduce manufacturing cost**	Improve high-level goal (DN1)	*Percent of idle time* *Average amount of stock and Inventory turnover rate*	**(a) Reduce capacity cost** **(b) Reduce inventory cost**
DN4	**Reduce response time to demand**	Improve service level (DN2)	*Average amount of stock and Inventory turnover rate* *Average amount of stock and Inventory turnover rate*	**(a) Increase buffer stock** (b) Increase capacity to response demand
DN5	**Improve throughput (Focus on bottleneck stations)**	Improve service level (DN2)	*Percent of production time and idle time* *Percent of setup time and breakdown time* *Percent of waiting time* *Maximum throughput*	**(a) Transfer capacity** (b) Reduce non-added value time (c) Reduce production blocking **(d) Increasing capacity**
DN6	**Improve capacity to respond demand (Focus on non-bottleneck stations)**	Reduce response time to demand (DN4)		
DN7	**Reduce non-added value time**	Improve throughput (DN5) Improve capacity to respond demand (DN6)	*Percent of setup time at target station* *Percent of breakdown time at target station*	**(a) Reduce setup time loss** **(b) Reduce equipment downtime loss**
DN8	**Reduce production blocking**	Improve throughput (DN5) Improve capacity to respond demand (DN6)	*Average amount of stock before target workstation* *Average amount of stock at target workstation*	**(a) Adjust stock before the target station** **(b) Adjust stock after the target station**

4.3. Action Guidelines

The improvement objectives obtained from D-Tree help identifying system performance which is needed to improve to accomplish the expectation or goal. Once the objective is addressed, control factors are logically adjusted to achieve that objective, and then the system performances are evaluated through operational performance measures (OPMs). The adjustment of control factors can be viewed as the ability to rearrange or adjust system components and hence leads to changes in system performances [20, 21]. For example, if "reduce setup time loss" is set as an improvement objective, one can increase lot size to reduce setup time occurring with batch changes. In this case, lot size is a control factor. Once it is changed to an appropriate direction, the objective can be attained.

The understanding of the relationships between control factors and performance measures can link the control factors setting to attainable levels of performance measures [25]. This relationship can be represented in analytic models and simulation models [32] which can be found in the knowledge of OM literature as well as factory physics [17]. However, in a complex manufacturing system, the relationships may not be straightforward. There might be risks as leverage when making changes in control factors. In addition, one improvement objective can be achieved in many ways. The decision for the most desirable solution is limited to case by case under production environment and business strategy such as cost restriction, inventory storage restriction, or product shelf-life restrictions.

In this section, action guidelines are suggested to adjust control factors to achieve each improvement objective. The details of guidelines for actions for each objective are described as follows.

1. Reduce capacity cost

This objective is derived from having too much capacity in the systems. This excess capacity might be in the form of too many machines or equipment. This large amount of idle time on resources incurs unnecessary investment cost. Thus, a possible guideline for this objective is to **reduce the number of machines**. The machine investment cost can be reduced before acquiring machines or resources by carefully planning systems capacity during the design phase of a manufacturing system. However, if reduced too much, it may cause shortages in capacity and lead to a poor service level.

2.Reduce inventory cost

Inventory cost is another imperative cost in manufacturing systems. Hence, stock reduction can help to have more cash flow. This objective is intended to reduce excess inventory costs if the service level is already achieved. Since the stock level is tightly related to production lot size and the safety stock level, the possible guidelines for this objective are connected those aforementioned factors as follows.

a. Reduce safety stock level: The safety stock reduction should be considered with caution otherwise it may hurt throughput and service level because the system has less buffer stock to respond to unpredicted demand and unexpected situations [33]. In addition, there are usually more than one stock points within a manufacturing system. Thus, determining the right stock points to be reduced is also crucial.

b. Reduce production lot size: The reduction of lot size can lead to frequent setup which causes setup time loss.

3. Increase buffer stock

This objective is resulted from poor responsiveness to demand rather than not enough capacity. Buffer stocks can be prepared for unexpected situations or demand variations to enhance responsiveness. The buffer stock can be either finished goods or WIP. Thus, the following guidelines are suggested for this objective.

a. Increasing finished goods buffer stock can respond to demand immediately [17, 33]. To increase buffer stock, it can be done through increasing lot size and/or safety stock. Note that stocking finished goods costs more than stocking WIP at other stock points earlier in the production line [30].

b. Increase WIP: Inventory costs are expected to be increased with this action.

4.Transfer capacity

This objective aims to reallocate the capacity of shared resources to properly match with product demands. This objective can be achieved by either changing product priority or changing production lot size [34]. Adjusting production lot size affects how often the product is changed in production. The amount of time dedicated between production changes or setups implies how much effective time available for production. The frequency of production changes is related to the amount of time spent on each production lot size before moving to the next station, hence it can affect the demand response time. Whether increasing or decreasing lot size, they affect all states of resources performance change. The details of each action are as follows.

a. Change product priority: The resource capacity or production time is available more to high priority products. The product priority should be set according to product demands otherwise, some resources may be underutilized and have shortages in some products at the same time. This could lower throughput and service level.

b. Increase production lot size: This action reduces the frequency of production setups and gains more effective production time. However, if the lot size is set too high, there might be a long waiting time for product changes and/or the next station.

c. Decrease production lot size: This action shortens waiting time for the next station and results in less time to response demand. However, the setup time can become larger.

5. Increase target station capacity

This objective aims to improve throughput and demand responsiveness by focusing on increasing capacity at the target station, which is selected from a set of BN station and post-BN stations. The idea of this objective is to focus on expanding the capacity. Usually this could be done in several options such as extending working time, upgrading equipment, reducing rework, adding, or training operators, and adding or upgrading a machine. Since the control factor related to this objective is the number of machines, **adding more machines** at the target station is suggested for this objective. However, if too much capacity is added, more idle time may occur.

6. Reduce setup time loss

This objective aims to eliminate the non-added value time by either improving throughput or increasing capacity to respond to demand. The setup time loss in this study focuses on product changeover from sharing resources under multi-product environment and setting production lot size or replenishment order. Possible guidelines to reduce setup time loss are as follows.

a. Reduce setup time of product changeover by **dedicating machine/s to some products**. The decision of workstations and/or products to be dedicated is crucial otherwise, some unexpected disruptions may happen due to capacity decrease in those products which capacity are taken away [34].

b. Reduce the frequency of production setups by **enlarging the production lot size** at the selected station [35, 36]. The large lot size inflates production cycle time and the waiting time due to longer time to finish each production batch.

c. Avoid product changeovers by **using buffer stock or increasing safety stock level** at the selected station [33]. The buffer stock can delay time to trigger the production setup by absorbing more demand fluctuation. However, the high inventory cost must be paid.

7.Reduce machine downtime loss

Like reducing setup time loss, this objective also aims to eliminate the non-added value time. Machine downtime is a common event in any manufacturing system. It can be either pre-emptive outages or non-pre-emptive outages. Pre-emptive outages are random failures (e.g., power outages, machine breakdowns). Non-pre-emptive outages are planned downtime (e.g., setups, rework, maintenance). Since capacity and production are lost during machine downtime, it is important to add more buffer in terms of inventory and capacity when it occurs. Thus, possible guidelines are as follows.

a. Increase buffer inventory by **increasing safety stock** at a selected (could be BN or post BN) workstation [33]. Adding more buffer inventory can lead to more inventory costs [37].

b. Increase buffer capacity by **sharing machine (resource)** at a selected (could be BN or post BN) workstation [34]. Setup time loss is expected due to sharing machine (resource).

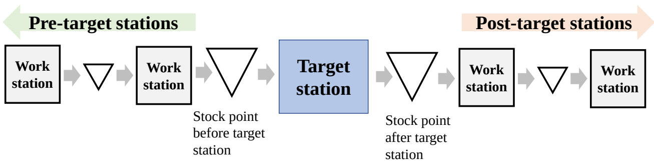

Fig. 5. Target station.

8.Adjust the stock point before the target station

This objective aims to reduce waiting time from lacking WIP or starving WIP at the target station. This starving effect degrades the performance of the target station such as loss throughput and long cycle time. The major causes of starvation are variability in process and

DOI:10.4186/ej.2023.27.9.55

flow rate as well as unsynchronized flow within the production line. The following guidelines are suggested to prepare for variability.

a. Increase safety stock: The safety stock at the point feeding to the target station dampens the effects of uncertain situation and promotes the production time of the target station. However, an increase in safety stock may result in high inventory level or low inventory turnover rate.

b. Decrease production lot size: The smaller production lot size requires less WIP to start production [16]. As the production lot size is getting smaller, the more setup time loss is expected. In addition, as in a flow shop environment, the smaller lot size reduces the cycle of each lot travelling through the production line. Hence, the waiting time of the first lot to arrive downstream workstations can be reduced as well.

c. Identify the new target station from a set of current pre-target stations: Sometimes starvation is caused by unsynchronized flow from another station in front of the current target station. That new target station is the station that yields the smallest throughput. It is the station that is not giving enough flow of WIP down to current target station. Once the new target station is identified, it will be diagnosed to determine the improving objective for this new target station.

9.Adjust the stock after the target station

This objective aims to eliminate overflown WIP at stock point after the target stations. The WIP is overflowing due to lacking WIP consumption at the post-target stations. There are two possibilities for this: 1) no production signal, and 2) unexpected situations to stop production. Usually, the signal to start and stop production can be set according to the inventory policy including determining lot size and safety stock especially in made-to-stock environment. The inventory policy at target and post-target station should be synchronized to enhance efficient flow of WIP within the production line. Thus, it is suggested to **adjust the inventory policy at the post-target station** to concur with the target station production. The possible unexpected situations to stop consuming WIP are defects and machine breakdowns. Thus, to sustain production, it is suggested that to **re-diagnose DN 4 to determine a new objective to improve** by focusing on the post-target stations.

5. Analysis Process Demonstration with a Case

This section demonstrates how the analysis process works step by step and shows major insights in which are used to solve a case study. According to the framework, the proposed analysis process will solve problems by analyzing the whole system performance and diagnosing potential improvement objective/s. Then, it also suggests good improvement guidelines or directions.

➢ *The detail of case study*

The selected case study is a real problem in one manufacturer in Thailand. This factory produces pallets to serve other factories. The considered production line produces only one type of pallet. The process and the layout of the production line can be shown in Fig. 6.

A pallet consists of two parts: part 1 and part 2. Each part must pass the process of shaving round 1, shaving round 2 and finishing. Then, part 1 and part 2 are assembled. Now, line of part 1 and part 2 are separated as shown in the figure and each station has a dedicated machine. For shaving and finishing station, there is one operator per station (blue). For the assembly station, there are two operators (blue). Transportation between the shaving station and finishing station is done by operators (red), while transferring from finishing station to assembly station is done by a forklift. The shaving machine of part 1 can produce part 2 and vice versa. Also, the finishing machine part 1 can produce part 2 and vice versa. However, the setup time is 15 minutes. There is no work-in-process across the day.

Now, this production line can produce around 164 pallets per day on average with 8 working hours and around 231 pallets per day with additional 3 hours of overtime. However, the required capacity for the customer is 360 pieces per day. The developed framework is applied to this case study to give the direction for improvement to the production manager step by step.

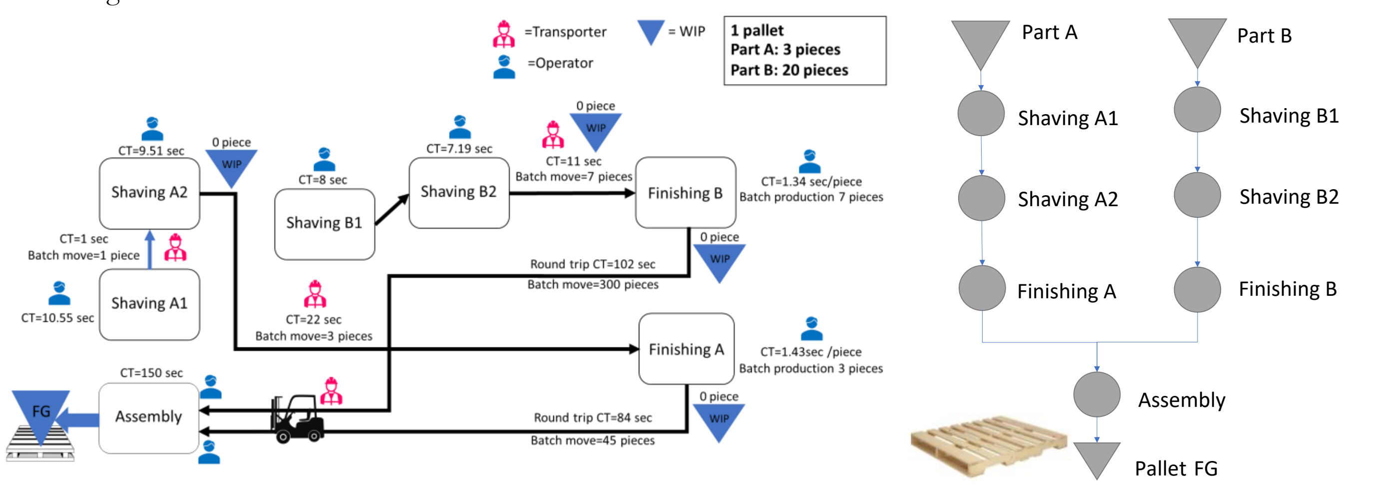

Fig. 6. Production process and layout of case study.

➢ *Methodology for demonstration*

For the methodology of analysis, case study is analyzed according to the diagnostic tree. For each node, operation performance measures (OPMs) are calculated and used for defining the next branch. An analysis process is done until reaching the end of the tree. The block at the end of the tree is the direction for improvement and action guideline of that block is considered as an additional information. These processes are done iteratively until the goal is met. The goal of this problem is to increase the capacity of the production line to meet customer demand, 360 pallets per day. Computer simulation is used to demonstrate the current problem and to show the improvement of each step.

➢ *Analysis process of case study*

Analysis round 1

Node: DN1

Input/OPMs:

• Current Throughput = 164 pieces/day

• Target = 360 pieces/day

Diagnostic criteria: If Current Throughput < Target, go to Improve service level.

Decision/Direction: Go to Improve service level.

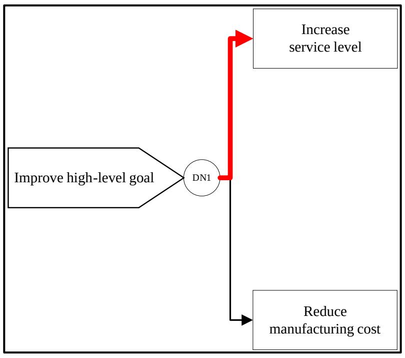

Fig. 7. Analysis round 1: DN1.

Node: DN2

Input/OPMs:

• Capability of each station. <value shown in Table 5>

• Required capability =360 pallets per day.

Table 5. Capability of each station.

Station	Cycle time	Number of pieces per pallet	Max throughput per day (8 hours) [Capability of station]	Enough ?
Shaving part1 round 1	10.55	3	(8*60*60/10.55)/3=910	Yes
Shaving part1 round 2	9.51	3	(8*60*60/9.51)/3=1009	Yes
Shaving part2 round 1	8	20	(8*60*60/8)/20=180	No*
Shaving part2 round 2	7.19	20	(8*60*60/7.19)/20=200	No*
Decorating part 1	1.43	3	(8*60*60/1.43)/3=6713	Yes
Decorating part 2	1.34	20	(8*60*60/1.34)/20=1075	Yes
Assembly	150	1	8*60*60/150=192	No*

Diagnostic criteria: If the Capability of some stations is less than the Required capability, go to Improve throughput.

Decision/Direction: Go to Improve throughput for stations whose Capability are less than Required capability.

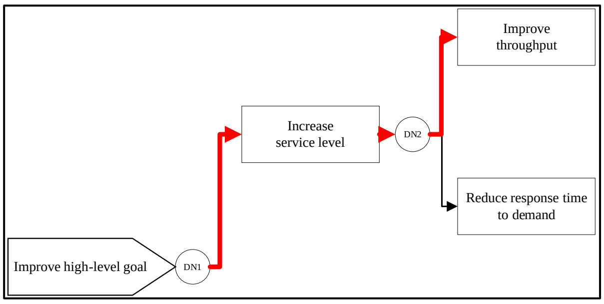

Fig. 8. Analysis round 1: DN2.

Node: DN5

Input/OPMs:

• Required capability =360 pallets per day.

• Stations that have insufficient capabilities: Shaving part2 round 1, Shaving part2 round 2 and Assembly.

• % Operation, % Setup, % Idle, % Waiting, % Blocked and % Down of all stations. <value shown in Table 6>

Table 6. % Operation, % Setup, % Idle, % Waiting, % Blocked and % Down of each station.

Name	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Shaving part1 round 1	39.56	0.00	60.44	0.00	0.00	0.00
Shaving part1 round 2	35.66	0.00	64.34	0.00	0.00	0.00
Shaving part2 round 1	100.00	0.00	0.00	0.00	0.00	0.00
Shaving part2 round 2	89.85	0.00	10.15	0.00	0.00	0.00
Decorating part 1	5.36	0.00	94.64	0.00	0.00	0.00
Decorating part 2	16.71	0.00	83.29	0.00	0.00	0.00
Assembly	91.63	0.00	2.52	11.73	0.00	0.00

Diagnostic criteria: Action guideline for increasing throughput: 1) Transfer capacity 2) Reduce non-added value time 3) Reduce production blocking or 4) Increase target station capacity.

Decision/Direction: Increasing throughput of each considered station.

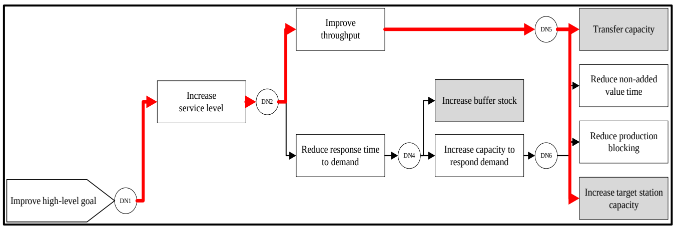

Fig. 9. Analysis round 1: DN5_1.

Decision for Shaving part2 round 1

Table 7. Decision for Shaving part2 round 1.

Action guideline	Details
1)Transfer capacity	Can transfer capacity to Shaving part 1 round 1 station because %Operation is only 39.56% ➢ Additional time from Shaving part 1 round 1 station= Total operation time – Production time of Shaving part1 round 1 – setup time = 8*60*60 -10.55*3*360 – 15*60 = 16,506 second. New capacity = Current capacity + (Additional time from Shaving part 1 round 1 station/cycle time of Shaving part2 round 1)/Number of pieces per pallet of Shaving part2 round 1 = 180 + (16,506/8)/20 = 283 pieces New capacity is not enough, so go to next action.

2)Reduce non-added value time	Cannot reduce because %Setup and % Down is 0%, so go to next action.
3)Reduce production blocking	Cannot reduce because %Blocked is 0%, so go to next action.
4)Increase target station capacity	For this problem, the choices for increasing capacity are to increase the number of station or time of station (Overtime). Start with overtime, the step for increasing overtime is 0.5, 1, 1.5, 2, 2,5 and 3 hours. Required overtime is 2.5 hours. ➢ New additional time from Shaving part 1 round 1 station= Total operation time – Production time of Shaving part1 round 1 – setup time = 10.5*60*60 - 10.55*3*360 – 15*60 = 25,506 second. New capacity = New capacity of Shaving part2 round 1 station + (New additional time from Shaving part 1 round 1 station/cycle time of Shaving part2 round 1)/Number of pieces per pallet of Shaving part2 round 1 = (10.5*60*60/8)/20+ (25,506 /8)/20 =395 pieces

Decision for Shaving part2 round 2

Table 8. Decision for Shaving part2 round 2.

Action guideline	Details
1)Transfer capacity	Can transfer capacity to Shaving part 1 round 2 station because %Operation is only 35.66% ➢ Additional time from Shaving part 1 round 2 station= Total operation time – Production time of Shaving part2 round 2 – setup time = 8*60*60 - 9.51*3*360 – 15*60 = 17629.2 second. New capacity = Current capacity + (Additional time from Shaving part 1 round 1 station/cycle time of Shaving part2 round 1)/Number of pieces per pallet of Shaving part2 round 1 = 200 + (17629.2/7.19)/20 = 322 pieces New capacity is not enough, so go to next action.
2)Reduce non-added value time	Cannot reduce because %Setup and % Down is 0%, so go to next action.
3)Reduce production blocking	Cannot reduce because %Blocked is 0%, so go to next action.
4)Increase target station capacity	For this problem, the choices for increasing capacity are to increase the number of station or time of station (Overtime). Start with overtime, the step for increasing overtime is 0.5, 1, 1.5, 2, 2,5 and 3 hours. Required overtime is 1.5 hours. ➢ New additional time from Shaving part 1 round 2 station= Total operation time – Production time of Shaving part1 round 2 – setup time = 9.5*60*60 - 9.51*3*360 – 15*60 = 23029.2 second. New capacity = New capacity of Shaving part2 round 2 station + (New additional time from Shaving part 1 round 2 station/cycle time of Shaving part2 round 2)/Number of pieces per pallet of Shaving part2 round 2 = (9.5*60*60/7.19)/20+ (23029.2 /7.19)/20 =397 pieces

Decision for Assembly

Table 9. Decision for Assembly.

Action guideline	Details
1)Transfer capacity	Choice a) Change product priority: Cannot change because there is only one product and only one station that can do this process. Choice b) Increase production lot size of considered station: Can increase but not affect the capacity because there is only one product. Choice c) Decrease production lot size of previous station: Can decrease and affect the capacity because now %Wait+%Idle = 2.52+11.73 =14.25%. For the problem having transfer time between station, the transfer time can be seen as production time and transfer lot size can be seen as production lot size. %Wait+%Idle is rather large because of a large transfer lot size between assembly station and previous stations (Finishing part 1(45 pieces) and Finishing part 2(300pieces)). Consequently, reducing this lot size can reduce %Wait+%Idle. According to the condition of the factory, the transfer lot size can be reduced to the number of required parts for assembly, so transfer lot from Finishing part 1 and Finishing part 2 are reduced to 3 and 20 respectively and to reduce transport time between station, assembly station is moved to close to Finishing part 1 and Finishing part 2 station. Assume that additional time that Assembly station has is 14.25% which is 8*60*60*0.1425=4104 sec. New capacity = Current capacity + Additional time from assembly/cycle time of Assembly station = 192+4104/150 = 219 pieces. New capacity is not enough, so go to next action.
2)Reduce non-added value time	Cannot reduce because %Setup and % Down is 0%, so go to next action.
3)Reduce production blocking	Cannot reduce because %Blocked is 0%, so go to next action.
4)Increase target station capacity	For this problem, the choices for increasing capacity station are to increase the number of station or time of station (Overtime). Normal working time plus three hours of overtime is not enough so the choice of increasing the number of station is chosen. Required station = 2 stations. New capacity = (8*60*60/150)*2 =384 pieces.

Conclusion of Decision/Direction:

- Action1: Assign Shaving part1 round 1 station to share capacity with Shaving part2 round 1 station and assign Shaving part1 round 2 station to share capacity with Shaving part2 round 2 station.
- Action2: Increase capacity of assembly station by adding a new station.
- Action3: Reduce transfer lot from 45 pieces at Finishing part 1 to 3 pieces and from 300 pieces at Finishing part 2 to 20 pieces and shorten transport time between Finishing part 1 and Finishing part 2 to Assembly station from 84 seconds and 102 seconds to 5 seconds.
- Action4: Add Overtime. There are two choices of OT.
    - 2.5 hrs. for Shaving part2 round 1
    - 1.5hrs for Shaving part2 round 2

  The suitable overtime is the highest overtime to cover demands. Consequently, the amount of overtime that the factory should have is 2.5 hrs. Working time = 8+2.5=10.5 hrs.

Analysis round 2

Node: DN1

Input/OPMs:

• Current Throughput = 384 pieces/day

• Target = 360 pieces/day

Diagnostic criteria: If Current Throughput > Target, the analysis process can stop because the aim of improvement is satisfied.

Decision/Direction: -

➢ ***Conclusion of the case***

From the analysis process, the manufacturing system is changed as follows: adjusting dedicated resources to shared resources and reassigning jobs to available shared resources, increasing the resource at selected bottleneck station, reducing transfer lot size, and increasing production time to some workstations.

The result is that throughput of the manufacturing system is increases from 231 pallets per day to 384 pallets per day, which meets the customer demand (360 pallets per day). In addition, the overtime is reduced from 3 hours to 2.5 hours.

6. Conclusion

This research has introduced a hierarchical analytic process framework to improve the performance of a manufacturing system. The output of the analytic process is improvement directions and action guidelines which rationally formulated based on various knowledge regarding operations management, factory physics and the science of manufacturing system to improve production capability. Under the proposed framework, various key performance measurements are analyzed with the embedded diagnostic tree to identify potential improvements as well as their action guidelines. The proposed framework is put in an easy-to-handle tool which provides step-by-step decision making to reach practical action guidelines. It is not only can be easily applied to real-life problems but also suggests efficient improvement directions. To demonstrate the proposed framework, a computer simulation of a case study manufacturing system is constructed. Even though the optimal value of control parameters in action guidelines are not yet determined, the simulation has shown improvement of performance measures for the directions recommended by the framework. It is also noted that the recommended guidelines are not ranked. This decision to act depends on many factors, e.g., budget, urgency, market, etc., which is specific to case by case. In addition, the concept of diagnostic tree can extend to be more comprehensive and grow as it is utilized. It could devote to consider other parameters for improvement such as defects, processing time, delivery time. In addition, it could be transformed into a better analytic process for specific industries to give a specific recommendation in terms of operations which would be more efficient and effectively in practice.

Acknowledgement

The authors would like to acknowledge Graduate School, Department of Industrial Engineering, Faculty of Engineering, Integrated Management System and Smart Technology Research Group, Chulalongkorn University, Bangkok, Thailand. This research is funded by Chulalongkorn University, Government Budget. In addition, the authors would like to acknowledge King Mongkut's University of Technology North Bangkok too. This research was funded by King Mongkut's University of Technology North Bangkok. Contract no. KMUTNB-64-DRIVE-28.

References

[1] D. S. Cochran, J. F. Arinez, J. W. Duda, and J. Linck, “A decomposition approach for manufacturing system design,” *Journal of Manufacturing Systems*, vol. 20, no. 6, pp. 371-389, 2001.

[2] D. S. Cochran, J. Kim, and Y. S. Kim, “Performance measurement and manufacturing system design,” in *CIRP International Seminar on Manufacturing*, 2000.

[3] D. S. Cochran, Y. S. Kim, and J. Kim, “The impact of performance measurement on manufacturing system design,” in *International Conference on Axiomatic Design*, 2000.

[4] M. Fertsch, K. Grzybowska, and A. Stachowiak, “Models of manufacturing systems—Classification framework,” Research in Logistics And Production, Poznan University of Technology, 2011.

[5] S. Supsomboon, “Simulation for jewelry production process improvement using line balancing: A case study,” *Management Systems in Production Engineering*, vol. 27, pp. 127-137, 2019.

[6] A. Burduk, D. Łapczyńska, and P. Popiel, “Simulation modeling in production effectiveness improvement—Case Study,” *Management and Production Engineering Review*, vol. 12, pp. 75-85, 2021.

[7] L. Zonga and W. Kongkaewb, “A multi-objective variable neighborhood search algorithm for precast production scheduling,” *Engineering Journal*, vol. 24, pp. 139-157, 2020.

[8] C. Gonzalez-Val, A. Pallas, V. Panadeiro, and A. Rodriguez, “A convolutional approach to quality monitoring for laser manufacturing,” *Journal of Intelligent Manufacturing*, vol. 31, no. 3, pp. 789-795, 2020.

[9] O. Caballero, “Modeling and simulation for analysis and improvement of a sock manufacturing system in a micro-enterprise,” *The International Journal of Industrial Engineering: Theory, Applications and Practice*, vol. 22, pp. 382-398, 2015.

[10] M. Filho and R. Uzsoy, “The effect of shop floor continuous improvement programs on the lot size–cycle time relationship in a multi-product single-machine environment,” *International Journal of Advanced Manufacturing Technology*, vol. 52, pp. 669-681, 2011.

[11] M. Filho, “Effect of lot-size reduction and continuous improvement programmes on work in process and utilisation: A study for single-machine and flow-shop environments,” *International Journal of Logistics*, vol. 15, 2012.

[12] Y. Leung and R. Suri, “Performance evaluation of discrete manufacturing systems,” *IEEE Control Systems Magazine*, vol. 10, no. 4, pp. 77-86, 1990.

[13] J. F. W. Peeters, R. J. I. Basten, and T. Tinga, “Improving failure analysis efficiency by combining

FTA and FMEA in a recursive manner," *Reliability Engineering & System Safety*, vol. 172, pp. 36-44, 2018.

[14] M. Brundage, B. Kulvatunyou, T. Ademujimi, and R. Badarinath, "Smart manufacturing through a framework for a knowledge-based diagnosis system," in *International Manufacturing Science and Engineering Conference*, 2017.

[15] J. C. Hernandez-Matias, A. Vizan, A. Hidalgo, and J. Rios, "Evaluation of techniques for manufacturing process analysis," *Journal of Intelligent Manufacturing*, vol. 17, no. 5, pp. 571-583, 2006.

[16] W. Hopp, S. Iravani, and B. Shou, "A diagnostic tree for improving production line performance," *Production and Operations Management*, vol. 16, pp. 77-92, 2009.

[17] W. Hopp, Factory Physics: Foundations of Manufacturing Management, 2nd ed. Boston: Irwin/McGraw-Hill, 2001.

[18] C. Lin, T. S. Baines, J. O. Kane, and D. Link, "A generic methodology that aids the application of system dynamics to manufacturing system modelling," in *International Conference on Simulation*, 1998.

[19] K. Suthar and V. Deshpande, "Review on reducing manufacturing throughput time: Various tools and techniques," *Journal of Emerging Technologies and Innovative Research*, vol. 1, pp. 542-546, 2014.

[20] A. L. Andersen, T. D. Brunoe, K. Nielsen, and C. Rösiö, "Towards a generic design method for reconfigurable manufacturing systems: Analysis and synthesis of current design methods and evaluation of supportive tools," *Journal of Manufacturing Systems*, vol. 42, pp. 179-195, 2017.

[21] I. Maganha, C. Silva, and L. M. D. F. Ferreira, "Understanding reconfigurability of manufacturing systems: An empirical analysis," *Journal of Manufacturing Systems*, vol. 48, pp. 120-130. 2018.

[22] M. Battesini, C. S. ten Caten, and D. A. d. J. Pacheco, "Key factors for operational performance in manufacturing systems: Conceptual model, systematic literature review and implications," *Journal of Manufacturing Systems*, vol. 60, pp. 265-282, 2021.

[23] A. Neely, "The evolution of performance measurement research—Developments in the last decade and a research agenda for the next," *International Journal of Operations & Production Management*, vol. 25, pp. 1264-1277, 2005.

[24] C. Burja and N. M. Lesconi-Frumuşanu, "Analysis model for inventory management," *Annals of the University of Petrosani, Economics,* vol. 10, pp. 43-50, 2010.

[25] K. K. B. Hon, "Performance and evaluation of manufacturing systems," *CIRP Annals - Manufacturing Technology*, vol. 54, pp. 139-154, 2005.

[26] S. New, "Modeling and analysis of manufacturing systems," *Journal of the Operational Research Society*, vol. 45, 1994.

[27] P. Košťál and K. Velisek, "Flexible manufacturing system," vol. 77, pp. 825-829, 2011.

[28] K. Mahmood, T. Karaulova, T. Otto, and E. Shevtshenko, "Performance analysis of a flexible manufacturing system (FMS)," *Procedia CIRP*, vol. 63, pp. 424-429, 2017.

[29] I. Taifa and T. Vhora, "Cycle time reduction for productivity improvement in the manufacturing industry," *Journal of Industrial Engineering and Management Studies*, vol. 6, pp. 147-164, 2019.

[30] C. Schultz, "Spare parts inventory and cycle time reduction," *International Journal of Production Research*, vol. 42, pp. 759-776, 2004.

[31] C. Roser, K. Lorentzen, and J. Deuse, "Reliable shop floor bottleneck detection for flow lines through process and inventory observations," *Procedia CIRP*, vol. 19, pp. 63–68. 2014.

[32] C. R. Standridge, "How factory physics helps simulation," in *Winter Simulation Conference*, 2004.

[33] R. S. Russell and B. W. Taylor, *Operations Management*. Wiley, 2011.

[34] C. Papadopoulos, M. O'Kelly, M. Vidalis, and D. Spinellis, *Analysis and Design of Discrete Part Production Lines*. Springer, 2009.

[35] M. Filho, "Effect of lot-size reduction and continuous improvement programmes on work in process and utilisation: A study for single-machine and flow-shop environments," *International Journal of Logistics*, vol. 15, 2012.

[36] M. G. Filho and R. Uzsoy, "The impact of simultaneous continuous improvement in setup time and repair time on manufacturing cycle times under uncertain conditions," *International Journal of Production Research*, vol. 51, no. 2, pp. 447-464, 2013.

[37] L. Zhang, Q. Deng, Z. Wang, G. Gong, X. Wen, and X. Liu, "Collaborative scheduling of production resources and spare parts inventory for distributed equipment with feedback guidance and minimum capacity loss," *Swarm and Evolutionary Computation*, vol. 75, 2022.

Jongkon Sukjamnong
Thailand
B.Eng. (Industrial Engineering), Chulalongkorn University
M.Eng. (Industrial Engineering), Chulalongkorn University

Paveena Chaovalitwongse
Thailand
B.Eng. (Industrial Engineering), Chulalongkorn University
M.Eng. (Industrial and Systems Engineering), University of Florida
Ph.D. (Industrial and Systems Engineering), University of Florida

Siravit Swangnop
Thailand
B.Eng. (Industrial Engineering), Chulalongkorn University
M.Eng. (Industrial Engineering), Chulalongkorn University
Ph.D. (Industrial Engineering), Chulalongkorn University

Poom Luangjarmekorn
Thailand
B.Eng. (Engineering Synthesis), University of Tokyo
M.Eng. Micro System Engineering, Nagoya University