Measuring Leanness of Manufacturing Systems and Identifying Leanness Target by Considering Agility

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Abstract

The implementation of lean manufacturing concepts has shown significant impacts on various industries. Numerous tools and techniques have been developed to tackle specific problems in order to eliminate wastes and carry out lean concepts. With the focus on "*how to make a system leaner*," little effort has been made on determining "*how lean the system is*." Lean assessment surveys evaluate the current status of a system qualitatively against predefined lean indicators. Lean metrics are developed to quantify performance of improvement initiatives, but each metric only focuses on one specific area. Value Stream Maps demonstrate the current and future states graphically with the emphasis on time-based performance only. A truly quantitative and synthesized measure for overall leanness has not been established.

In some circumstances, being lean may not be the only goal for manufacturers. In order to compete in the rapidly changing marketplace, manufacturing systems should also be agile to respond quickly to uncertain demands. Nevertheless, being extremely agile may increase the cost of regular operations and reduce the leanness of the system. Similarly, being extremely lean may reduce flexibility and lower the agility level. Therefore, a manufacturing system should be agile enough to handle the uncertainty of demands and meanwhile be lean enough to deliver goods with competitive prices and lead time. In order to achieve the appropriate leanness level, a leanness measure is needed to address not only "*how lean the system is*" but also "*how lean it should be*."

In this research, a methodology is proposed to quantitatively measure leanness level of manufacturing systems using the *Data Envelopment Analysis* (DEA) technique. The production process of each work piece is defined as a *Decision Making Unit* (DMU) that transforms inputs of *Cost* and *Time* into output *Value*. Using a *Slacks-Based Measure* (SBM) model, the DEA-Leanness Measure is developed to quantify the leanness level of each DMU by comparing the DMU against the frontier of leanness. A *Cost-Time-Value* analysis is developed to create virtual DMUs to push the frontier towards ideal leanness

so that an effective benchmark can be established. The DEA-Leanness Measure provides a unit-invariant leanness score valued between 0 and 1, which is an indication of "*how lean the system is*" and also "*how much leaner the system can be.*" With the help of *Cost-Time Profiling* technique, directions of potential improvement can be identified by comparing the profiles of DMUs with different leanness scores. The leanness measure can also be weighted between *Cost, Time* and *Value* variables. The weighted DEA-Leanness Measure provides a way to evaluate the impacts of improvement initiatives with an emphasis on the company's strategic focus.

Performing the DEA-Leanness measurement requires detailed cost and time data. A Web-Based Kanban is developed to facilitate automated data collection and real-time performance analysis. In some circumstances where detailed data is not readily available but a Value Stream Maps (VSM) has been constructed, the applications of DEA-Leanness Measure based on existing VSM are explored.

Besides pursuing leanness, satisfying a customer's demand pattern requires certain level of agility. Based on the DEA-Leanness Measure, appropriate leanness targets can be identified for manufacturing systems considering sufficient agility level. The *Online-Delay* and *Offline-Delay Targets* are determined to represent the minimum acceptable delays considering inevitable waste within and beyond a manufacturing system. Combining the two targets, a *Lean-Agile Performance Index* can then be derived to evaluate if the system has achieved an appropriate level of leanness with sufficient agility for meeting the customers' demand.

Hypothetical cases mimicking real manufacturing systems are developed to verify the proposed methodologies. An Excel-based DEA-Leanness Solver and a Web-Kanban System have been developed to solve the mathematical models and to substantiate potential applications of the leanness measure in real world. Finally, future research directions are suggested to further enhance the results of this research.

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List of Acronyms

ADMU	Actual Decision Making Unit
BCC Model	Banker-Charnes-Cooper Model
CCR Model	Charnes-Cooper-Rhodes Model
CTP	Cost-Time Profile
CTV Analysis	Cost-Time-Value Analysis
CTV Chart	Cost-Time-Value Chart
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
IDMU	Ideally Lean Decision Making Unit
ERP	Enterprise Resources Planning
JIT	Just-in-time Production
NVA	Non-Value-Added
SBM Model	Slacks-Based Measure Model
SME	Small and Medium Enterprise
TPM	Total Productive Maintenance
TPS	Toyota Production System
VA	Value-Added
VSM	Value Stream Map
WIP	Work-in-Process

Chapter 1 Introduction

Many successful cases from various industries have demonstrated the effectiveness of lean manufacturing concepts. The waste reduction and continuous improvement techniques help lean practitioners pursue perfection. However, an effective measure of the leanness level is absent. A measure of leanness is needed to provide decision support information such as the current leanness level, the progress of lean implementation, and the extent of potential improvements. In this research, a methodology is proposed to measure the leanness level of manufacturing systems and to identify the target of leanness level considering sufficient agility level. The background information, motivation and an overview of this research are presented in this chapter.

1.1 Background and Motivation

While the efficiency and effectiveness of shop floor activities are continuously improved by tools and techniques of lean manufacturing, a quantitative measure of the leanness level to support the improvements has not been well developed. Without a leanness measure, the leanness level of the current value stream is unknown, and the improvement of leanness cannot be tracked. The success of lean manufacturing concepts has urged the development of a leanness measure.

1.1.1 The Success and Limits of Lean Manufacturing

Ever since the research group in *Massachusetts Institute of Technology* (Womack et al., 1990) started to promote the concepts of lean manufacturing in the 1990's, the "*Lean Thinking*" (Womack and Jones, 1996) has helped manufacturers improve their performance by eliminating unnecessary activities in the manufacturing system from the view point of customer defined value. Adapted from the *Toyota Production System* (Ohno, 1988), lean thinking helps manufacturers identify various types of *Waste*, such as waiting and overproduction, which were once acceptable to the *Mass Production* strategy. By the efforts of eliminating theses wastes, materials can flow through the system smoothly, and consequently, less resources are required to perform the manufacturing tasks. The waste reduction efforts result in better performances, which typically include lower cost, shorter lead time, more stable quality, lower work-in-process (WIP) and inventory level, and increased product variety. Eventually, the benefits from implementing lean concepts lead to a higher customer satisfaction level and, as a result, better chance to survive and thrive in the global competition.

Various tools and techniques have been developed to identify and eliminate the wastes in manufacturing systems. The mistake-proof techniques and continuous improvement activities reinforce the advantages of lean implementation in the long run. Each lean tool or technique usually focuses on solving a specific problem, such as high work-in-process level, low availability of equipment, long setup time, etc. Therefore, many of the tools are often applied simultaneously in order to improve the overall leanness of a system. Performance metrics corresponding to the lean tools were developed to track the improvements. Similarly, the lean metrics usually evaluates the performance of a fraction of the overall leanness. Most of the time, a group of lean metrics are used simultaneously to evaluate the effectiveness of the lean initiatives. An integrated measure of leanness which is quantitative and objective is absent. Only by reviewing a whole set of lean metrics, the lean practitioners can track the improvement in each specific area and build a rough image of the overall leanness. The current level of overall leanness is not measured, and the progress of improvement on overall leanness cannot be tracked. As a result, lean practitioners know "*how to improve the leanness*" and "*what has been improved*" but do not have the knowledge of "*how lean the system is*" or "*how much leaner it can become*." An integrated leanness measure should be developed to guide the efforts of leanness improvements.

The benefits of implementing lean manufacturing concepts have been proven by numerous lean practitioners reportedly. In addition to manufacturing activities, the impact of lean thinking has been extended to other areas, such as service industries and administrative sectors. It appears that the lean concepts can be effectively applied to all activities in any system. However, empirical studies pointed out that the effectiveness of lean implementation is limited when the contents of the activities are non-repetitive (White and Prybutok, 2001). In other words, when the demand volume fluctuates, or when the product types change frequently, the implementation of lean manufacturing concepts becomes less beneficial.

Although the advantages are less significant, companies who do not have a stable demand from customers can still apply the lean tools and techniques to lower the cost of production, shorten the lead time, and stabilize the quality. Strategies for applying lean principles in the environments of high product variety and low volumes have been suggested by previous research (Jina et al., 1997). On the other hand, a different strategy, *Agile Manufacturing*, has been developed to cope with the uncertainty of changing demands (Goranson, 1999). The objective of an agile manufacturing system is to respond swiftly to demand changes and gain the market before competitors can react. As a result, the agile strategy is more advantageous than the lean manufacturing strategy in the volatile, customer-driven environment.

1.1.2 Enhancing Performance Based on Leanness and Agility

Lean manufacturing and agile manufacturing strategies are both created to gain advantage in the global competition, but the two solutions aim at different problems. The major contribution of lean manufacturing is to improve efficiency, while the agile strategy contributes mainly to responsiveness. Early research on agile manufacturing argues that the agile strategy is an alternative to the well accepted lean strategy since the market demand is increasingly more volatile. However, not all companies are targeting at the extremely volatile or extremely stable market (Mason-Jones et al., 2000b). Most organizations face a market that is between the two extremes. Being lean and agile at the same time would be beneficial. Nevertheless, the two manufacturing strategies are not fully compatible. Controversies are found in the objectives of the two strategies, e.g., lower unit cost versus higher flexibility. As a result, maximizing the agility of a system may be harmful to the leanness, and vice versa (Goranson, 1999). A compromise between lean and agile strategies would be more favorable in practice.

For different products and industries, different patterns of market demand can be observed. For example, a demand can be categorized as steady, increasing, decreasing, seasonal, or volatile. From a supplier’s point of view, the pattern of market demand is not a controllable issue. The decision is either accepting the pattern or giving up the market. Therefore, when a company is aiming at a certain market, the agility level required to handle the uncertainty of the demand pattern has been defined by the market. In other words, the preferred compromise between leanness and agility should be achieved by maximizing the leanness level while a certain level of agility is maintained. Thus, a supplier facing a stable demand should be as lean as possible while keeping minimal level of agility. On the other hand, a supplier receiving custom orders frequently may need to sacrifice its leanness to be highly agile. In order to achieve the balance between leanness and agility, the decisions on performance improvement cannot be made only based on "*how lean the system is*." A methodology to decide "*how lean the system should be*" also needs to be developed.

1.2 Problem Statement and Research Objectives

In this research, a methodology is developed to measure the leanness level of manufacturing systems and identify the appropriate target of leanness. The objectives and the framework of this research are presented in this section.

1.2.1 Problem Statement

While applying lean principles to a system, the progress and effectiveness of the lean implementation are always the major concerns for decision makers. The following three essential questions illustrate the decisions on lean implementation: "*How lean is the system?*", "*How to become leaner?*", and, "*How lean the system should be?*"

Various tools and techniques have been developed to help lean practitioners reduce wastes and enhance the leanness of the manufacturing system. The question, *"how to become leaner"* has been answered by these lean tools and techniques. However, the existing performance measures do not provide an explicit indication on *how lean a system is*. Also, for the balance between leanness and agility, the target of appropriate leanness level can not be identified or presented due to the absence of an effective leanness measure. Therefore, the answers to *how lean the system is" and "how lean the system should be"* are still absent.

In order to support the decisions made for lean implementation, a methodology that identifies the leanness level of a system needs to be developed. The measurement of leanness should be quantitative and objective, which can be applied on different systems and can be compared between the systems. For a certain level of agility, a target of appropriate leanness level needs to be identified. The leanness measure should be able to present the leanness target in the same format as the leanness measure of current status so that the lean practitioners can evaluate their performance by comparing the current leanness level against the leanness target. The leanness measure and the target should lead to improvement actions that can enhance leanness of the system in order to thrive in the competitive market.

1.2.2 Research Objectives and Scope

The objective of this research is to develop a series of methodologies to help lean practitioners ensure the effectiveness of the implementation of lean initiatives. Three aspects of the objective are listed below.

1) **Measuring Leanness of Manufacturing Systems:** A leanness measure needs to be developed that can quantify the leanness level of a manufacturing system to provide an integrated index for "*how lean the system is.*"
2) **Identifying Leanness Target:** A leanness target needs to be identified that shows the minimum of acceptable leanness level while maintaining sufficient agility. The question "*how lean the system should be*" is answered by the leanness target.
3) **Identifying Directions of Improvement:** Directions of potential improvements need to be identified to help the lean practitioners improve from current leanness level to the leanness target. The concern of "*How to achieve the leanness target*" is addressed by the improvement directions.

A methodology for leanness measurement and target identification is illustrated in this research to carry out the three aspects of the research objective. Based on the context of manufacturing systems, the proposed methodology is developed and verified. Due to the availability of time and other resources, the scope of the research on leanness measurement and target identification is limited to shop floor activities. A potential application of the leanness measure on supply chain level is suggested, but it will be verified in future research work. In the development of the methodology, existing mathematical models for *Data Envelopment Analysis* (DEA) are adapted to develop the measure of leanness scores. Computer programs are developed to solve the mathematical models and substantiate practical applications of this methodology in real manufacturing systems. Hypothetical cases of different scenarios are created to verify the effectiveness of the proposed methodology. These cases depict the scenarios commonly found in real manufacturing systems.

Although the scope of this research is limited to manufacturing systems, the concepts of the leanness measurement and target identification can possibly be applied to other circumstances. Potential extensions of the research scope include service industries, administrative works, transportation industries, research and development sectors, etc. The way to adapt and implement the proposed methodology in these circumstances is beyond the current research.

1.3 Framework of the Research

The dissertation is organized based on the framework of this research. Chapters are developed to present the components of the framework, and the order of the chapters corresponds to the timeline of the research activities. The components of this research are listed as follows, and Figure 1.1 portrays the framework graphically.

1) **Problem Statement (Chapter 1):** Including background information, motivation, objectives and scope of this research.

2) **Literature Review (Chapter 2):** Including the review of previous research on lean manufacturing, agile manufacturing, leanness measurement, and Data Envelopment Analysis.
3) **Methodology Development (Chapter 3 to 5):** Including the approaches to measuring leanness of manufacturing systems, identifying leanness target for the system, and some extended applications of the proposed leanness measure.
4) **Hypothetical Case Studies (Chapter 3 to 5):** Hypothetical cases associated with the proposed methodologies are included in the chapters where the methodologies are introduced. The cases are created to imitate the real manufacturing systems with conditions commonly found in practice.
5) **Software Program Development (Chapter 6):** Including an MS Excel-based program for solving the linear program models and a Web-based Kanban program to facilitate data collection.
6) **Conclusions (Chapter 7):** Summarizing the methodologies, case studies, software programs, and future research areas.

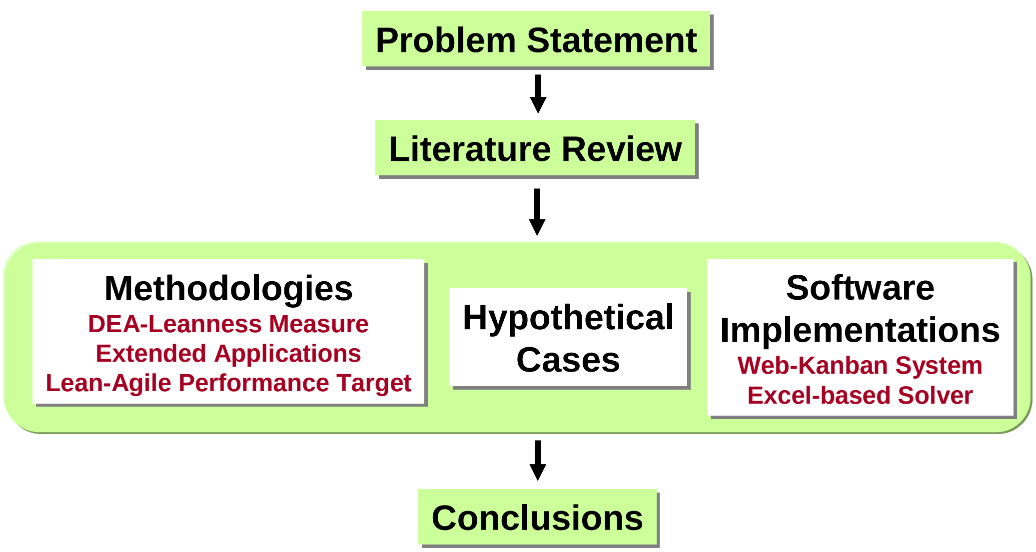


Figure 1.1 Framework of Research

Chapter 2 Literature Review

In this chapter, previous research relevant to leanness measurement and target identification is reviewed. First, the lean and agile manufacturing strategies are introduced, and the relationship between lean and agile strategies is investigated. Following that, previous research on leanness measurement is reviewed. The definition of leanness is examined, and different ways to evaluate the leanness level are investigated. After the review of leanness, the development of *Data Envelopment Analysis* (DEA) is introduced, including the concepts, mathematical models and the modeling issues are illustrated. Finally, a summary of the literature review wraps up this chapter.

2.1 Development of Lean and Agile Manufacturing Strategies

The lean and agile manufacturing strategies were both developed to make manufacturing firms more competitive in the marketplace. However, conflicts exist between the enablers of the two strategies. This section reviews the concepts of the two strategies, the relationship between them, and the methodologies to be lean and agile simultaneously.

2.1.1 Lean Manufacturing

The idea of conducting manufacturing processes in a lean manner is originated from Toyota, the Japanese automaker that has been thriving in the global competition for decades. In *Toyota Production System*, Ohno (1988) introduces the unique production concepts developed in this company that helped them overcome difficult times since World War II. In an environment lacking of resources, the Toyota Production System (TPS), also known as Just-in-time (JIT) system, was developed to survive with minimum amount of resources. The limited availability of resources made all mistakes unaffordable, and reducing wastes in the shop floor became the mission of survival. When the oil crisis struck the global economy in 1973, Toyota sustained and prospered because of the high efficiency of the TPS. As a result, the lack of resources which was originally an obstacle to this company turned out to be the stepping stone for them to become a world-class manufacturer.

In the 1980's, a research group in MIT investigated the success of TPS. In contrast to the mass production techniques inherited from *Henry Ford* almost a century ago, the term "Lean Production" was coined to describe the highly efficient production system which uses less of every resource to produce the same amount of products with good quality. The findings of the investigations were summarized in *The Machine that Changed the World* (Womack et al., 1990), which compares lean production with mass production and points out several advantages and issues of becoming lean. This book caught the attentions of manufacturers and researchers rapidly and popularized the concept of lean manufacturing. Following that, Womack and Jones (1996) published the book, *Lean Thinking*, which scrutinizes the concept of being lean. A vision of "lean enterprise" was introduced by the authors that expanded the scope of implementing lean principles to activities beyond the shop floor. It inspired later research, such as the lean implementation in administrative work (William, 2003) and service sectors (Arbos, 2002). More applications can be found in various environments which are beyond the scope of this research.

The foundation of lean manufacturing is inherited from TPS. Ohno (1988) points out that the basis of TPS is eliminating waste, and the two pillars supporting the system are JIT and Autonomation. JIT implies a pull system where parts are moved only when needed by the next process. Autonomation means "automation with human touch" which prevents from producing defective parts when a mistake occurs or the machine fails. In terms of waste, JIT eliminates the expected wastes caused by the design of the system. On the other hand, Autonomation prevents the unexpected wastes caused by mistakes and machine failures. Therefore, implementing JIT and Autonomation together eliminates the two major aspects of waste in a manufacturing system. To realize the two concepts, all wastes must be identified and eliminated. A "5 whys" procedure is used to find the root cause of all wastes. The questions are driven by a philosophy that distinguishes TPS from the others, which is to "rethink the common senses." A well known result of the "rethinking" is the finding that inventory, which was once considered as a tool to earn more profit, is really a form of waste. Based on this philosophy, Ohno (1988) identifies seven types of wastes, which are listed as following, together with corresponding issues identified by Feld (2000).

1) **Waste of Overproduction:** Excess Production – batch production, bottlenecks, and curtain operations.
2) **Waste of Time on Hand:** Waiting – down time, part shortages, and long lead time.
3) **Waste in Transportation:** Transportation – poor utilization of space, operator travel distance, and material flow backtracking.
4) **Waste of Processing Itself:** Over Processing – redundant systems, misunderstood quality requirements, poor process design.
5) **Waste of Stock on Hand:** Inventory – long changeover time, high raw material inventory, high WIP, high finished goods inventory, and excessive management decisions.
6) **Waste of Movement:** Motion – low productivity, multiple handling, and operator idle time.
7) **Waste of Making Defective Products:** Defects – poor process yield, employee turnover, low employee involvement, limited processing knowledge, and poor communications.

In order to eliminate the seven types of wastes, revolutionary techniques were developed in TPS. Ohno (1988) introduces the concepts of these techniques. Most of them have become the fundamental techniques of lean manufacturing, including *pull system, Kanban, supermarket, demand leveling, flow, teamwork, multi-skilled worker, small lot sizes, quick setup, mistake proof,* and *visual control*. Monden (1998) illustrates the details of all the tools and techniques used in TPS. Examples and instructions were also provided which guide the readers through the implementation of a complete TPS. By distinguishing the determinants of lean manufacturing, Detty and Yingling (2000) summarize eight tenets for the philosophy of lean, which includes *process stability, standardized work, level production, just-in-time, quality-at-the-source, visual control, production stop policy,* and *continuous improvement*. Shah and Ward (2003) review 16 key references of practices of lean manufacturing from 1977 to 1999. The "lean practices," which are the tools and techniques of lean implementation, are summarized with the frequency of reference in the 16 papers. Among the 22 lean practices, the *JIT/continuous flow production, Pull system/Kanban,* and *Quick changeover techniques* were included in all 16 papers, and the *Lot size reductions* was referred 15 times out of 16. The four lean practices appeared to be the most frequently implemented techniques for lean implementation.

The vast number of tools or techniques included in TPS is an accumulation of solutions over a long period. Every tool or technique was developed to solve a problem and eliminate the waste found in Toyota's production line, and it helps a manufacturing system to become leaner in some aspects. However, for other companies, it is often difficult to select a proper tool from the huge TPS tool box for their own problems. In order to help the lean practitioners, Womack and Jones (1996) further investigate the meaning of being lean which is published in the *Lean Thinking*. Five major steps to make a system leaner are concluded as the following.

1) Identify customer defined ***Value***
2) Specify ***Value Stream***
3) Make value ***Flow*** smoothly
4) ***Pull*** the flow by customer
5) Pursue ***Perfection***

The lean thinking generalized the process to become leaner. Therefore, the steps can also be applied to non-manufacturing sectors. Although an action plan was provided in the book to guide the reader through the transformation process, the authors found that readers often try to pick a target without systematically analyze the value stream (Foreword in Rother and Shook, 1998). Therefore, Rother and Shook developed a graphical tool, the *Value Stream Mapping* (VSM), to help lean practitioners identify the wastes visually and systematically. VSM has become one of the most important tools for the implementation of lean principles. Further discussions are listed in Section 2.2.4.

2.1.2 Advantages and Limitations of Lean Manufacturing Implementation

The purpose of implementing lean manufacturing is to become leaner. Ultimately, the goal of a "leanest" manufacturing system is to become totally "waste-free." Hopp and Spearman (2000) introduce two statements on the waste-free state that were given as early as 1983. The first statement used the term "*zero inventories*" to describe the ideally lean state. Another statement described the ideal goal by "*seven zeros*" corresponding to the different types of wastes. These are: *zero defects, zero (excess) lot size, zero setups, zero breakdowns, zero handling, zero lead time,* and *zero surging* (i.e. smooth flow). Hopp and Spearman pointed out that these "zeros" are physically unachievable in practice, but the goals inspire an environment of continual improvement. Nevertheless, the vision of the idea goals played an important role in developing the measure of leanness, which is discussed in the next section.

Although the ideally lean state is typically not achievable, the waste-reduction process of lean implementation helps manufacturers improve the efficiency and effectiveness of the manufacturing activities. As shown in *The Machine that Changed the World* (Womack, 1990), Toyota was able to assemble cars with shorter lead time and lower defects rates using a smaller area and maintaining a significantly lower inventory level when compared to GM in 1987. Many other cases have also shown that becoming lean can enhance the competence of a manufacturing firm in the market place. One of the key differences between lean and mass productions is the *pull system*, which prevents most of the wastes from happening by blocking unnecessary activities. Sipper and Bulfen (1997) point out that the major advantages of implementing pull system include:

1) *Shorter lead time* and hence *higher flexibility* to demand changes,
2) *Reduced* levels of *inventory* and other *wastes*,
3) *Capacity considerations* that are restricted by the system design, and
4) *Inexpensive* to implement.

Hopp and Spearman (2000) compare pull systems with traditional push systems in terms of production planning and control:

1) **More Efficient:** same throughput rate with less average WIP.
2) **Easier to Control:** rely on settings of easily observable WIP levels rather than release rates.
3) **More Robust:** performance degrades much less than the push system by a comparable percentage of error in release rate.
4) **More Supportive of Improving Quality:** the low WIP levels require high quality to prevent from disruptions.

As to the overall advantages of implementing lean manufacturing, Callen et al. (2000) carry out a plant-level cross-sectional analysis to analyze the performance of JIT and non-JIT plants. Advantages of JIT plants against non-JIT plants are listed below.

1) Significantly less WIP and finished goods inventory.
2) Significantly lower variable cost and total cost.
3) Significantly more profitable.
4) JIT plants that adopted JIT earlier are more successful at reducing WIP, minimizing costs, and maximizing profits.
5) JIT plants with better process quality are more successful in minimizing WIP and finished goods inventories.

In general, the benefits from implementing lean concepts can be transferred into a higher customer satisfaction level by providing products with lower cost, shorter lead time, and more stable quality. Consequently, the lean practitioners can remain competitive in the marketplace.

Despite of the advantages discussed above, a few drawbacks and limitations of lean implementations were identified by previous research. First of all, the drawbacks of becoming lean by implementing a pull system are pointed out by Sipper and Bulfen (1997):

1) **Myopic:** Pull systems do not plan well for future events.
2) **Reactive:** Pull systems do not operate well under great variations of demand.

3) **Lack of Tracking:** Pull systems cannot perform lot tracking, such as pegging a lot for a customer.

As a result, the advantages of becoming lean are compromised when the demand fluctuates and/or the number of custom orders increases. Furthermore, the types of manufacturing systems are also factors that determine the effectiveness of lean implementations. Several observations made by previous research are summarized as follows.

1) **For High Product Variety and Low Volumes (HVLV) Environment:** Jina et al. (1997) point out the difficulties to apply lean principles to HVLV environments. Turbulence is the major cause of the difficulties. Four types of turbulence are identified which cause the major impacts on lean implementation in HVLV environments. They are the turbulences in *schedule, product mix, volume,* and *design*.
2) **For Repetitive and Non-repetitive Systems:** White and Prybutok (2001) conduct an empirical study on the relationship between lean practices and the type of production systems. The findings of this research show that lean practices are less likely to be implemented in the non-repetitive systems than in the repetitive systems, although the benefits from implementing most of the lean practices do not differ significantly between the two systems. The cause of the lower implementation rate in non-repetitive systems was suggested by the authors that the lean practices were designed in and have their roots in a repetitive production system, namely Toyota.
3) **For Small and Large Manufactures:** Another empirical study conducted by White et al. (1999) suggests that large manufacturers are more likely to implement lean practices than small ones. Only the lean practice, *multifunction employee*, is more likely to be implemented by small companies. The results also show that the performance of both small and large manufacturers improved significantly because of the lean implementation. Further investigations were

suggested to help small firms to implement lean practices in order to compete more successfully.

4) **For Small and Medium Enterprises (SMEs):** Ramaswamy et al. (2002) investigate the issues of implementing lean practices in the SMEs. The results suggest that *buffer stock removal* and *lot size reduction* are the most important issues for SMEs, and the *multifunctional workers* and *preventive maintenance* are least important. The authors pointed out a finding that the SMEs trying to implement several lean initiatives simultaneously did not show remarkable improvement over a period of time. Therefore, lacking of a well structured implementation plan for SMEs may be the reason that lean practices are less likely to be employed by SMEs.

Based on the review of past research, it can be concluded that the implementation of lean manufacturing tools and techniques can bring forth remarkable improvements to various type of manufacturing systems. However, the benefits are limited when the demand changes dramatically in volume and product mix. Thus, the agile manufacturing strategy was developed to complement the weakness of being lean.

2.1.3 Agile Manufacturing

The concept of *Agile Manufacturing* provides a different approach from lean manufacturing to seeking for competence in the marketplace. While lean principles are helping manufacturers to achieve lower cost, shorter lead time and better quality, it is expected that the customers will want more. A common opinion shared by industry leaders in the 1990’s was that the challenge of running business in the 21st century is to provide high-quality, low-cost products, and “be responsive to customers’ specific unique and rapidly changing needs” (Gunasekaran and Yusuf, 2002). Sanchez and Nagi (2001) describe the context of the origin of agile manufacturing which initiated in 1991 as follows. A report put together by a research group, the *21st Century Manufacturing Enterprise Strategy*, describes how US industrial competitiveness would evolve during the next 15 years. Based on this effort, an *Agile Manufacturing Enterprise Forum* was formed at the Iacocca Institute at Lehigh University in 1991, which published the above mentioned report and introduced the term “Agile Manufacturing” for the first time. Katayama and Bennett (1990) state that the objective of agile manufacturing is to cope with demand volatility by making changes in an economically viable and timely manner. They also pointed out that the principles of agility are equally applicable to other sectors of a business although the word “manufacturing” is used.

Unlike lean principles, agile manufacturing aims for unexpected situations. The goal is to respond swiftly to demand changes and hence gain the market before competitors can react (Goranson, 1999). Therefore, being agile is more advantageous than being lean in terms of surviving in the volatile, customer-driven environment (Yusuf and Adeleye, 2002). How agile a system can be is represented by the “agility.” Gunasekaran and Yusuf (2002) review various definitions of agility given by previous researchers and concluded that the agility in manufacturing system may be defined as:

> *The capability of an organization, by proactively establishing virtual manufacturing with an efficient product development system, to (i) meet the changing market requirements, (ii) maximize customer service level and (iii) minimize the cost of goods, with an objective of being competitive in a global market and for an increased chance of long-term survival and profit potential.*

The authors further state that the agility must be supported by the flexibility of people, processes and technologies. To achieve a high agility level, the system must focus on *strategic planning*, *product design*, *virtual enterprise*, and *automation and information technology*. Among the four enablers of agility, the *Virtual Enterprise* is a unique concept that distinguishes agile manufacturing from the other strategies.

The formation of a virtual enterprise is based on temporary partnership between companies or facilities. When a new demand appears, a virtual enterprise is formed with a group of companies who are capable of handling the demand. When the demand is met, the partnership is dismissed at the same time. It is an important technique to dramatically increase the flexibility of a supply chain, and thus, enhance the agility. Goranson (1999) introduce a framework of the *Agile Virtual Enterprise* together with a performance measurement model. Goldman et al. (1995) uses the term *Virtual Organization* to present the importance of virtual partnership in agile manufacturing. Similar to the virtual enterprise that is applied in the supply chain level, an approach named *Virtual Cell* was developed to increase the agility of manufacturing systems in the shop floor level (Babu et al., 2000; Baykasoglu, 2003).

Several measures to evaluate the level of agility have been proposed previous by researchers. The measures can be categorized into three types.

1) **Qualitative Assessment:** Using survey questionnaires, the agility level is evaluated by qualitatively assessing the performance of the system based on a set of predefined agility indicators. Examples include the surveys developed by Ramasesh et al. (2001) and Jackson and Johansson (2003). The assessment approach evaluates how close the system is to the suggested agile guideline, which may not be suitable for every system. Also, the result of qualitative survey is subjective.
2) **Attribute Measurement:** The agility level is evaluated by measuring some of the attributes of agility. Examples include the "sensitivity of productivity" used by Helo (2004), and the "complexity index" developed by Arteta and Giachetti (2004). This type of measure may be biased since the attribute may not be able to fully represent the agility level. For example, increasing the complexity of a system may cause unexpected situations and actually lower the agility level.
3) **Target Fitness:** The agility level is measured as the capability to change the system in order to meet a set of potential situations. Examples include the "*reference model*" developed by Goranson (1999), and the "state variable based performance metrics" used by Sieger et al. (2000) This type of agility measure needs a sophisticated methodology to determine the appropriate "targets" in order to validate the measurement. However, since the targets are picked by the model users, the measure may not be representing the real agility to cope with unexpected situations.

Beside of the issues associated with the three types of measures, Goranson (1999) points out that agility may not be represented by a 0 to 1 scale which is commonly used by performance metrics, such as efficiency and quality. The reason is that the absolute target is not available. In other words, the state of 100% agile cannot be defined since product variety and fluctuation of demand have no limit. As a result, no value obtained from an agility measure can be interpreted correctly. Therefore, instead of trying to measure the agility direction, it would be more reasonable to aim for an uncertainty level (i.e., the demand pattern) and evaluate the capability to satisfy this demand agilely.

2.1.4 Between Lean and Agile Strategies

The relationship between lean and agile strategies has been intensely discussed by researchers. As mentioned by Goranson (1999), some earlier researchers think that agile and lean strategies are the same, while the other argue that agile manufacturing is an advance of lean concepts. The author clarifies that the two strategies do have their difference. Being too agile may harm the leanness of the system, while being too lean could also reduce the agility level. Using an analogy to human body, Radnor and Boaden (2004) utilize the word "*anorexia*" to describe the problem of a system that is too lean. The *corporate anorexia* was referred to the inability to utilize or balance the facets/resources of the organization effectively. The cause of the anorexia is being too lean that the leanness level has gone beyond the "fitness" for the organization. In an effort to develop a benchmark for lean initiatives, Comm and Mathaisel (2000) also point out that the target of being lean is not "skinny or anorexic," but that being lean is being "fit." In terms of lean and agile, the improvement efforts should aim at enough of agility (leanness) while improving the other.

Mason-Jones et al. (2000a) summarize the distinguishing attributes of lean and agile strategies concerning 11 aspects. Based on this summary, lean manufacturers typically aims for predictable demands with low variety, long product lifecycle, and lower profit margin. On the other hand, agile manufacturers demonstrate their core competencies on volatile demand with high product variety, short product life cycle, and higher profit margin. Similarly, Yusuf and Adeleye (2002) summarize the essential difference between lean and agile manufacturing based on 12 factors. Although conflicts exist between the two strategies, researchers also point out that the two strategies are not mutually exclusive (Aitken et al., 2002). Instead, they should be mutually supporting (Katayama and Bennett, 1999). For manufacturing system in reality, the demand pattern is normally neither extremely stable nor extremely volatile. In order to maximize the competence, a manufacturing system should be benefited from both lean and agile strategies. Different methodologies were developed to make a system lean and agile at the same time. Three major approaches are listed in Table 2.1 with detailed discussions following that.

Table 2.1 Approaches to Achieving Leanness and Agility Simultaneously

Approach	Description
Virtual Group	Applying *Virtual Cells* on functional layout
Safety Stock	Balancing between inventories and disturbances
Leagile Supply Chain	Positioning the decoupling point

The first methodology considers the flow of material. Prince and Kay (2003) introduce the concept of virtual group to combine the lean and agile characteristics. The virtual group is an application of virtual cells with functional layout. Similarly, other research on virtual cells and virtual enterprises also inherits the characteristics of both lean and agile strategies.

The second methodology to integrate lean and agile strategies is the use of safety stock. Svensson (2003) investigate the relationship between companies' inventories and disturbances in logistics flow. It is suggested that the supply chains need to be agile while striving to be lean. A balance between the inventories and disturbances is the objective, but the approach to achieving the balance is not provided in this paper.

The third methodology is a "*leagile*" system that uses a decoupling point to separate a supply chain into lean upstream section and agile downstream section. The term "*leagility*" was first introduced by Naylor et al. (1999). In this paper, the meaning of agility and leanness are reexamined, the function of a decoupling point in a supply chain is investigated, and the term leagility is coined. Mason-Jones et al. (2000b) summarized the elements of the leagile system as below.

Agility: *Use market knowledge and a virtual corporation to exploit profitable opportunities in a volatile marketplace.*

Leanness: *Develop a value stream to eliminate all waste, including time, and to ensure a level schedule.*

Leagile: *Combining the lean and agile paradigms within a total supply chain strategy by positioning the decoupling point so as to best suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the marketplace.*

Decoupling Point: *The point in the material flow streams to which the customer's order penetrates. It is the meeting point of the order-driven and the forecast-driven activities. It coincides with a main stock point, from which the customers are supplied.*

Therefore, using a decoupling point as a buffer, the upstream section of the supply chain can produce to a leveled rate while the downstream section is pulled directly by the customer demand. Thus the system combines the characteristics of both lean and agile. Because of the safety stock at the decoupling point, Van Hoek (2000) argues that the thesis of leagility challenges lean thinking in terms of efficiency and waste elimination. Nevertheless, considering the "fitness" of the system to the demand, sacrificing part of the leanness to keep the agility can be justified.

In summary, in order to be lean and agile simultaneously, *safety stock* (WIP or finished goods) is necessary for the agility in production volume, and *flexible routing* or machine grouping is helpful to the agility in product mix. In the view of waste reduction in manufacturing systems, setups required by flexible routing can be reduced as much as possible with proper designs of system layout, fixture, product design, and worker training. However, safety stock cannot be eliminated because of the uncertainty of demand. Consequently, the waste of waiting is inevitable to a lean and agile system when the demand is not stable. Therefore, internally, WIP results in delays at the decoupling point. Externally, finished goods inventory also results in delay. These observations form the foundation for the proposed methodology of leanness target identification introduced in Chapter 5.

2.2 Measuring Leanness

Numerous tools and techniques have been developed to eliminate wastes and enhance leanness of manufacturing systems. However the needs to evaluate the level of leanness did not receive comparable attention. Little effort was committed to the development of leanness measures. A possible reason is that the meaning of leanness was not well defined. This review starts with the definition of leanness of manufacturing systems. After that, previous research on leanness measurement is reviewed in three categories, namely *Quantitative*, *Qualitative*, and *Graphical* measures.

2.2.1 Leanness of Manufacturing Systems

The term *Leanness* has been used by several researchers while discussing on lean manufacturing. However, the perceptions of leanness found in the literatures differ from one author to another. Their opinions are reviewed in this section.

A definition of leanness is given by Naylor et al. (1999) while introducing the concept of "leagility." As shown in Section 2.1.4, "leanness" was used to describe a process of implementing lean principles. This definition was quoted several times by the proponents of leagility (Christopher and Towill, 2000; Mason-Jones et al., 2000a and 2000b; Towill and Christopher, 2002). Comm and Mathaisel (2000) describe leanness as a relative measure of whether a company is "lean" or not. They also stated that "leanness is a philosophy intended to significantly reduce cost and cycle time throughout the entire value chain while continuing to improve product performance." The term "total leanness" was used by McIvor (2001) to imply a perfectly lean state of several key dimensions of lean supply. The definition of leanness was not stated explicitly. Soriano-Meier and Forrester (2002) develop a model to evaluate the degree of leanness of manufacturing firms. In the model, the "Degree of Leanness" is the mean value of nine variables suggested by Karlsson and Ahlstrom (1996). The nine variables are developed to assess the changes toward lean production, and the degree of leanness assesses the adoption of lean production practices concerned with work organization in the production and operation function. Finally, Radnor and Boaden (2004) attempted to outline the concept of leanness by reviewing the previous uses of the word. In the review, "leanness" is interpreted as an ideal state of lean, a context-dependent process, an ideal to be pursued, a condition of being lean, a particular state of the relationships between the facets of a system, or a journey to the ideal. A definition of leanness was not concluded in this paper, and the attempt to outline the concept of leanness led to confusion because of the diversity the various interpretations.

In summary, the meaning of leanness was interpreted in various ways by previous researchers. One finding from the review is that the terms "leanness level" or "degree of leanness" are used more often than "leanness" itself. Since the leanness of a system can be represented as levels, a reasonable conclusion of the diversified opinions is that "leanness level" is the state of a system which is in the range between the worst and perfect. Therefore, the leanness level of a system can be defined and measured by comparing the current state with the worst case and the perfect case. Thus, the level of leanness can be quantified.

2.2.2 Qualitative Leanness Evaluation: Lean Assessment Approaches

Various lean assessment surveys have been suggested by the books that guide readers through the implementation of lean manufacturing (Connor, 2001; Feld, 2000; Jordan et al., 2001). The surveys are used to help the readers evaluate the degree of adoption of the lean principles. Results of the surveys are often shown as scores presenting the differences between the current state of the system and the ideal conditions predefined in the surveys.

Scores obtained by the surveys provide an overview of the level of leanness and indicate the percentages of completion of the suggested lean indicators. However, the predefined lean indicators may not be appropriate for every system. The leanness score obtained from a survey is only an evaluation of the compliance between the system and the lean indicators, instead of a quantitative score representing the real level of leanness. Besides, the responses to the questionnaire are inevitably subjective. The results of the surveys could be biased.

A dynamic assessment approach proposed by Wan and Chen (2006b) applies different templates of lean indicators to different systems adaptively. The dynamic assessment approach evaluates leanness level of a system based on a set of lean indicators that are suitable for the system. A web-based tool is developed to perform the selection of templates and the lean assessment. Leanness scores and improvement suggestions are generated after the survey is completed. One difficulty of carrying out this approach is that a large amount of templates for various environments need to be developed and updated continuously. This weakness limits the effectiveness of this approach.

Beside the lean assessment surveys suggested by books for lean implementation, there is an assessment model developed by Karlsson and Ahlstrom (1996) to assess the changes of a system towards lean production. Nine groups of "measurable determinants" were employed to measure the progress of lean implementation. Based on this model, Soriano-Meier and Forrester (2002) proposes another model to evaluate the degree of leanness of manufacturing firms. Similar to the previous models, this model evaluates the "Degree of Adoption" of nine variables of leanness to be the leanness score.

Sanchez and Perez (2001) further developed a check-list of 36 lean indicators in six groups to assess the changes towards lean. Although the indicators or determinants were designed for qualitative evaluation, the survey type assessment is inevitably subjective and still provides only rough estimates of the characteristics of leanness. Furthermore, the suggested lean principles, indicators, and determinants are not necessarily the best choices for various industries, and they may be outdated when technology or management techniques advance dramatically.

2.2.3 Quantitative Leanness Evaluation: Lean Metrics

Lean metrics are the performance measures that are used to track the effectiveness of lean implementation or continuous improvement. Allen et al. (2001) summarize a collection of lean metrics categorized in four major groups, i.e., *Productivity, Quality,* *Cost, and Safety*. In each group, several lean metrics are suggested, such as “changeover time” in *Productivity*, “yield and “scrap” in *Quality*, “material” and “labor” in *Cost*, and “injuries” in *Safety*. Usually, a group of lean metrics are applied simultaneously. Each metric is developed to evaluate the progress of improvement in a specific area. In other words, a lean metric measures only a fraction of the overall leanness. A group of lean metrics may be able to outline the overall leanness, but appropriate metrics must be selected and synthesized into an integrated indicator of leanness. The Balanced Scorecard (BSC) developed by Kaplan and Norton (1992) is a common method to select and synthesize the performance measures for the decision making on improvements. However, the scores provided by BSC indicate the progress of improvements instead of leanness, and the target of full score changes when the BSC is reviewed. Therefore, a benchmark for each lean metric or for the synthesized measure is needed if the level of leanness is measured using the lean metrics.

Among the existing lean metrics, a measure of *Manufacturing Cycle Efficiency* (MCE) was introduced as a lean metric for cycle time reduction (Levinson and Rerick, 2002). The MCE compares value-adding time with total cycle time to show the efficiency of a manufacturing process.

$$MCE = \frac{Value - adding \quad Time}{Total \quad Cycle \quad Time}$$

This metric is commonly used by lean practitioners to get a picture of how lean a manufacturing cycle is in terms of time efficiency. A MCE scored under 5% is not uncommon, which urges lean practitioners to perform setup reduction. However, the MCE cannot fully represent the leanness of the process because of two reasons. The first reason is that MCE only considers time efficiency. Wastes occurred on other resources were not included. The other reason is that the traditional MCE measure can be misleading. Fogarty (1992) points out that MCE grossly overestimates manufacturing efficiency because it measures the VA time in batches without considering the waiting time of individual work piece. An alternative measure, the *Value Added Efficiency* (VAE), was introduced to correct this problem. The VAE is calculated by dividing the processing

(VA) time of a work piece by the manufacturing lead time for that work piece. The result of this modification reinforced the needs to reduce the wastes in the manufacturing processes. Although the VAE still lacks attention on the wastes of other resources, the powerful concept of VAE becomes a foundation for the proposed methodology of leanness measurement.

Beside of the lean performance metrics, Katayama and Bennett (1999) point out that "*labour productivity*" was once used as a measure of leanness. It was argued that this measure could mislead the decision makers to over invest on automation and ignore the other benefits of leanness. However, the paper did not offer a substitute for the measure of leanness. In a research of manufacturing competitiveness, Leung and Lee (2004) identify "*operation leanness*" and "*new-value creativeness*" as the two principal competencies of manufacturing firms. The operational leanness is defined as the "performance" reflecting the competencies of a manufacturing firm by "utilizing its input in more efficient ways." The way to achieve "*operation leanness*" is to eliminate wastes from the system. The seven types of wastes in TPS are categorized into three principal types of wastes to be eliminated. Yet, no quantitative measure of leanness was presented in the paper.

In summary, an effective measure that can quantify the level of leanness has not been developed. A leanness measure is needed which can synthesize the various aspects of the overall leanness into an integrated measure. Also, a benchmarking methodology is needed to derive a meaningful value that represents the level of leanness.

2.2.4 Graphical Leanness Evaluation: Value Stream Mapping

Value Stream Mapping (VSM) is a graphical tool that maps out the process of a system with a selected granulation in a selected scope. The tool was developed by Rother and Shook (1998) and published in the book *Learning to See*. The tool itself does not provide a quantitative measure of the level of leanness. Instead, the graphical representation of the manufacturing processes visualized the value-adding activities and wastes in the system. As stated by the authors:

> *"It is much more useful than quantitative tools and layout diagrams that produce a tally of non-value-added steps, lead time, distance traveled, the amount of inventory, and so on. The VSM is a qualitative tool by which you describe in detail how your facility should operate in order to create flow. Numbers are good for creating a sense of urgency or as before/after measures. Value stream mapping is good for describing what you are actually going to do to affect those numbers."*

A current VSM and a future VSM are generated when an improvement project starts. The current VSM graphically shows the level of leanness of the current system, and the future VSM, serving as a target of improvement, is the benchmark of the leanness level. By comparing the maps of the two stages, it can provide answers to the questions "*how lean is our system*" and "*how lean can it be*". From there, improvement tactics can be made to guide the actions to reduce wastes and change the system toward the proposed future state. The maps are reviewed periodically to track the progress of improvement and determine whether the two maps need to be redrawn.

In *Learning to See*, a sample case of manufacturing system is used to illustrate the procedures of creating the maps. Duggan (2002) introduces detailed procedures to apply the VSM on mixed model production. In fact, the VSM has the potential to be applied to various types of value streams, including non-manufacturing systems. As long as the inputs/outputs and the internal processes of a system can be defined, the VSM technique can be applied.

In the sense of leanness measurement, VSM does not provide a synthesized quantitative measure like the lean assessment or lean metrics. To compliment this weakness, Allen et al. (2001) develop a VSM *Calibrate* that shows the results of leanness assessment on a radar chart. A current state calibrate and a future state calibrate are generated based on the two stages of VSM. Thus, the gap between current state and future state can be shown with measurements.

Since average numbers are employed to represent the time frames of the flow in the value stream, the difference between individuals cannot be shown in the map. It reduces the power of the VSM because the average numbers can deceive the real conditions and mislead the decision makers. Another weakness of the VSM is that "cost" is not shown explicitly, since it is created strictly based on the time frames of the processes. Although the other resources, such as material and labor, are included in the map, it is difficult to identify the overall cost of a process merely from the map. Therefore, complementary figures or tables must be provided if the VSM is used as a representation of leanness level.

2.3 Data Envelopment Analysis (DEA)

In this research, a methodology is developed to measure the leanness level of manufacturing systems. As discussed in previous sections, an effective measure of leanness should be able to integrate the different aspects of the leanness, and a benchmark need to be identified for the measure. The Data Envelopment Analysis (DEA) is capable of analyzing multiple input/output variables and identifying a benchmark based on each data set. With these features, the DEA model appears to be a suitable tool for the leanness measurement. This section reviews the concepts and models of DEA. Also, the issues of applying DEA in the leanness measurement are discussed.

2.3.1 Overview of Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a methodology developed for performance measurement. It identifies the best practices of Decision Making Units (DMU) and determines the production frontier accordingly by solving a mathematical program based on historical data. The concept and the mathematical model are first introduced by Charnes et al. (1978). The production frontier identified by the model envelopes all DMUs of the data set and serves as the performance benchmark for each DMU. The efficiency of the DMU can then be evaluated by calculating the distance from the DMU to its benchmark. The components of a DEA Model are listed below.

1) **Decision Making Units (DMUs):** objects of the observation
2) **Input Variables:** resources consumed by a DMU

3) **Output Variables:** products or services delivered by a DMU
4) **Transformation Processes:** the procedure that transforms inputs into outputs

A simplest form of *performance measure* or *efficiency* is the ratio between output and input (Boussofiane, 1991). When multiple inputs and outputs are considered simultaneously, the efficiency measure can be formulated as:

$$\text{Efficiency} = \frac{\text{Weighted sum of outputs}}{\text{Weighted sum of inputs}}$$

Based on microeconomic theories, a system is more productive if it can produce more output(s) with a same or less input level. Therefore, an *Input-oriented* DEA model evaluates the inefficiency of a system based on the extent that the input variable(s) can possibly be decreased while producing the same level of output(s). On the other hand, the *Output-oriented* DEA model addresses the inefficiency of a system by determining the extent that the output variable(s) can possibly be increased while using the same level of input(s). The relationships between the efficient DMUs, inefficient DMUs, and the Technical Efficiency Frontier are shown in Figure 2.1 with two different scenarios. Cases with higher dimensions (more input/output variables) are difficult to be presented graphically, but they can be solved by mathematical programs.

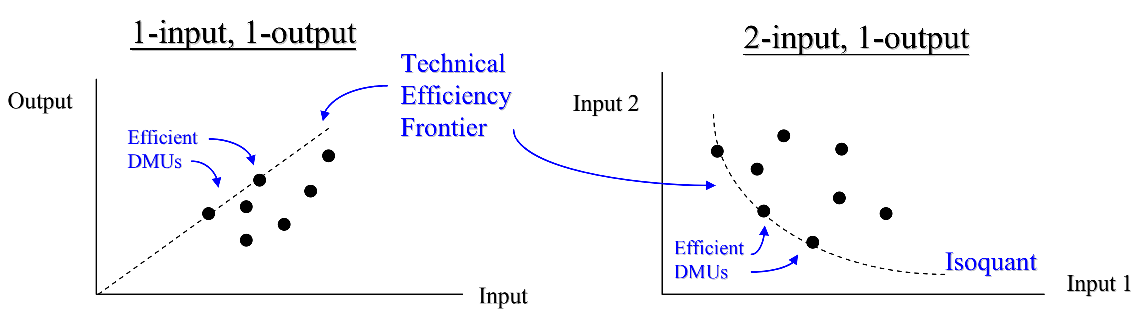


Figure 2.1 DMU versus Technical Efficiency Frontier

In the DEA model, the production frontier and efficiency scores are determined using a mathematical that addresses the weighted multiple inputs and outputs. The

2.3 Data Envelopment Analysis (DEA)

Charnes-Cooper-Rhodes (CCR) model is introduced by Charnes et al. (1978) as the first mathematical model for DEA.

$$\text{Max } h_0 = \frac{\sum_{r=1}^{t} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \quad (1)$$

$$\text{Subject to } \frac{\sum_{r=1}^{t} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, j = 1,2,...,n \quad (2)$$

where u, v, x and y are all nonnegative variables.

<u>Notation of CCR Model:</u>

h_0: Efficiency score of DMU_0

x_{ij}: Input variable i of DMU_j

y_{rj}: Output variable r of DMU_j

n: Number of DMUs

v_i: Weight for input variable i

u_r: Weight for output variable r

m: Number of input variables

t: Number of output variables

Due to the difficulty of solving the fractional mathematical program, the model is later transformed into an equivalent linear program as following (modified from Boussofiane et al., 1991):

$$\text{Max } h_0 = \sum_{r=1}^{t} u_r y_{r0} \quad (3)$$

Subject to

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \quad (4)$$

$$\sum_{r=1}^{t} u_r y_{rj} \leq \sum_{i=1}^{m} v_i x_{ij}, j = 1,2,...,n \quad (5)$$

where u, v, x and y are all nonnegative variables.

Thus, the DEA model can be solved by linear programming techniques, and the frontier and the efficiency score of each DMU can be determined accordingly. In the solution, the weights for the Input/Output variables of each DMU are derived by the DEA model which maximizes the efficiency score of the unit. Therefore, the weights also imply the sensitivities of the variables.

The empirical frontier determined by the DEA model is composed by the best practices. The projection of each DMU on the frontier is either a best practice unit or a linear combination of a set of best practice units. These best practice units are known as *peers* or *reference set* of the DMUs. As a result, each DMU can be represented as a convex combination of a set of peer DMUs, and the frontier "envelops" all the DMUs in a convex hall. By analyzing the relationships between each DMU and its peers, the DEA model determines the efficiency score of each DMU based on the distance to the benchmark frontier. It also suggests realistic goals of efficiency in different aspects for each DMU. The routes from the DMU to the goals of efficiency can be identified as the potential improvements to reach the highest efficiency. Based on the directions of potential improvements, decision makers can look into the details of the transformation processes, so that the causes of inefficiency can be identified and avoided. Thus the highest efficiency can be achieved in future practices.

The features of the basic DEA modeling are summarized below.

1) DEA evaluates "Efficiency" of previous operations without outsourcing for benchmark.
2) DEA is capable of analyzing multiple input/output variables.
3) DEA provides "dimension-free" efficiency scores that can be easily compared.

2.3.2 Mathematical Models of DEA

The CCR model introduced in the previous section is the original model of DEA. Two types of CCR model can be formulated based on the direction of improvement (Cooper et al., 2000).

Input-oriented CCR (CCR-I) model: aims at reducing the input amounts by as much as possible while keeping at least the present output levels.

Output-oriented CCR (CCR-O) model: maximizes output levels under at most the present input consumption.

Some other DEA models were developed for different situations. Cooper et al. (2000) summarize the features of the models as follows.

Banker-Charnes-Cooper (BCC) Model: defines the production possibility set by means of the existing DMUs and their convex hull. An efficiency value is given which is not less than the CCR model.

Additive Models: deal with input excesses and output shortfalls simultaneously.

Slack-Based Measure (SBM) of efficiency: deals with the input excesses and output shortfalls and use the Additive Model to give a scalar measure ranging from 0 to 1 that encompasses all of the inefficiencies that the model can identify.

Among the different models, BCC model can also have the options of either Input-oriented or Output-oriented. The Additive Model and SBM Model encounter the slacks in the linear program, which are the input excesses and output shortage. The efficiency scores derived from CCR and BCC models does not encounter the slacks. However when slacks exist, the actual efficiency is lower than the score. Therefore, when the output results of a data set contains large amount of slacks, the Additive Model or the SBM Model should be considered. More detailed discussions on the slacks can be found in Section 3.2 and 3.3.

The DEA models compare all DMUs in a data set together to determine the efficiency scores. It is considered as a static snap shot of the performances of DMUs in a frozen time frame. In some cases, understanding the changes of the efficiency of a DMU over time is more important. An approach to capturing the dynamics of the performances of DMUs was proposed by Charnes et al. 1985. The "Window Analysis" approach displays the efficiency scores of DMUs in "windows" of time frames. In each window, the performance of each DMU is traced for several consecutive periods of time. Consequently, the performance of a DMU can be compared to other DMUs in each period and meanwhile compared to itself over time. An example of window analysis is listed in Table 2.2. The columns of the table represent the relative efficiency scores of DMUs in each quarter. Each window compares the n branches in three consecutive quarters. A window shifts to the next by adding a new quarter and dropping the earliest quarter from the window. Therefore, the window analysis captures the changes of efficiency over time.

Table 2.2 An Example of Window Analysis with Relative Efficiency (%)

Week	**1**	**2**	**3**	**4**	**5**
Line 1					
Window 1	51.3	60.2	64.1		
Window 2		85.4	72.5	91.2	
Window 3			83.7	100	78.6
Line 2					
Window 1	93.5	92.6	100		
Window 2		83.4	100	88.2	
Window 3			95.4	70.7	85.5
Line 3					
Window 1	100	80.0	74.9		
Window 2		100	82.2	100	
Window 3			93.2	85.7	100

2.3.3 Measuring Leanness with DEA

According to the literature review of leanness measurement, an effective measure of leanness has not been developed. The measure must be able to synthesize the various aspects of the overall leanness into an integrated measure. Also, an appropriate benchmark for leanness is not always available. Furthermore, the technology frontier changes continuously over time, and the benchmark needs to be updated accordingly. With the features of DEA model, these difficulties can be resolved. Using the DEA model to measure leanness, the benchmark can be identified from historical data and the frontier can be updated whenever new observations become available. Therefore, DEA appears to be a suitable tool for leanness measurement.

However, DEA determines the "*best practices*" (the DMUs forming the frontier) as 100% efficient. Since practically no manufacturing system can perform the production tasks without any waste, leanness level of the best practices can never reach 100%. The efficiency score obtained by using DEA is not a reasonable measure for leanness measurement. To adapt the DEA model into an appropriate measure of leanness, a virtual frontier with 100% leanness needs to be identified. A methodology is developed in this research to identify the appropriate leanness frontier and measure leanness level using DEA model. Details of the modification of DEA approach are illustrated in Chapter 3.

In the review of the applications of DEA in leanness measurement, similar adaptation of DEA approach has not been found. Typical applications of DEA such as performance measurement and benchmarking a performance measure are still the major role of DEA in the implementation of lean manufacturing. Only part of this research has been publicly presented at the *Annual Industrial Engineering Research Conference* to demonstrate the concept of measuring leanness with DEA, including the concept of creating Ideal DMUs to obtain an appropriate frontier (Wan and Chen, 2005) and the leanness measure based on SBM model (Wand and Chen, 2006a).

2.4 Summarizing Literature of Leanness

For lean practitioners, the desires to be able to evaluate the level of leanness quantitatively and objectively are not successfully met. The assessment approach commonly used in industry gives a vague impression of the current state of the system based on "what lean initiatives have been applied" and "what other lean initiatives are currently available." A direct measure of leanness is not provided by using this approach. Several lean metrics have been developed to quantitatively evaluate the performance of lean implementation. However, each lean metric only evaluates a fraction of the overall leanness. Moreover, such measurements often evaluate only the progress of improvement without providing appropriate targets for the lean metrics. With the knowledge that leanness should be improved without compromising the desired level of agility, the continuous improvement efforts should aim for a target that does not harm the other source of competence. Consequently, an integrated measure of leanness with an appropriate target should be developed.

The term “leanness” has been described and used in different ways by previous researchers. However, the perceptions of leanness did not converge to a consensus. In order to develop a leanness measure for manufacturing systems, a proper definition of leanness must be provided.

Enhancing competence in the market is a fundamental objective for lean implementation. From a customer’s point of view, the competence of a supplier comes from the performance in three aspects, namely, cost, time, and quality. For a lean practitioner, these three elements of competence are carried out by working efficiently and effectively. The outcome of practicing lean principles gives “leanness” the appearances such as lower cost, shorter lead time, better quality, higher product variety, lower inventory, etc. Various lean metrics were developed to track these effects in order to understand the benefits from implementing lean concepts. However, these effects are the various results of being lean. The root cause of all these effects is waste reduction. The various benefits from implementing lean concepts are the results of reducing waste in different aspects. For example, eliminating wastes in waiting results in shorter lead time. Therefore, the level of leanness can be interpreted as how little “waste” exists in a system.

For a lean manufacturing system, the performance of production relies on the suitability of three elements: (1) a configuration of manufacturing, management and information systems, (2) a design of product to be produced, and (3) a pattern of market demand. Manufacturing systems are normally configured to support a limited range of product mix and volume. Typically, dedicated flow lines do not handle high-variety and low-volume products very well. On the other hand, producing a single product type with high and steady demand in a job shop layout is not as efficient as producing it in a flow line. Therefore, as shown in Figure 2.2, wastes occur when the three elements do not fit to each other.

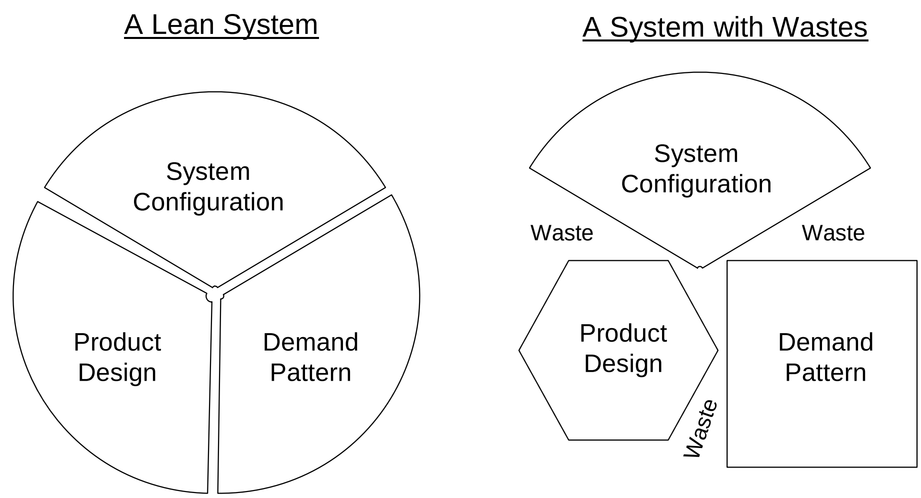


Figure 2.2 Three Elements of a Lean System

A system is lean when the system configuration supports the product design and demand pattern. "Leanness" is the indicator of how little waste exists in a combination of these three elements. In lean thinking, this combination results in a flow of value stream. Therefore, the leanness level of a system can be defined as follows.

Leanness Level: *The performance measurement that indicates how little waste exists in the flow of value stream.*

From another point of view, the measure of leanness represents the maximum extent of possible improvement within a system. As shown in Figure 2.2, improvement of leanness can be possibly achieved by modifying the three elements for a better fitting, e.g., revising the system configuration, changing the product design, or aiming for some other market demand. Lean practitioners have developed various methods and tools to perform the first two changes. The third element, demand pattern, cannot be easily changed by a supplier. Leveling the external demand into a steady production rate is a commonly used technique. However, when the demand fluctuates too much, the lean metrics, such as WIP level, may indicate bad performance which frustrates lean practitioners. Instead of calling off the lean practices or giving up the business opportunity, a target of leanness level that considers the desired agility level to cope with fluctuating demand should be developed.

Chapter 3 DEA-Leanness Measure for Manufacturing Systems

In this chapter, a methodology using DEA technique is proposed for measuring the leanness level of manufacturing systems. As discussed in Section 2.3, the performance score derived from DEA is not equal to leanness score directly. Through a *Cost-Time-Value* analysis, the DEA-Leanness measure creates virtual DMUs to push the frontier towards an ideal state of leanness. Thus the benchmark for leanness score is established. This methodology is explained in Section 3.1 in detail. Following that, two mathematical models (i.e., CCR and SBM models introduced in Section 2.3) are introduced to perform the computation of leanness scores. Due to a weakness of CCR model, the SBM model delivers better results on the application of leanness measurement. Hence, SBM model is selected as the core model of the DEA-Leanness Measure and is employed in subsequent chapters.

3.1 DEA-Leanness Measure

In this section, a methodology combining DEA and Cost-Time-Value Analysis is proposed for measuring leanness level of manufacturing systems. This methodology consists of three major components: Actual DMUs, Virtual DMUs, and a Leanness Frontier. The DEA-Leanness Measure uses virtual DMUs to push the frontier towards ideal leanness in order to obtain a viable benchmark for leanness. Before the DEA-Leanness Measure can be performed, the DMUs must be clearly defined.

3.1.1 Decision Making Units (DMU) of DEA-Leanness Measure

In Section 2.4, leanness level has been defined as the performance of the production flow of a value stream. According to the lean concepts, the ideal case of lean manufacturing is one-piece flow without interruption. Therefore, the leanness level of a system can be measured as the performance of the flow of each work piece. In other words, the DMU for DEA-Leanness should be defined as the work piece that flows through the manufacturing system, and the leanness level of each DMU is calculated by comparing the input-output ratio using the DEA models. Yet different systems or product types consume different resources and deliver different functions or values to satisfy customers. If the input/output variables need to be modified for different scenarios, the leanness measure would not be user-friendly.

Considering the competitiveness in the marketplace, *Cost*, *Time* and *Quality* are the three key performance measures for surviving and winning. Cost and Time are clearly the input variables where decreasing the consumption of them improves the performance. Since the consumption of all types of resources, such as material, labor or energy, can be fully translated into values of cost and time, the two variables are perfect representations for the inputs of the DEA-Leanness Measure. As to the output variable, the narrowly defined Quality of a product does not cover other elements of output, such as service level, customer satisfaction, or on-time delivery. Note that "on-time delivery" is not part of the Time variable because it is the performance of meeting customer's requirement where early shipments are actually not welcomed. Actually, quality problems identified within the manufacturing system lead to rework or scrap, which can be translated into cost and time as input resources. In contrast, the quality problems found by customers after the product are delivered do not increase the cost and time of the production process. Instead, the price may be discounted to compensate the defects (if acceptable), or the customer may express a low satisfaction rating on that product. In other words, a defective product delivers lower *Value* to the customer than originally expected.

Johansson et al. (1993) proposes a "Total Value" metric as follows:

$$Total\ Value = \frac{Quality \times Service}{Cost \times Lead\ \ Time}$$

This ratio has been cited by researchers to represent a performance metric in terms of "*value to customers*" (Naylor et al., 1999; Mason-Jones et al., 2000a). However, the *Cost*, *Time*, and *Internal Quality* issues may not have any effect on a customer's purchasing experience directly. Instead, the factors that really affect the customer's perception of *Value* should be *Price, On-time Delivery or Availability, After-sales Quality* problems, and *Service*. Therefore, the *Total Value* metric proposed by Johansson et al. is defined from a supplier's point of view, instead of a customer's perception.

In the lean concepts, *Value* should be defined by customers. Delivering highest value of products or services to customers is the objective of every business sector. *Lean Thinking* (Womack and Jones, 2005) describes value as the whole experience for a customer to involve with a product or service. Therefore, in order to broadly cover the output results of a DMU, the customer defined *Value* is selected to be the output variable of the DEA-Leanness Measure. The quantitative measure of value is defined as retail price multiplied by customer satisfaction rate.

$$\textit{Value (Customer's point of view)} = \textit{Price} \times \textit{Customer Satisfaction Rate}$$

The Customer Satisfaction Rate should include *On-time Delivery or Availability, After-sales Quality* problems, and *Service*. Thus, *Cost, Time* and *Value* are the three input/output variables of the DMUs for DEA-Leanness Measure.

In Figure 3.1, the formation of a DMU for DEA-Leanness measure is graphically illustrated. The input Costs and Times are summarized from the processes along the value stream, and Value is the final output. In contrast to Critical Path Method (CPM) where components on non-critical paths are often overlooked, the DEA-Leanness Measure aggregates input resources of all components to compare with the final output value so that the wastes of every section of the production process can be identified and improved.

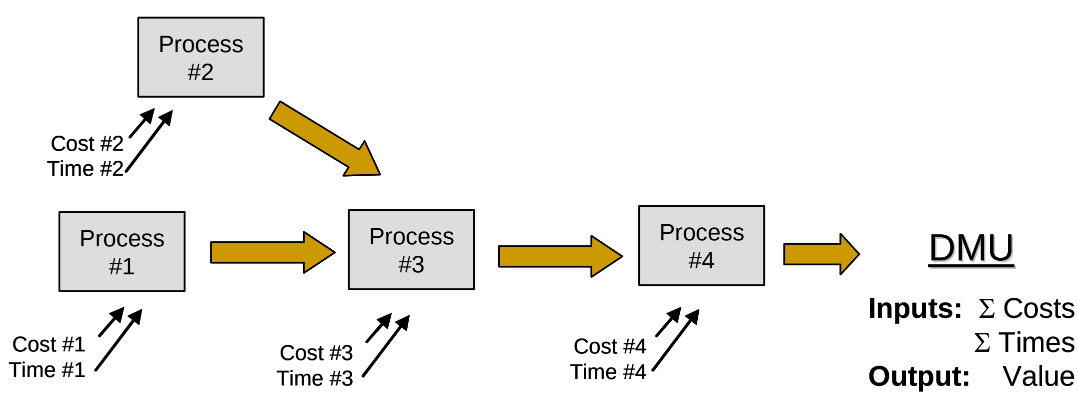


Figure 3.1 Input and Output Variables of a DMU in DEA-Leanness Measure

After aggregating the cost and time data for each DMU, it can be plotted graphically as a data point in a three dimensional chart. Figure 3.2 maps the DMUs under various manufacturing conditions onto the *Cost-Time-Value* space. Comparing to the "Normal Processes," the reworked DMUs deliver same value but require more time and cost investments. Defective and delayed DMUs suffer from a reduction of value, while the scrapped DUMs equate no value at all.

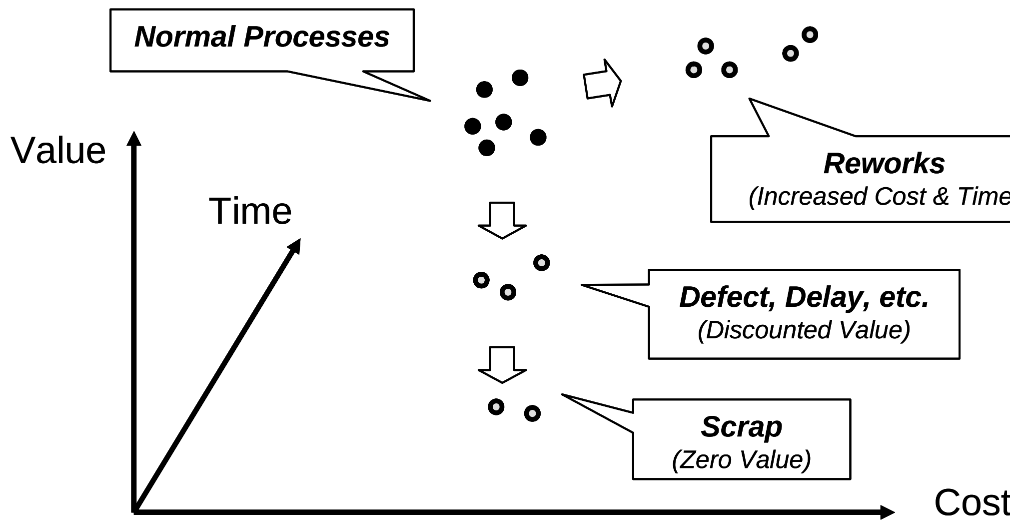


Figure 3.2 DMUs with Various Conditions Mapped in Cost-Time-Value Space

3.1.2 Virtual DMUs and Leanness Frontier

The DEA technique is originally developed for performance measurement. Using DEA, the empirical frontier of efficiency can be identified using existing data. The DMUs are then compared to the frontier to derive efficiency scores. Similarly for the measure of leanness, the benchmark for leanness can be identified from historical data, and the frontier can be updated whenever new observations are available. However, DEA determines the "best practices" (the DMUs on the frontier) as 100% efficient, which may not be a reasonable leanness measurements since there is practically no system performing a production job without incurring any waste. To adapt the DEA approach for the purpose of measuring leanness level, the frontier needs to be pushed further towards a perfectly lean status. In contrast to Actual DMUs (ADMU), the Ideally Lean DMUs

(IDMU) are created virtually in order to push the frontier toward ideal leanness. Figure 3.3 demonstrates this concept by showing the DMUs and different levels of frontiers on a Cost-Time diagram where the DMUs are normalized into same output Value.

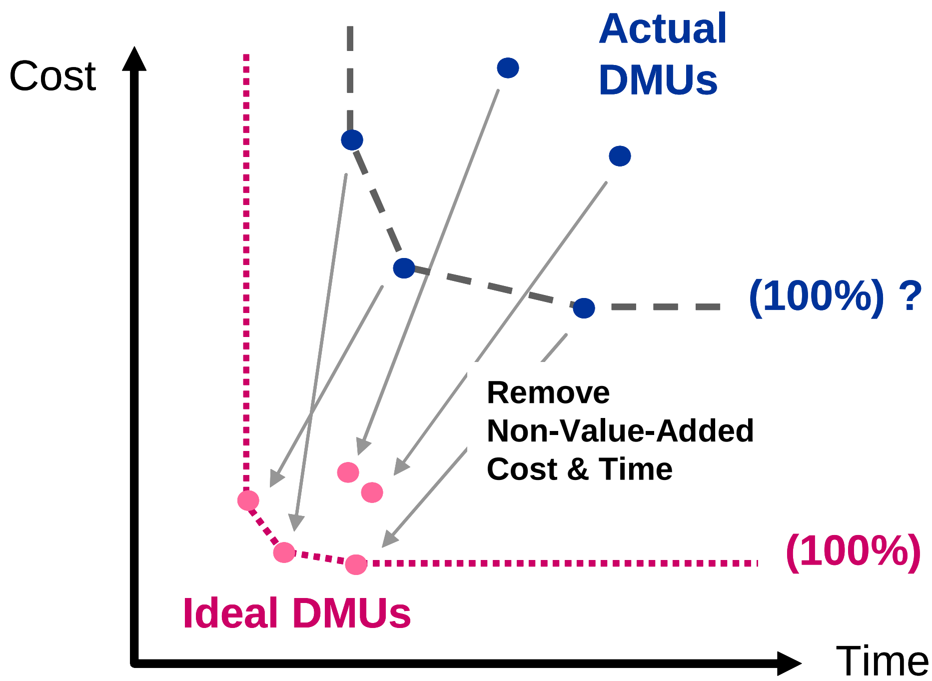


Figure 3.3 Pushing Frontier towards Ideal Leanness by Ideal DMUs

To achieve a reasonable benchmark for leanness, the DEA-Leanness measure pushes the frontier with the IDMUs which represent the perfect condition of the production flow in the same value stream without any waste. That is to consider the Value-Added (VA) inputs only. The input/output variables of the actual and ideally lean DMUs are compared in Table 3.1.

Table 3.1 Actual DMU (ADMU) vs. Ideally Lean DMU (IDMU)

	Actual DMU (ADMU)	**Ideally Lean DMU (IDMU)**
Input Variables	Total Cost Total Time	Value-added (VA) Cost Value-added (VA) Time
Output Variable	Output Value	Output Value

3.1 DEA-Leanness Measure

One of the characteristics of leanness measure is that the benchmark needs to be updated over time. When the technologies of production or management skills improve dramatically, new IDMUs need to push the leanness frontier further to update the benchmark continuously. Therefore, if a frontier is obtained from only one data set, it is possible that the frontier is not close enough to the ideal leanness due to some problems associated with the data set. In order to ensure that the IDMUs are capable of achieving an appropriate benchmark, the following three methods of obtaining IDMUs should be considered.

Methods to Obtain IDMUs:

1) *Virtually created by removing Non-Value-Added (NVA) inputs from the Actual DMUs.*
2) *Obtained from the frontier of previous DEA-Leanness measurements of the same system.*
3) *External benchmark obtained from other industrial group, consultants, etc.*

Mathematical models have been developed for DEA which identify the Empirical Frontier based on ADMUs. The IDMUs obtained from all sources push the frontier toward the origin to become an adequate benchmark for leanness measurement. Figure 3.4 depicts the relationships between the ADMUs, IDMUs, wastes, and different levels of frontiers on the Cost-Time diagram where Value has been normalized into same level. From the *ADMUs* to the *Empirical Frontier*, individual operational inefficiencies are identified, and the best practices (most efficient DMUs) form the frontier which is not really lean. From the *Empirical Frontier* to the *DEA-Leanness Frontier*, wastes that can be identified are removed from each DMU. If all wastes are identified and completely removed, the *Ultimate Leanness Frontier* can be reached by the IDMUs. However, for the production activities in reality, some types of wastes are easier to identify (e.g., waiting or defects), and some other types of wastes may not be easily recognized (e.g., over processing). Since it is difficult to identify all wastes, the ultimate leanness may not be reached by the DEA-Leanness Frontier. A delicate analysis of value-added versus non-value-added activities or a good source of external benchmarks can bring the two frontiers closer. The *Cost-Time-Value Analysis* for building the DMUs is introduced in the next section.

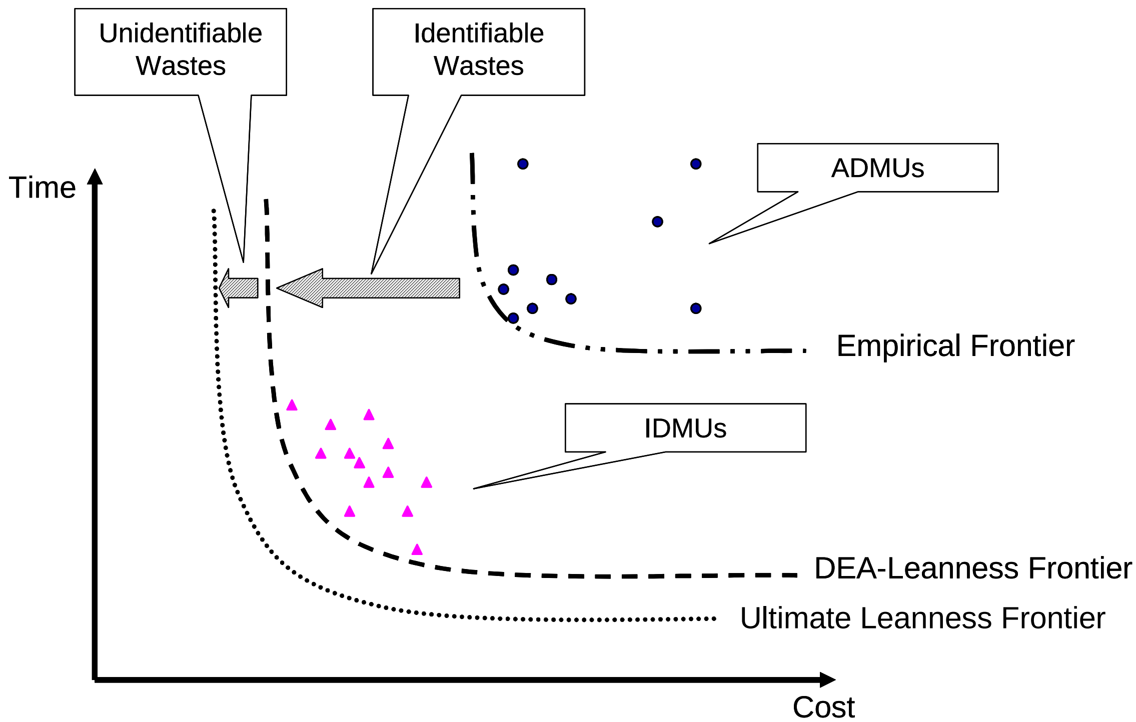


Figure 3.4 Pushing from the Empirical Frontier to the Ultimate Leanness

3.1.3 Cost-Time-Value Analysis

A *Cost-Time-Value Analysis* is developed to create ADMUs and IDMUs from production data. In Figure 3.5, an example of a two-station manufacturing system with three buffer areas is employed to demonstrate the procedure of the analysis. The production processes of each work piece flowing through the system are mapped in the Cost-Time diagram. The diagram differentiates value-added (VA) and non-value-added (NVA) time spans according to the characteristics of the activities. Costs of each time span are identified and differentiated into VA and NVA costs. The ADMUs and IDMUs are then created using the cost, time and value data collected from this analysis. The detailed procedure of the analysis is listed following the figure.

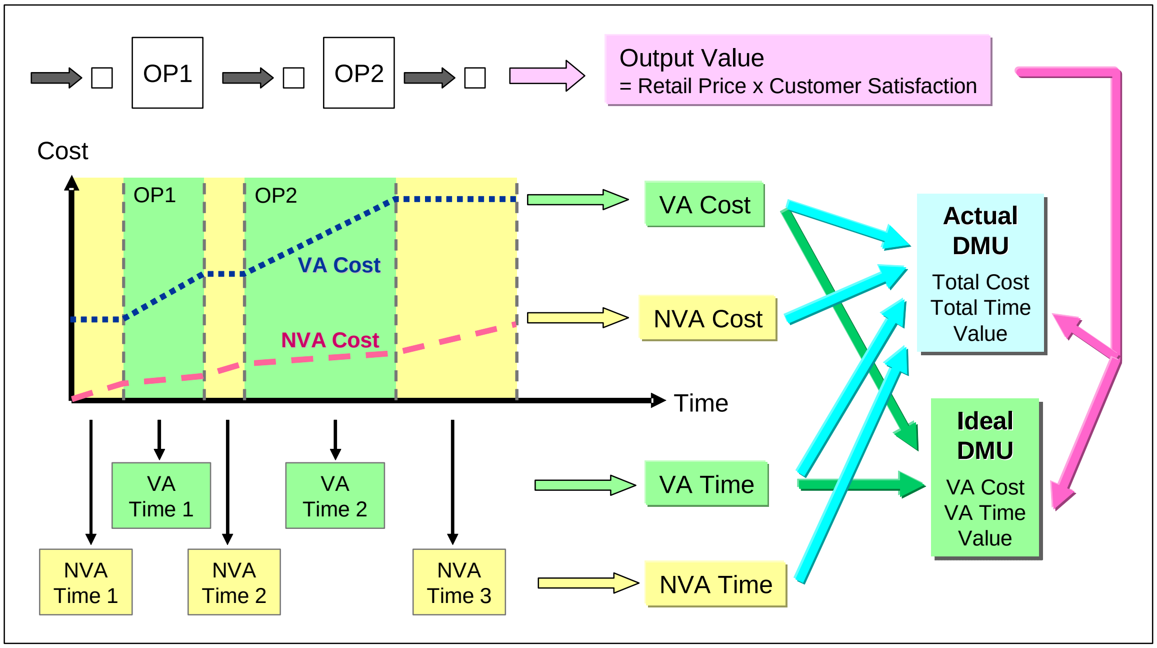


Figure 3.5 Cost-Time-Value Analysis for Creation of ADMUs and IDMUs

<u>Cost-Time-Value Analysis for DMUs</u>

Step 1: **Identify the scope to be analyzed.** In manufacturing systems, the scope can be a cell, a production line, a department, or the whole shop floor, depending on the scope that the Value Stream Map covers.

Step 2: **Map the value stream.** Identify the customer, supplier, workstations (operations), online buffer areas, and offline inventory that are involved in the selected scope of value stream.

Step 3: **Collect cost and time data.** For each work piece that flows through the value stream, record the time and other resources (labor, machine, material, etc.) that are consumed by each production activities.

Step 4: **Identify VA and NVA activities.** Based on the customer defined value and the seven types of wastes in Toyota Production System, differentiate the VA activities from the NVA activities.

Step 5: **Separate VA time and NVA time.** For each work piece, identify the VA and NVA time spans over the total manufacturing lead time.

Step 6: **Identify VA and NVA costs for each time span.** The resources consumed by each process are translated into costs. During VA time spans, VA costs and

NVA costs may exist simultaneously. NVA time spans contain only NVA costs. The two categories of costs are plotted as line segments in the Cost-Time diagram. The final heights represent the accumulated VA and NVA costs.

Step 7: Summarize total costs, total time, and created value to generate ADMUs. An ADMU is an observation of the actual production of a single work piece. The actual time and costs invested on the work piece are the input variables for the ADMU. The created value is the only output variable.

Step 8: Summarize the VA cost and VA time to create IDMUs. An IDMU is obtained from each ADMU by removing NVA costs and NVA time spans from the corresponding ADMU. Therefore, only the VA costs and VA time spans are included in IDMUs.

Step 9: Run DEAL model with the created ADMUs and IDMUs. The two types of DMUs are used in the DEA-Leanness measurement to evaluate the leanness level of the production of each work piece.

For the Cost-Time-Value Analysis, a cost breakdown of each process is required to identify VA and NVA costs. More details being included in the cost breakdown can lead to more accurate evaluation of leanness. Figure 3.6 illustrates a procedure of the cost breakdown for DEA-Leanness Measure. Identifying the costs associated with an individual work piece is not always trivial since some types of cost are shared by a set of work pieces. In order to allocate the costs to each work piece, identifying the aggregated cost of the selected value stream over a period would be a more feasible starting point. The aggregated costs, including material costs and conversion costs, can then be differentiated into Time-based Costs and Unit-based Costs for each work piece. The final values of the cost variable for the DEA-Leanness Measure are obtained by further differentiating the costs based on the VA and NVA time spans in the Cost-Time diagram as shown in Figure 3.6.

After collecting all the required data, the DEA-Leanness Measure can be performed using the mathematical models developed by previous researchers. Two different models are employed in this research which are introduced in the following sections.

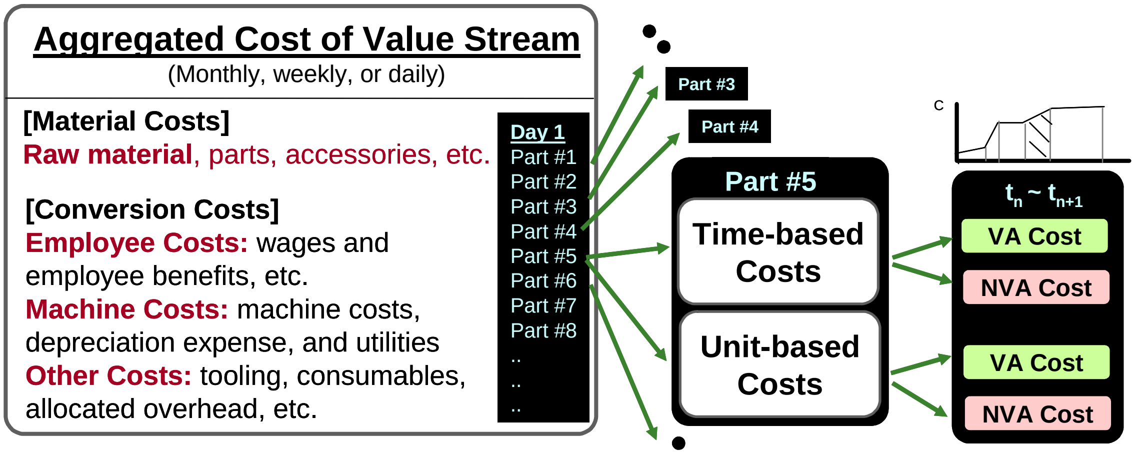


Figure 3.6 Procedure of Cost Breakdown

3.2 DEA-Leanness based on Charnes-Cooper-Rhodes (CCR) Model

As introduced in the literature review, the first mathematical model for DEA is developed by Charnes, Cooper and Rhodes (1978). Since then, various mathematical models have been developed to carry out the performance evaluation of DEA. Due to the simplicity of the original CCR model, it is still commonly used by DEA practitioners. Therefore, this research establishes the proposed DEA-Leanness Measure starting with CCR model. However, due to a weakness of the model, the scores tend to overestimate the leanness level. The development and the problem of DEA-Leanness using CCR model are introduced in this section. In order to eliminate the weakness, another solution is introduced in Section 3.3 which demonstrates better results.

3.2.1 Charnes-Cooper-Rhodes (CCR) Model

As introduced in Section 2.3, the original CCR model is a fractional program that compares inputs with outputs to compute the efficiency score for each DMU. This fractional program can be transformed into an equivalent linear program to simplify the solving process. The original fractional program is listed again together with the linear program as follows.

CCR Fractional Program (FP) (Charnes et al., 1978)

$$\text{Max } h_0 = \frac{\sum_{r=1}^{t} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \tag{1}$$

$$\text{Subject to } \frac{\sum_{r=1}^{t} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, \, j = 1,2,...,n \tag{2}$$

where u, v, x and y are all nonnegative variables.

Notation:

h_0: Efficiency score of DMU_0

x_{ij}: Input variable i of DMU_j

y_{rj}: Output variable r of DMU_j

n: Number of DMUs

v_i: Weight for input variable i

u_r: Weight for output variable r

m: Number of input variables

t: Number of output variables

CCR Linear Program (LP) (Modified from Boussofiane et al., 1991)

$$\text{Max } h_0 = \sum_{r=1}^{t} u_r y_{r0} \tag{3}$$

Subject to

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \tag{4}$$

$$\sum_{r=1}^{t} u_r y_{rj} \leq \sum_{i=1}^{m} v_i x_{ij}, \, j = 1,2,...,n \tag{5}$$

where u, v, x and y are all nonnegative variables.

By including IDMUs, the efficiency score "$\mathbf{h_0}$" of DMU_0 is the "**Leanness Score**," which is the performance measure of the manufacturing system on producing DMU_0.

For each DMU (denoted as DMU_0 when selected) in a data set (DMU_1 to DMU_n), one CCR program is set up to derive the leanness score $\mathbf{h_0}$. Totally, "n" CCR programs are needed to compute the scores of the whole data set, where only the objective function (i.e., Equation (1) in the FP or Equation (3) and (4) in the LP) changes for different DMU targets while constraints remain the same.

Using a 1-Input 1-Output case as in Figure 3.7, the mechanism of CCR model can be clearly demonstrated. First, the ratio between Output (Y) and Input (X) is the slope of the line segments from the origin to each DMUs. Greater slope means more output with same input level and, hence, more efficient. The CCR model scales the two axes so that the maximum slope of all DMUs equals to 1. Then the slope of any DMU in the data set is between 0 and 1, where a higher value means more efficient. Therefore, the performance of each DMU can be represented by the transformed slope.

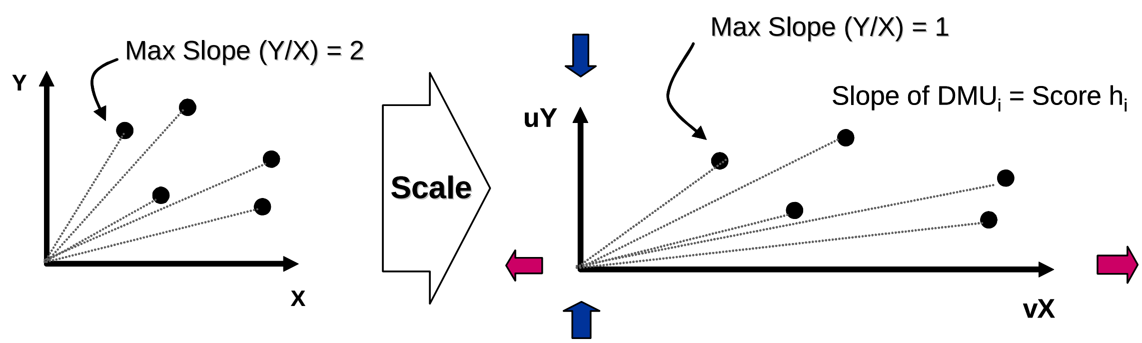


Figure 3.7 CCR Model Scales the Input/Output Axis to Obtain the Efficiency Scores

One important feature of the DEA approach is its capability of handling multiple inputs and outputs. The CCR model compares the weighted sums of inputs (Σuy) and outputs (Σvx) similarly to the 1-to-1 case in Figure 3.7, but the determination of the weights (u and v) to synthesize the inputs or outputs is more complicated. For the DEA-Leanness Measure where a DMU has two inputs and one output, the mechanism of CCR model can still be displayed by plotting the DMUs. For convenience, the DMUs can be normalized into same output level (by assuming linear relationships between the output level and the input consumptions) so that a two dimensional chart can be plotted. If producing one unit of product requires one unit of material and one unit of time, then the same production cell is assumed to be able to produce two units of products by using two units of material and time. Figure 3.8 and 3.9 demonstrate how the scores of DMU **A** to **F** are determined by the CCR model.

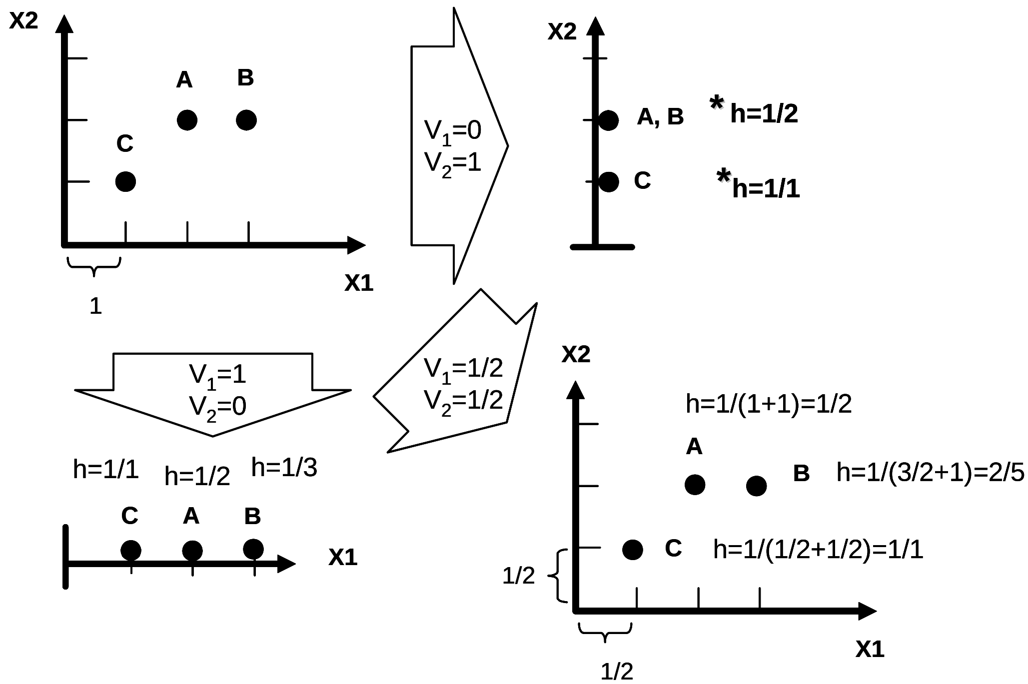


Figure 3.8 CCR Scores Determined by Projecting to One Axis (2 Inputs with Same Level of Output)

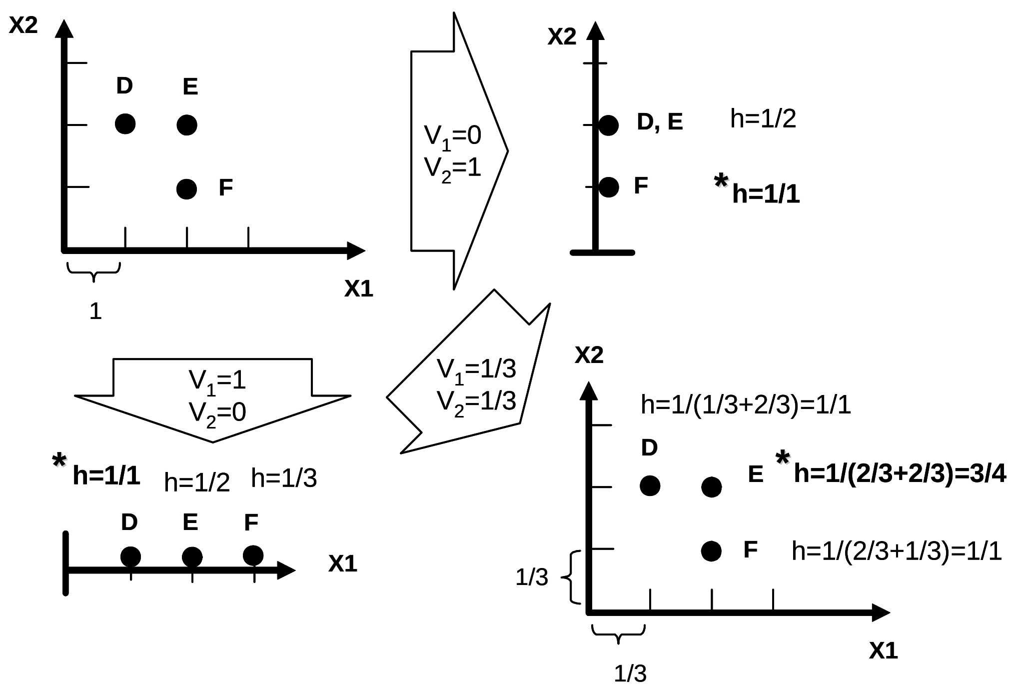


Figure 3.9 CCR Scores Determined by Scaling Two Axes Simultaneously (2 Inputs with Same Level of Output)

In Figure 3.8, **C** is apparently the most efficient DMU, so the score is 1. Since **A** lies on the radio line from the origin to **C**, the score of **A** is always 1/2, no matter how the two axes are scaled. As for **B**, the maximum score is obtained when projecting all DMUs onto the X2 axis. Therefore, the score of **B** is 1/2. In Figure 3.9, the scores of **D** and **F** reached the upper limit when projected to X1 and X2 respectively. For DMU **E**, the maximum score (3/4) is found when the two axes are scaled down simultaneously. The figures show two special cases where the numbers can be determined easily. For general scenarios, the scaling is not so trivial. However, the dual program of the CCR model sheds some light on the geometric characteristics.

CCR Dual Linear Program (DLP) (Modified from Boussofiane et al., 1991)

$$\text{Max } \theta \tag{6}$$

Subject to

$$\theta\, x_{i0} - \sum_{j=1}^{n} x_{ij}\lambda_j \geq 0,\ \ i = 1,2,\ldots,m \tag{7}$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{r0},\ \ r = 1,2,\ldots,t \tag{8}$$

where θ, λ, x and y are all nonnegative variables.

Notation:

θ: Efficiency score of DMU_0
x_{ij}: Input variable i of DMU_j
y_{rj}: Output variable r of DMU_j
λ_j: Weight for DMU_j

n: Number of DMUs
m: Number of input variables
t: Number of output variables

In the dual program, a weight λ is assigned to each of the DMUs to be compared with DMU_0. It turns out to be the variable that identifies the "reference set" of DMUs forming the benchmark for DMU_0. When λ has a positive value, that reference DMU (also known as "peer") determines the frontier for DMU_0. More than one λ can have positive values simultaneously, and the others are assigned to be zero indicating inactive DMUs. The efficiency score θ is equivalent to the ratio between the radio line segment from the origin to the benchmark and the segment to DMU_0, which is also the ratio between "efficient segment" and "efficient + inefficient segments." The "reference set" contains the DMUs that form the section of frontier where the intersection occurs. Actually, the λ's sum up to 1, which makes the benchmark of DMU_0 a convex combination of the reference set. Figure 3.10 illustrates the relationships between DMU, reference set and the score.

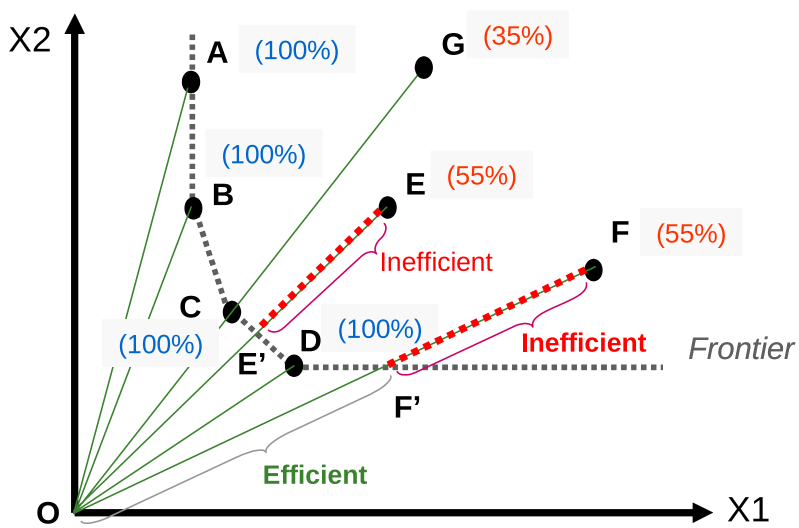


Figure 3.10 Leanness Scores Obtained from CCR Model

In the figure, **A**, **B**, **C** and **D** are the most efficient DMUs which forms the frontier. They are also their own reference set, which makes the scoring ratio 100%. **E'** and **F'** are the intersections (also known as "projection point") of the frontier and the radio lines. They are the benchmarks for **E** and **F** to calculate the scoring ratio. As shown in the figure, **E'** is a convex combination of **C** and **D.** Therefore, **C** and **D** are the two DMUs in the reference set of **E**. As for **F**, the projection point **F'** lies on the horizontal section. Therefore, DMU **D** is the sole reference for **F** because the other end of the frontier goes to infinity. DMU **G** lies on the radio line from **O** through **C**, so **C** is also the sole reference for **G**. These relationships are summarized in Table 3.2.

For DEA-Leanness Measure, the two inputs are Time and Cost, and the output is Value. Using the expression similar to Figure 3.10, the leanness score is the ratio between the "Value-added Investments" and the "Value-added + Non-value-added Investments." It is an indication of how far away the DMU is from the ideally lean status. Using the leanness score, the performance of the production activities can be evaluated and compared. Further comparing the highly scored DMUs with the others can identify potential improvement actions for pursuing perfection.

Table 3.2 Reference Sets and Scores of DMUs

DMU_0	Positive λ	Reference Set	Score
A	λ_A	A	$\frac{\overline{OA}}{\overline{OA}}$=100%
B	λ_B	B	$\frac{\overline{OB}}{\overline{OB}}$=100%
C	λ_C	C	$\frac{\overline{OC}}{\overline{OC}}$=100%
D	λ_D	D	$\frac{\overline{OD}}{\overline{OD}}$=100%
E	λ_C, λ_D	C, D	$\frac{\overline{OE'}}{\overline{OE}}$=55%
F	λ_D	D	$\frac{\overline{OF'}}{\overline{OF}}$=55%
G	λ_C	C	$\frac{\overline{OC}}{\overline{OG}}$=35%

In summary, the DEA-Leanness Measure determines the following items:

1) **Leanness Frontier:** the ultimate limit of the leanness performance that can possibly be achieved.
2) **Leanness Score:** the indication of proximity between current state and perfection.
3) **Direction of Improvement:** the distance between the DMU and the frontier indicates the potential improvement of each input/output variable.

In practice, some situations causing wastes in production processes cannot be fully avoided. Therefore, the leanness frontier may not be a practical goal for the continuous improvement efforts. A methodology that identifies appropriate leanness target is proposed in Chapter 5. The use of DEA-Leanness Measure is demonstrated using hypothetical cases in the next section.

3.2.2 Hypothetical Cases Using CCR Model

In this section, hypothetical cases are created to test the DEA-Leanness Measure based on CCR model. The basic setting of the cases is a dedicated flow line with three workstations as shown in Figure 3.11. The production line produces one type of product. There is no buffer between workstations, so the operators need to wait after finishing a product when the next station is busy. Also, the downstream operators need to wait for the previous station to provide the required material. The detailed settings are listed after Figure 3.11. Table 3.3 lists the detailed cost breakdown.

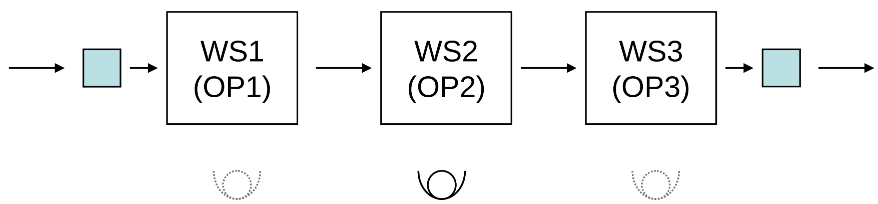


Figure 3.11 Hypothetical Case: Dedicated Flow Line with Three Workstations

<u>Hypothetical Case Basic Settings</u>:

Production Schedule: *20 units of Product A*

Available Time: *8 hours/day*

Takt Time: *24 minutes/unit*

Output: *Value = 1 if not delayed or defective, otherwise Value < 1*

Processing Time: (Data generated by MS Excel Random Number Generator)

OP1: 20 min. ± 2 min. (Uniformly distributed, random seed: #1000)
OP2: 20 min. ± 2 min. (Uniformly distributed, random seed: #2000)
OP3: 20 min. ± 2 min. (Uniformly distributed, random seed: #3000)

Table 3.3 Costs Breakdown in Case 1

	WS1		WS2		WS3	
	VA	NVA	VA	NVA	VA	NVA
Labor	\$0.1/min	0	\$0.1/min	0	\$0.1/min	0
Machine	\$0.2/min	0	\$0.2/min	0	\$0.25/min	0
Material	\$20/unit	\$1/unit	\$3/unit	\$0.5/unit	\$2/unit	0
Miscellaneous (Energy, Space, etc.)	\$0.01/min	\$0.01/min	\$0.01/min	\$0.01/min	\$0.01/min	\$0.01/min

Based on the aforementioned settings, the following hypothetical cases are created to represent three different manufacturing scenarios.

Case 1: Batch Production

Case 2: Pulled Production

Case 3: Batch Production with Undesirable Conditions

The numerical data sets are created and prepared using Microsoft Excel (version: *MS Office 2003 Professional*). The CCR model is solved by *DEA-Solver-LV* (*Learning Version*), which is developed by *SAITECH, Inc.* (http://www.saitech-inc.com). The detailed numerical data sets of the hypothetical cases are listed in Appendix A. The input/output data of DMUs and final results are presented as follows.

3.2.2.1 Hypothetical Case 1: Batch Production

The first hypothetical case is a batch production scenario where raw materials arrive in two batches and finished products are removed from the system four times a day. The time stamps of the movements of the parts are listed in Table 3.4 while detailed cost and time data can be found in Appendix A.

The time stamps and detailed costs are aggregated into the input and output data of DMUs. Figure 3.12 shows plots of the 20 ADMUs and 20 IDMUs in the Cost-Time space. The figure shows four groups of ADMUs (Time = 143, 146, 241, or 248) because of the batch arrival and removal of products.

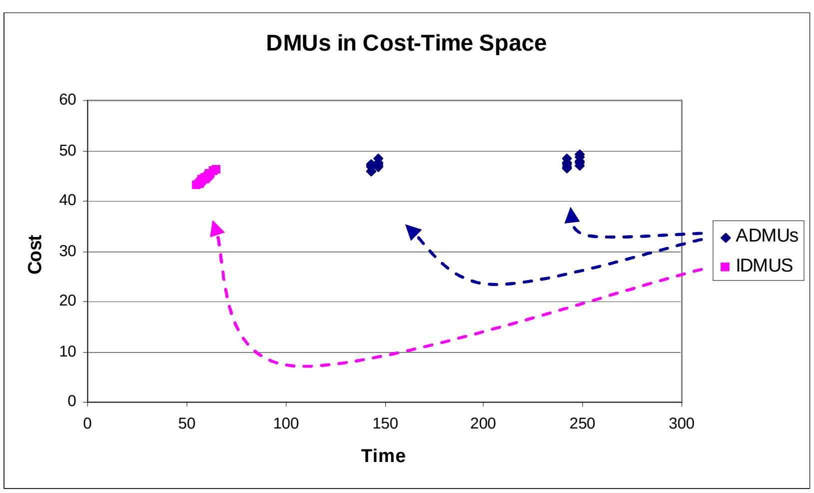


Figure 3.12 ADMUs and IDMUs of Case 1

Table 3.4 Time Stamps of Case 1

DMU	Material Arrive	Enter WS1	Leave WS1	Enter WS2	Leave WS2	Enter WS3	Leave WS3	Leave System
Part 1	0.00	0.00	18.40	18.40	37.21	37.21	56.41	143.46
Part 2	0.00	18.40	37.41	37.41	56.47	56.47	75.60	143.46
Part 3	0.00	37.41	58.68	58.68	80.65	80.65	99.29	143.46
Part 4	0.00	58.68	78.40	80.65	101.78	101.78	120.32	143.46
Part 5	0.00	78.40	96.58	101.78	123.06	123.06	143.46	143.46
Part 6	0.00	96.58	115.36	123.06	141.18	143.46	164.91	241.93
Part 7	0.00	115.36	134.32	141.18	160.08	164.91	183.74	241.93
Part 8	0.00	134.32	154.93	160.08	179.35	183.74	205.68	241.93
Part 9	0.00	154.93	173.78	179.35	197.78	205.68	223.68	241.93
Part 10	0.00	173.78	193.02	197.78	218.52	223.68	241.93	241.93
Part 11	200.00	200.00	220.66	220.66	239.26	241.93	262.48	346.68
Part 12	200.00	220.66	239.47	239.47	259.65	262.48	284.04	346.68
Part 13	200.00	239.47	260.11	260.11	279.24	284.04	305.68	346.68
Part 14	200.00	260.11	281.96	281.96	303.62	305.68	327.16	346.68
Part 15	200.00	281.96	303.47	303.62	322.14	327.16	346.68	346.68
Part 16	200.00	303.47	323.88	323.88	344.75	346.68	368.02	448.46
Part 17	200.00	323.88	344.65	344.75	363.21	368.02	388.16	448.46
Part 18	200.00	344.65	363.03	363.21	382.76	388.16	408.88	448.46
Part 19	200.00	363.03	384.87	384.87	406.19	408.88	429.68	448.46
Part 20	200.00	384.87	404.33	406.19	425.31	429.68	448.46	448.46

Unit: Minute

The data and results of the analysis are listed in Table 3.5 together with the "Slacks of Benchmark" associated with each leanness score. The slacks of benchmark are the excessive resources or output shortfalls contained in the benchmarking projection point, which is shown as a horizontal or vertical section of frontier in Figure 3.10. The existence of slacks means that the leanness score is overestimated and the slacks should be taken into account while reading the results. Since the inefficiency caused by the slacks is not included in the score, comprehending the results of a CCR model may not be an intuitive task. This has posted a major weakness of CCR model while performing the DEA-Leanness Measure. The meaning of the slacks and this weakness is further discussed in Section 3.2.3.

Figure 3.13 shows the leanness scores graphically. Among the DMUs, Part 1 receives highest score because of the zero waiting time when it enters the system. Part 19 receives lowest score due to longer waiting time. However, different amounts of slacks exist in the report of every DMU, which make the leanness scores less accurate.

Table 3.5 Data and Results of Case 1 Using CCR Model

DMU	*Inputs*				*Output*	*Score*	*Slacks of Benchmark*		
	Total Time	VA Time	Total Cost	VA Cost	Value	Leanness Score	Time (Excess)	Cost (Excess)	Value (Shortfall)
Part 1	143.46	56.41	45.82	43.45	1	**0.94**	79.47	0	0
Part 2	143.46	57.19	46.05	43.69	1	**0.93**	78.79	0	0
Part 3	143.46	61.89	47.43	45.12	1	**0.91**	74.88	0	0
Part 4	143.46	59.39	46.68	44.34	1	**0.92**	76.98	0	0
Part 5	143.46	59.86	46.91	44.58	1	**0.92**	76.32	0	0
Part 6	241.93	58.34	47.49	44.16	1	**0.91**	163.94	0	0
Part 7	241.93	56.69	46.87	43.52	1	**0.92**	166.87	0	0
Part 8	241.93	61.82	48.56	45.26	1	**0.89**	159.12	0	0
Part 9	241.93	55.28	46.40	43.04	1	**0.93**	169.10	0	0
Part 10	241.93	58.23	47.30	43.96	1	**0.91**	164.84	0	0
Part 11	146.68	59.81	46.94	44.57	1	**0.92**	79.21	0	0
Part 12	146.68	60.55	47.21	44.85	1	**0.91**	78.43	0	0
Part 13	146.68	61.42	47.47	45.12	1	**0.91**	77.69	0	0
Part 14	146.68	64.99	48.54	46.22	1	**0.89**	74.77	0	0
Part 15	146.68	59.55	46.81	44.44	1	**0.92**	79.59	0	0
Part 16	248.46	62.63	48.84	45.48	1	**0.88**	163.66	0	0
Part 17	248.46	59.36	47.80	44.41	1	**0.90**	168.42	0	0
Part 18	248.46	58.66	47.62	44.22	1	**0.90**	169.27	0	0
Part 19	248.46	63.96	49.21	45.87	1	**0.87**	162.01	0	0
Part 20	248.46	57.36	47.13	43.72	1	**0.91**	171.59	0	0

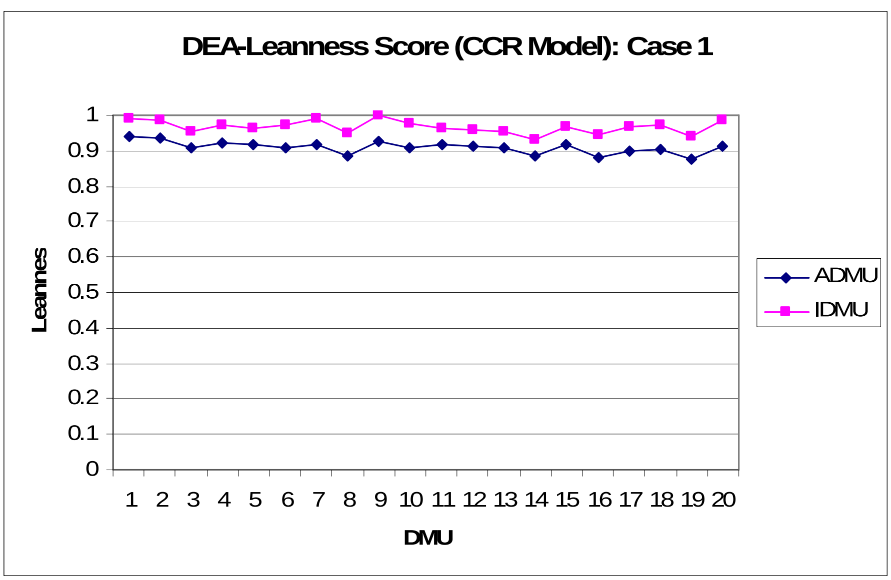


Figure 3.13 Leanness Scores of Case 1 Using CCR Model

3.2.2.2 Hypothetical Case 2: Pull Production

The second hypothetical case is a pull production scenario where the raw materials are pulled only when needed and every unit of finished product is removed immediately from the system. Again, the time stamps of the movements of the parts are listed in Table 3.6.

Table 3.6 Time Stamps of Case 2

DMU	Material Arrive	Enter WS1	Leave WS1	Enter WS2	Leave WS2	Enter WS3	Leave WS3	Leave System
Part 1	0.00	0.00	18.40	18.40	37.21	37.21	56.41	56.41
Part 2	18.40	18.40	37.41	37.41	56.47	56.47	75.60	75.60
Part 3	37.41	37.41	58.68	58.68	80.65	80.65	99.29	99.29
Part 4	58.68	58.68	78.40	80.65	101.78	101.78	120.32	120.32
Part 5	78.40	78.40	96.58	101.78	123.06	123.06	143.46	143.46
Part 6	96.58	96.58	115.36	123.06	141.18	143.46	164.91	164.91
Part 7	115.36	115.36	134.32	141.18	160.08	164.91	183.74	183.74
Part 8	134.32	134.32	154.93	160.08	179.35	183.74	205.68	205.68
Part 9	154.93	154.93	173.78	179.35	197.78	205.68	223.68	223.68
Part 10	173.78	173.78	193.02	197.78	218.52	223.68	241.93	241.93
Part 11	193.02	193.02	213.68	218.52	237.12	241.93	262.48	262.48
Part 12	213.68	213.68	232.48	237.12	257.31	262.48	284.04	284.04
Part 13	232.48	232.48	253.12	257.31	276.45	284.04	305.68	305.68
Part 14	253.12	253.12	274.97	276.45	298.11	305.68	327.16	327.16
Part 15	274.97	274.97	296.48	298.11	316.63	327.16	346.68	346.68
Part 16	296.48	296.48	316.89	316.89	337.77	346.68	368.02	368.02
Part 17	316.89	316.89	337.67	337.77	356.22	368.02	388.16	388.16
Part 18	337.67	337.67	356.05	356.22	375.78	388.16	408.88	408.88
Part 19	356.05	356.05	377.89	377.89	399.21	408.88	429.68	429.68
Part 20	377.89	377.89	397.35	399.21	418.33	429.68	448.46	448.46

Unit: Minute

Figure 3.14 gives plots of the ADMUs and IDMUs in the Cost-Time space, where the ADMUs are shown to be much closer to the IDMUs comparing to Case 1. The data and results of the analysis are listed in Table 3.7, and the scores are shown graphically in Figure 3.15. Among the DMUs, Part 1 receives nearly perfect score because of the zero waiting time throughout the processes. The non-value-added portion of Part 1 comes from the excessive material scrapped in the processes. Other DMUs also receive higher scores than those in Case 1 due to the zero waiting time in part arrival and departure.

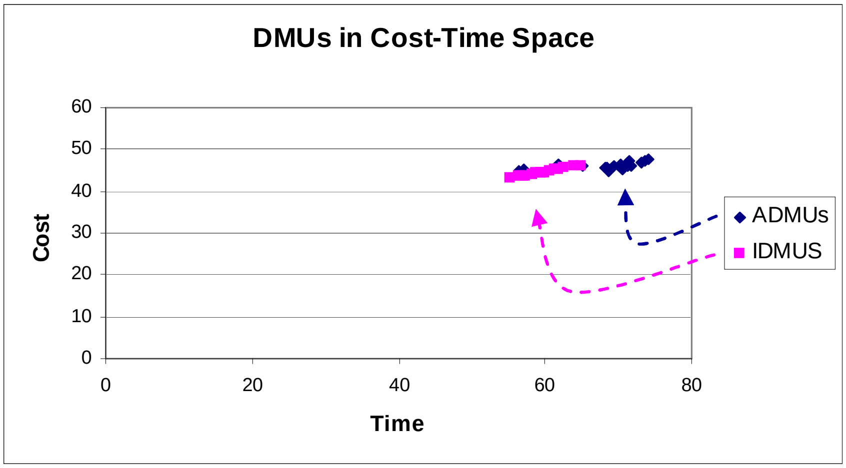


Figure 3.14 ADMUs and IDMUs of Case 2

Table 3.7 Data and Results of Case 2 Using CCR Model

DMU	*Inputs*				*Output*	*Score*	*Slacks of Benchmark*		
	Total Time	**VA Time**	**Total Cost**	**VA Cost**	**Value**	**Leanness Score**	**Time (Excess)**	**Cost (Excess)**	**Value (Shortfall)**
Part 1	56.41	56.41	44.95	43.45	1	**0.98**	0.00	1.01	0
Part 2	57.19	57.19	45.19	43.69	1	**0.97**	0.00	0.64	0
Part 3	61.89	61.89	46.62	45.12	1	**0.92**	1.86	0	0
Part 4	61.64	59.39	45.86	44.34	1	**0.94**	2.57	0	0
Part 5	65.06	59.86	46.13	44.58	1	**0.93**	5.42	0	0
Part 6	68.32	58.34	45.76	44.16	1	**0.94**	8.98	0	0
Part 7	68.38	56.69	45.13	43.52	1	**0.95**	9.93	0	0
Part 8	71.36	61.82	46.86	45.26	1	**0.92**	10.27	0	0
Part 9	68.76	55.28	44.67	43.04	1	**0.96**	10.96	0	0
Part 10	68.15	58.23	45.56	43.96	1	**0.94**	9.10	0	0
Part 11	69.46	59.81	46.17	44.57	1	**0.93**	9.48	0	0
Part 12	70.36	60.55	46.45	44.85	1	**0.93**	9.92	0	0
Part 13	73.20	61.42	46.74	45.12	1	**0.92**	12.12	0	0
Part 14	74.04	64.99	47.81	46.22	1	**0.90**	11.36	0	0
Part 15	71.71	59.55	46.06	44.44	1	**0.93**	11.73	0	0
Part 16	71.54	62.63	47.07	45.48	1	**0.91**	10.13	0	0
Part 17	71.26	59.36	46.03	44.41	1	**0.94**	11.35	0	0
Part 18	71.22	58.66	45.85	44.22	1	**0.94**	11.57	0	0
Part 19	73.63	63.96	47.46	45.87	1	**0.91**	11.49	0	0
Part 20	70.57	57.36	45.35	43.72	1	**0.95**	11.69	0	0

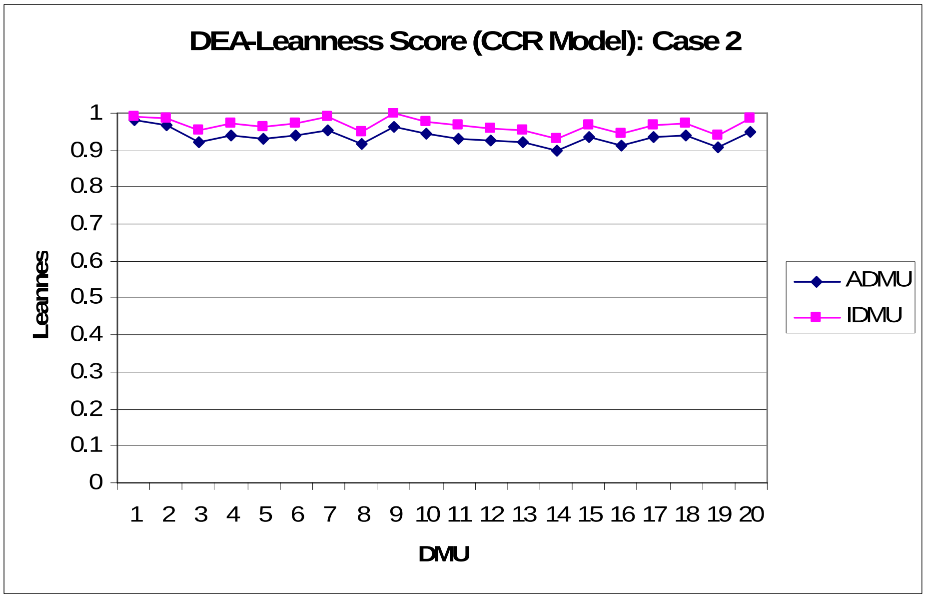


Figure 3.15 Leanness Scores of Case 2 Using CCR Model

3.2.2.3 Hypothetical Case 3: Batch Production with Undesirable Conditions

In the third hypothetical case, the batch production setting in Case 1 is used again. In addition, undesirable conditions are added into the case which better represents some common problems of manufacturing systems. The problems embedded in this case are:

Condition #1: Machine was down for 20 minutes at WS2 while processing Part 4.

Condition #2: Part 7 and 8 are defective but acceptable. The value is discounted as 0.6.

Condition #3: Part 10 was reworked at WS3 after all parts were processed. Part 11 replaces Part 10 as the last unit of the second batch.

Condition #4: Part 13 is scrapped during the final inspection. The value is 0.

Condition #5: Part 15 used extra material which costs $20 more than regular parts.

Based on these conditions, the time and cost data are adjusted. The time stamps of the movements of the parts are listed in Table 3.8. Figure 3.16 provides plots of the ADMUs and IDMUs in the Cost-Time space, where some of the ADMUs scatter away from the major group because of the undesirable conditions.

Table 3.8 Time Stamps of Case 3

DMU	Material Arrive	Enter WS1	Leave WS1	Enter WS2	Leave WS2	Enter WS3	Leave WS3	Leave System
Part 1	0.00	0.00	18.40	18.40	37.21	37.21	56.41	163.46
Part 2	0.00	18.40	37.41	37.41	56.47	56.47	75.60	163.46
Part 3	0.00	37.41	58.68	58.68	80.65	80.65	99.29	163.46
Part 4	0.00	58.68	78.40	80.65	121.78	121.78	140.32	163.46
Part 5	0.00	78.40	96.58	121.78	143.06	143.06	163.46	163.46
Part 6	0.00	96.58	115.36	143.06	161.18	163.46	184.91	282.48
Part 7	0.00	115.36	134.32	161.18	180.08	184.91	203.74	282.48
Part 8	0.00	134.32	154.93	180.08	199.35	203.74	225.68	282.48
Part 9	0.00	154.93	173.78	199.35	217.78	225.68	243.68	282.48
Part 10	0.00	173.78	193.02	217.78	238.52	243.68	504.96	504.96
Part 11	200.00	200.00	220.66	238.52	257.12	261.93	282.48	282.48
Part 12	200.00	220.66	239.47	257.12	277.31	282.48	304.04	388.02
Part 13	200.00	239.47	260.11	277.31	296.45	304.04	325.68	388.02
Part 14	200.00	260.11	281.96	296.45	318.11	325.68	347.16	388.02
Part 15	200.00	281.96	303.47	318.11	336.63	347.16	366.68	388.02
Part 16	200.00	303.47	323.88	336.63	357.50	366.68	388.02	388.02
Part 17	200.00	323.88	344.65	357.50	375.96	388.02	408.16	504.96
Part 18	200.00	344.65	363.03	375.96	395.51	408.16	428.88	504.96
Part 19	200.00	363.03	384.87	395.51	416.83	428.88	449.68	504.96
Part 20	200.00	384.87	404.33	416.83	435.95	449.68	468.46	504.96

Unit: Minute

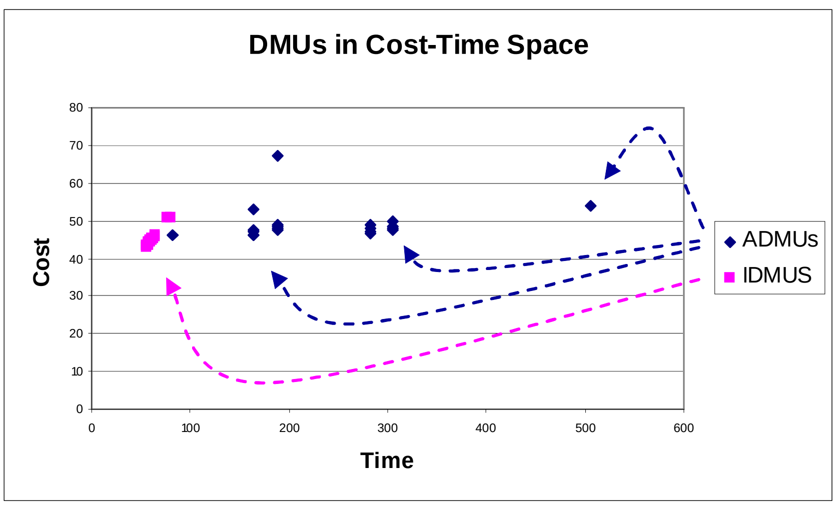


Figure 3.16 ADMUs and IDMUs of Case 3

The data and results of the analysis are listed in Table 3.9, and the scores are shown graphically in Figure 3.17. In general, DMUs having undesirable conditions receive apparently lower scores. The resulting leanness scores reflect the problems of the production line, but the slacks of benchmark undermine the accuracy. This weakness of CCR model lead to another solution discussed later in this chapter.

Table 3.9 Data and Results of Case 3 Using CCR Model

DMU	*Inputs*				*Output*	*Score*	*Slacks of Benchmark*		
	Total Time	VA Time	Total Cost	VA Cost	Value	Leanness Score	Time (Excess)	Cost (Excess)	Value (Shortfall)
Part 1	163.46	56.41	46.02	43.45	1	**0.94**	97.59	0	0
Part 2	163.46	57.19	46.25	43.69	1	**0.93**	96.82	0	0
Part 3	163.46	61.89	47.63	45.12	1	**0.90**	92.40	0	0
Part 4	163.46	79.39	52.88	50.54	1	**0.81**	77.75	0	0
Part 5	163.46	59.86	47.11	44.58	1	**0.91**	94.03	0	0
Part 6	282.48	58.34	47.90	44.16	1	**0.90**	198.52	0	0
Part 7	282.48	56.69	47.27	43.52	0.6	**0.55**	121.13	0	0
Part 8	282.48	61.82	48.97	45.26	0.6	**0.53**	115.79	0	0
Part 9	282.48	55.28	46.81	43.04	1	**0.92**	204.44	0	0
Part 10	504.96	76.48	54.07	50.53	1	**0.80**	346.63	0	0
Part 11	82.48	59.81	46.30	44.57	1	**0.93**	21.39	0	0
Part 12	188.02	60.55	47.62	44.85	1	**0.90**	114.63	0	0
Part 13	188.02	61.42	47.89	45.12	0	**0.00**	0.00	0	0
Part 14	188.02	64.99	48.95	46.22	1	**0.88**	110.02	0	0
Part 15	188.02	59.55	67.22	44.44	1	**0.64**	65.10	0	0
Part 16	188.02	62.63	48.24	45.48	1	**0.89**	112.48	0	0
Part 17	304.96	59.36	48.36	44.41	1	**0.89**	216.08	0	0
Part 18	304.96	58.66	48.18	44.22	1	**0.89**	217.09	0	0
Part 19	304.96	63.96	49.78	45.87	1	**0.86**	208.38	0	0
Part 20	304.96	57.36	47.70	43.72	1	**0.90**	219.88	0	0

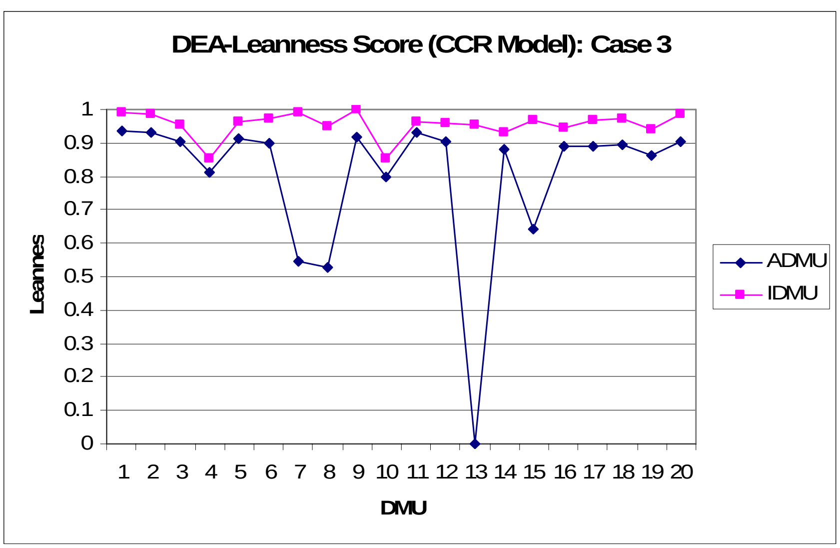


Figure 3.17 Leanness Scores of Case 3 Using CCR Model

3.2.3 Weakness of CCR Model

As mentioned briefly in the hypothetical case study, the CCR model has a weakness, not including the inefficiency caused by slacks into the scores. The “slacks” here means the input excesses or output shortfalls of a performance benchmark in the CCR model. It occurs when the DMU or its projection point lies on a horizontal or vertical section of the frontier. Figure 3.18 revisits the two input case shown in Section 3.2.1, where the DMUs are normalized into same output level. In the figure, DMU A lies on the vertical section of the frontier, carrying a score of 100% in the CCR model. However, DMU A apparently consumes more of resource X2 than DMU B while using the same level of resource X1 to produce the same level of output. Therefore, A is actually less efficient than 100%. Similarly, the projection point of DMU F lies on the horizontal section of the frontier. As a benchmark for F, the projection point (F’) consumes more of resource X1 than DMU D while producing same level of output. It is actually less efficient than 100%, posting the accuracy of the score of DMU F in question.

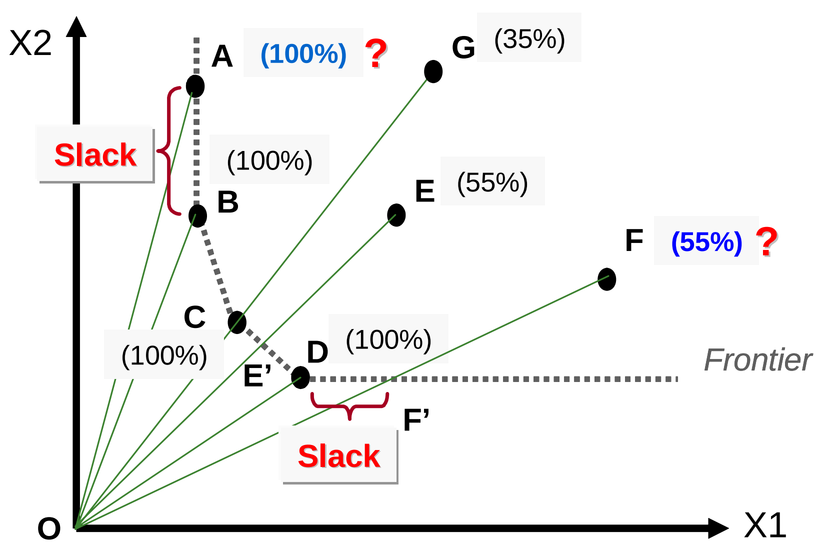


Figure 3.18 Slacks of Benchmark Undermine the Accuracy of CCR Scores

The report of CCR model usually lists the efficiency score together with slacks in every input/output variable. The existence of slacks indicates that the score is higher than it should be. However, it is very difficult to tell the actual level of efficiency just from the score and the slacks. For example, a 70% efficiency DMU with 80 units of slacks in X1 may or may not be more comparable with a 60% efficient DMU with 50 units of slacks in X1. Even slacks in different variable have different units. Therefore, a report of CCR model becomes hard to comprehend when slacks exist.

From the three hypothetical cases, it appears that IDMUs tend to cluster at a small area which leaves most of the frontier in vertical or horizontal sections. Therefore, slacks are found repeatedly in every hypothetical case which can be observed in Figure 3.12, 3.14, and 3.16. The reason behind is that the VA activities in a manufacturing system consumes similar amounts of cost and time, while NVA activities are usually the sources of variability and are responsible for the larger portion of the total cost and time. Table 3.10 collects four examples of Value Stream Maps to compare the Lead Time and VA Time of current state and future state. The results support that VA time does not change much when a system is improved from current state to the proposed future state. Similarly, Table 3.11 lists the costs and earnings of current and future states of the third example. The conversion cost, which makes up most of the VA time, does not decrease much, while the greatest improvement comes from the reduction of inventory value.

Table 3.10 Current and Future Value Stream Maps Have Similar VA Times

<table>
<tr><th colspan="2"></th><th>Example 1</th><th>Example 2</th><th>Example 3</th><th>Example 4</th></tr>
<tr><th rowspan="2">Current VSM</th><th>Lead Time</th><td>23.6 days</td><td>48 days</td><td>20.5 days</td><td>34 days</td></tr>
<tr><th>VA Time</th><td>188 sec.</td><td>315 sec.</td><td>30.3 min.</td><td>170 sec.</td></tr>
<tr><th rowspan="2">Future VSM</th><th>Lead Time</th><td>4.5 days</td><td>11 days</td><td>4.5 days</td><td>8 days</td></tr>
<tr><th>VA Time</th><td>169 sec.</td><td>315 sec.</td><td>23.3 min.</td><td>150 sec.</td></tr>
<tr><th>Source</th><td colspan="5">Examples 1 and 2: “Learning to See” (Rother and Shooks, 1998)
Example 3: “Practical Lean Accounting” (Maskell and Baggaley, 2003)
Example 4: “Value Stream Management” (Tapping et al., 2002)</td></tr>
</table>

Table 3.11 Current and Future Value Stream Maps Have Similar VA Costs

Example 3	Current State	Future State
Inventory Value	$58,502	$13,997
Revenue	$1,292,640	$1,292,640
Material Costs	$512,160	$447,160
Conversion Costs	$189,866	$181,416
Value Stream Profit	$590,614	$634,064

In summary, slacks can be found frequently in the DEA-Leanness Measure when applied on manufacturing systems due to the cluster of IDMUs. The CCR model is capable of evaluating the leanness level, but the result is not intuitively understandable. The DEA-Leanness Measure should employ another model that delivers leanness scores considering the inefficiency caused by slacks. A better solution is the Slacks-Based Measure (SBM) model introduced in the following section.

3.3 DEA-Leanness based on Slacks-Based Measure (SBM)

Due to the weakness of CCR model on handling slacks, finding a more suitable model for the DEA-Leanness Measure is necessary. The model of Slacks-Based Measure (SBM) is selected to be the replacement since it is designed to deal with slacks directly. The hypothetical cases are revisited in this section using the SBM model, and the results are satisfying. Therefore, the SBM model is a better choice than CCR model while performing the DEA-Leanness Measure.

3.3.1 Slacks-Based Measure (SBM) Model

The Slacks-Based Measure (SBM) of efficiency is proposed by Tone (2001) as a DEA model that deals with the slacks in the input and output variables directly. Using the input excesses and output shortfalls between a DMU and its benchmark, the SBM model gives an efficiency score that is unit invariant and valued between 0 and 1. As shown below, the original SBM model is also a fractional program. An equivalent linear program can be derived using the similar transformation of the CCR model.

SBM Fractional Program (Tone, 2001)

$$\text{Min.} \quad \rho = \frac{1-(1/m)\sum_{i=1}^{m} s_i^- / x_{i0}}{1+(1/s)\sum_{r=1}^{s} s_r^+ / y_{r0}} \tag{9}$$

$$\text{Subject to} \quad x_0 = X\lambda + s^- \tag{10}$$

$$y_0 = Y\lambda - s^+ \tag{11}$$

$$\text{Where } \lambda,\ s^-,\ s^+ \geq 0$$

<u>Notation:</u>

ρ: Efficiency score	s^- and s^+: Slacks associated with inputs/outputs
x_0: Inputs of DMU_0	m and s: Numbers of input/output variables
y_0: Outputs of DMU_0	λ: Weights for DMUs

Using the ADMUs and IDMUs simultaneously, the efficiency score ρ is equivalent to the leanness score.

The fractional program can be transformed using the similar technique for transforming the CCR model. Before the SBM model can be completely transformed into a linear program, a transitional nonlinear program is developed first. The transitional program is created by multiplying a scalar "t" to the objective function and separating the nominator and denominator.

SBM Transitional Nonlinear Program (Tone, 2001)

$$\text{Min.} \ \tau = t - \frac{1}{m}\sum_{i=1}^{m} ts_i^- / x_{i0} \tag{12}$$

$$\text{Subject to} \ \ 1 = t + \frac{1}{s}\sum_{r=1}^{s} ts_r^+ / y_{r0} \tag{13}$$

$$x_0 = X\lambda + s^-$$

$$y_0 = Y\lambda - s^+$$

$$\text{Where } \lambda,\ s^-,\ s^+ \geq 0$$

$$t > 0$$

In the transitional program, ts_r^+ and ts_i^- are a nonlinear term. The model is further transformed by replacing ts_r^+ and ts_r^- with S_r^+ and S_i^-, and tλ is represented by Λ.

SBM Linear Program (Tone, 2001)

$$\text{Min. } \tau = t - \frac{1}{m}\sum_{i=1}^{m} S_i^- / x_{i0} \qquad (14)$$

$$\text{Subject to } 1 = t + \frac{1}{s}\sum_{r=1}^{s} S_r^+ / y_{r0} \qquad (15)$$

$$tx_0 = X\Lambda + S^- \qquad (16)$$

$$ty_0 = Y\Lambda - S^+ \qquad (17)$$

$$\text{Where } \Lambda,\ S^-,\ S^+ \geq 0$$

$$t > 0$$

Tone (2001) suggests that, for the optimal solution of the SBM linear program (τ*, t*, Λ*, S^-*, S^+*), following relationships exist:

$$\rho^* = \tau^*$$

$$\lambda^* = \Lambda^* / t^*$$

$$s^{-*} = S^{-*}/t^*$$

$$s^{+*} = S^{+*}/t^* \qquad (18)$$

However, this is not always true. The optimal scores ρ* and τ* are equivalent, but the relationship λ*=Λ*/t* may not hold when the inputs variables or the output variable of the DMU can be scaled from its reference set. Examples can be found in Section 4.1 where a Weighted DEA-Leanness Measure is established. Nevertheless, the optimal leanness scores of the two programs are always the same.

Similar to the CCR model, the SBM model identifies a reference set for each DMU and calculates the efficiency score based on the relationship in between. However, there are differences between CCR and SBM models. First, the definition of "slack" is different in the two models. In the SBM model, the slacks are the input excesses or output shortfalls from a DMU to its benchmark, while CCR model use "slacks" to describe the excesses and shortfalls of a benchmark (Figure 3.18). Figure 3.19 shows that, in SBM model, every inefficient DMU can be represented as the benchmark plus the slacks in different axis even if the DMU is on the frontier. In other words, every DMU in the reference set identified by SBM model is 100% efficient, which means the DMUs or projection points lying on the vertical or horizontal sections of the frontier cannot be their own benchmark. Instead, the starting point of the horizontal or vertical sections (B and D in Figure 3.19) is the reference set for all the abovementioned DMUs and projection points. In the mathematical model, the slacks are represented as s^- and s^+ in Equations (10) and (11), which is the distance from the convex combination of the reference set ($X\lambda$ and $Y\lambda$) to the DMU along the selected axis. Note that the two equations resemble the constraints in the CCR Linear Model (7) and (8) only that no efficiency ratio is involved in the SBM equation (10). This is another difference between the two models.

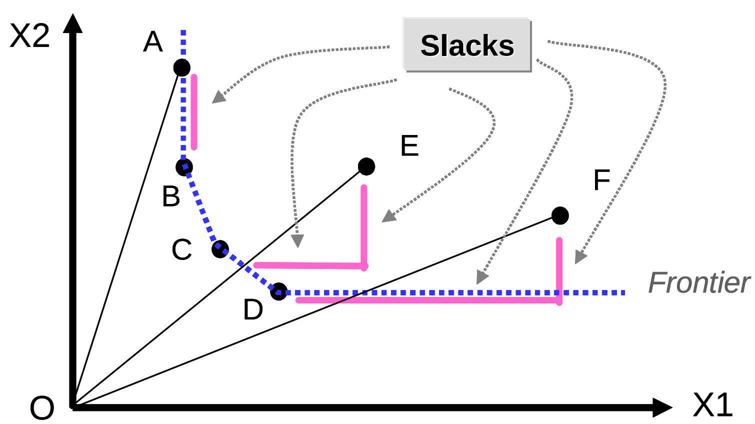


Figure 3.19 Slacks in SBM Model

The difference between Equations (7) of CCR model and (10) of SBM model shows the second difference between the two models. The CCR model scales the axis to find the optimal solution, while the SBM model calculates the scores directly using the slacks shown in Figure 3.19. The objective function of SBM has an upper bound $\rho=1$ when no slacks can be found in a DMU. Any excessive input deducts the nominator from 1 to 0, and the output shortfalls increase the denominator from 1 to infinity. Therefore, the SBM score has a value between 0 and 1, and it is monotone increasing with respect to slacks. These characteristics make the SBM model a perfect match for the DEA-Leanness Measure for manufacturing systems.

3.3.2 Hypothetical Cases Using SBM Model

In this section, the three hypothetical cases in Section 3.2.2 are revisited using the SBM Model. The settings and data of the hypothetical cases can be found in Section 3.3.2 and Appendix A. A DEA-SBM-Leanness Solver is developed for solving the SBM linear program. The solver is programmed with Visual Basic Applets (VBA) based on the Microsoft Excel Solver. Details of the software program are introduced in Chapter 6. Scores obtained from SBM model are compared with the CCR scores as follows.

Case 1: Batch Production

Case Setting:

Materials arrive twice a day.

Finished products are removed four times a day.

Table 3.12 Results of Case 1 Using SBM Model; Compared with CCR Model

DMU	*SBM Model*	*CCR Model*			
	Leanness Score	Leanness Score	*Slacks of Benchmark*		
			Time (Excess)	Cost (Excess)	Value (Shortfall)
Part 1	**0.662**	**0.939**	79.47	0	0
Part 2	**0.660**	**0.935**	78.79	0	0
Part 3	**0.646**	**0.907**	74.88	0	0
Part 4	**0.654**	**0.922**	76.98	0	0
Part 5	**0.651**	**0.917**	76.32	0	0
Part 6	**0.567**	**0.906**	163.94	0	0
Part 7	**0.573**	**0.918**	166.87	0	0
Part 8	**0.557**	**0.886**	159.12	0	0
Part 9	**0.578**	**0.927**	169.10	0	0
Part 10	**0.569**	**0.910**	164.84	0	0
Part 11	**0.647**	**0.917**	79.21	0	0
Part 12	**0.644**	**0.912**	78.43	0	0
Part 13	**0.642**	**0.907**	77.69	0	0
Part 14	**0.632**	**0.887**	74.77	0	0
Part 15	**0.648**	**0.919**	79.59	0	0
Part 16	**0.552**	**0.881**	163.66	0	0
Part 17	**0.561**	**0.900**	168.42	0	0
Part 18	**0.563**	**0.904**	169.27	0	0
Part 19	**0.548**	**0.875**	162.01	0	0
Part 20	**0.568**	**0.913**	171.59	0	0
Average	**0.606**	**0.909**			

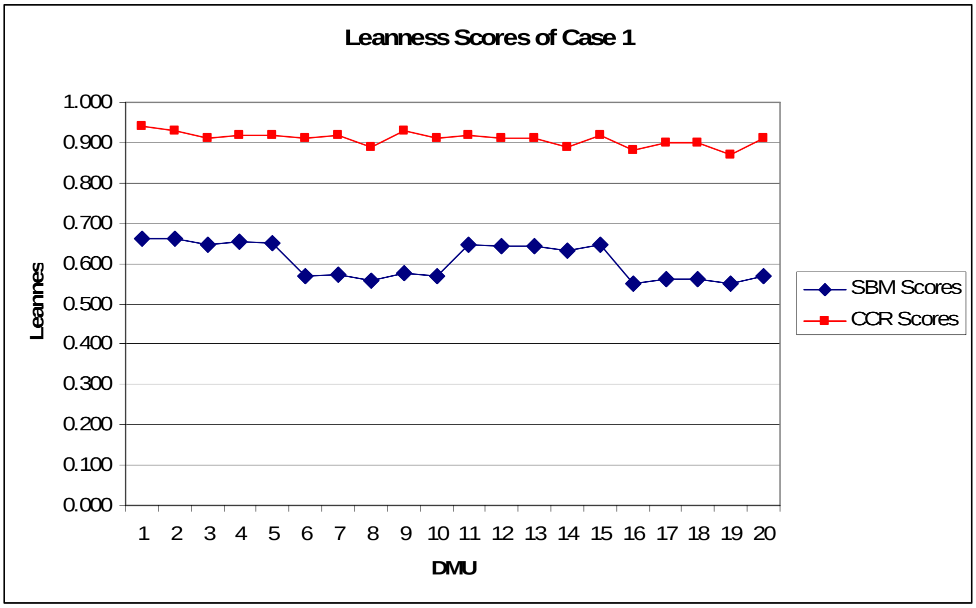


Figure 3.20 Leanness Scores of Case 1: SBM Model vs. CCR Model

The result of Case 1 shows that the SBM Leanness Scores are significantly lower than the CCR model. The production of 20 parts receives a score of 60.6%. The reason for the difference is that CCR model does not include the slacks of benchmark in the scores. More importantly, the hypothetical case is set to have four different batches of products flowing through the production line. Due to the total time of the different batches in the system, the ADMUs cluster into four groups as in Figure 3.12. The results from SBM model successfully reflect the situation, while using CCR model, it can only be observed from the value of slacks. Therefore, the SBM model provides a clearer indication of the leanness of production which is simple and intuitive.

Case 2: Pull Production

Case Setting:

Materials are pulled only when needed.

Finished products are removed immediately after their completion.

The results from both SBM and CCR models are shown in Table 3.13 and Figure 3.21.

Table 3.13 Results of Case 2 Using SBM Model; Compared with CCR Model

DMU	*SBM Model*	*CCR Model*			
	Leanness Score	Leanness Score	*Slacks of Benchmark*		
			Time (Excess)	Cost (Excess)	Value (Shortfall)
Part 1	**0.969**	**0.980**	0.00	1.01	0
Part 2	**0.959**	**0.966**	0.00	0.64	0
Part 3	**0.908**	**0.923**	1.86	0	0
Part 4	**0.918**	**0.938**	2.57	0	0
Part 5	**0.891**	**0.933**	5.42	0	0
Part 6	**0.875**	**0.940**	8.98	0	0
Part 7	**0.881**	**0.954**	9.93	0	0
Part 8	**0.847**	**0.918**	10.27	0	0
Part 9	**0.884**	**0.963**	10.96	0	0
Part 10	**0.878**	**0.945**	9.10	0	0
Part 11	**0.864**	**0.932**	9.48	0	0
Part 12	**0.856**	**0.927**	9.92	0	0
Part 13	**0.838**	**0.921**	12.12	0	0
Part 14	**0.823**	**0.900**	11.36	0	0
Part 15	**0.853**	**0.934**	11.73	0	0
Part 16	**0.843**	**0.914**	10.13	0	0
Part 17	**0.855**	**0.935**	11.35	0	0
Part 18	**0.857**	**0.939**	11.57	0	0
Part 19	**0.829**	**0.907**	11.49	0	0
Part 20	**0.866**	**0.949**	11.69	0	0
Average	**0.875**	**0.936**			

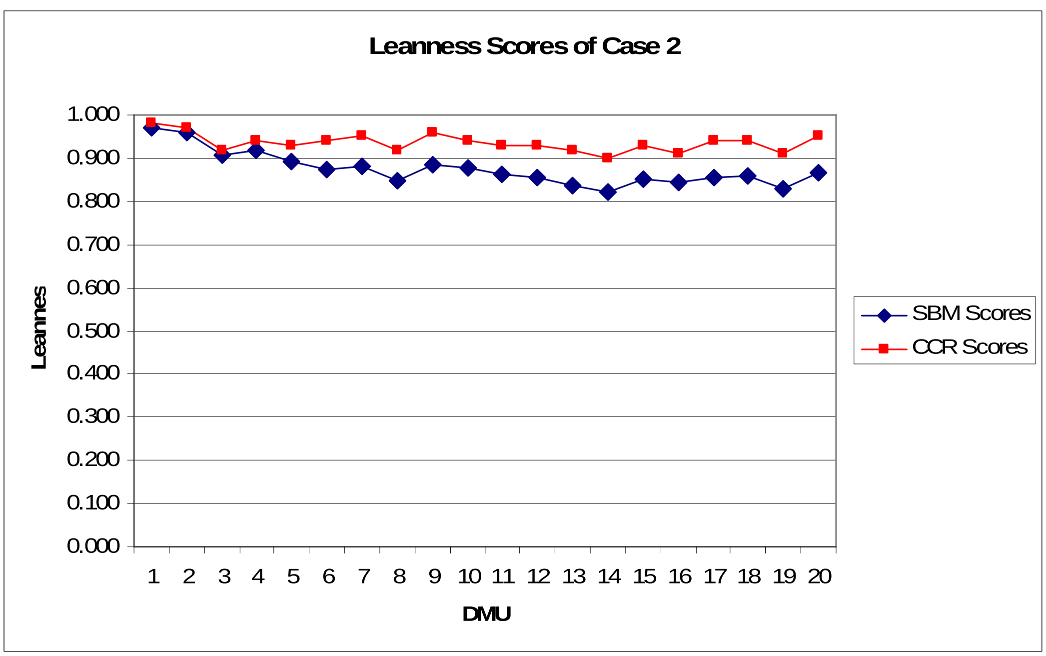


Figure 3.21 Leanness Scores of Case 2: SBM Model vs. CCR Model

From Figure 3.21, the scores obtained from the two models show similar pattern, but the average leanness score decrease from 93.6% (CCR) to 87.5% (SBM). The SBM scores are considerably lower than CCR scores after DMU#4, because the first few parts spent little or no waiting time while later parts suffer from the congestions in the production line caused by the parts already in the system. Therefore, the SBM model reflects the problem in the scores successfully.

Case 3: Batch Production With Undesirable Conditions

Case Setting:

Same configuration as Case 1 is used with undesirable conditions embedded. (See Section 3.2.2.3 for details of undesirable conditions.)

Table 3.14 Results of Case 3 Using SBM Model; Compared with CCR Model

DMU	*SBM Model*	*CCR Model*			
	Leanness Score	Leanness Score	*Slacks of Benchmark*		
			Time (Excess)	Cost (Excess)	Value (Shortfall)
Part 1	**0.637**	**0.935**	97.59	0	0
Part 2	**0.634**	**0.931**	96.82	0	0
Part 3	**0.621**	**0.903**	92.40	0	0
Part 4	**0.576**	**0.814**	77.75	0	0
Part 5	**0.626**	**0.913**	94.03	0	0
Part 6	**0.547**	**0.898**	198.52	0	0
Part 7	**0.332**	**0.546**	121.13	0	0
Part 8	**0.322**	**0.527**	115.79	0	0
Part 9	**0.558**	**0.919**	204.44	0	0
Part 10	**0.453**	**0.796**	346.63	0	0
Part 11	**0.800**	**0.930**	21.39	0	0
Part 12	**0.599**	**0.904**	114.63	0	0
Part 13	**0.000**	**0.000**	0.00	0	0
Part 14	**0.587**	**0.879**	110.02	0	0
Part 15	**0.467**	**0.640**	65.10	0	0
Part 16	**0.593**	**0.892**	112.48	0	0
Part 17	**0.536**	**0.890**	216.08	0	0
Part 18	**0.537**	**0.893**	217.09	0	0
Part 19	**0.523**	**0.865**	208.38	0	0
Part 20	**0.542**	**0.902**	219.88	0	0
Average	**0.524**	**0.799**			

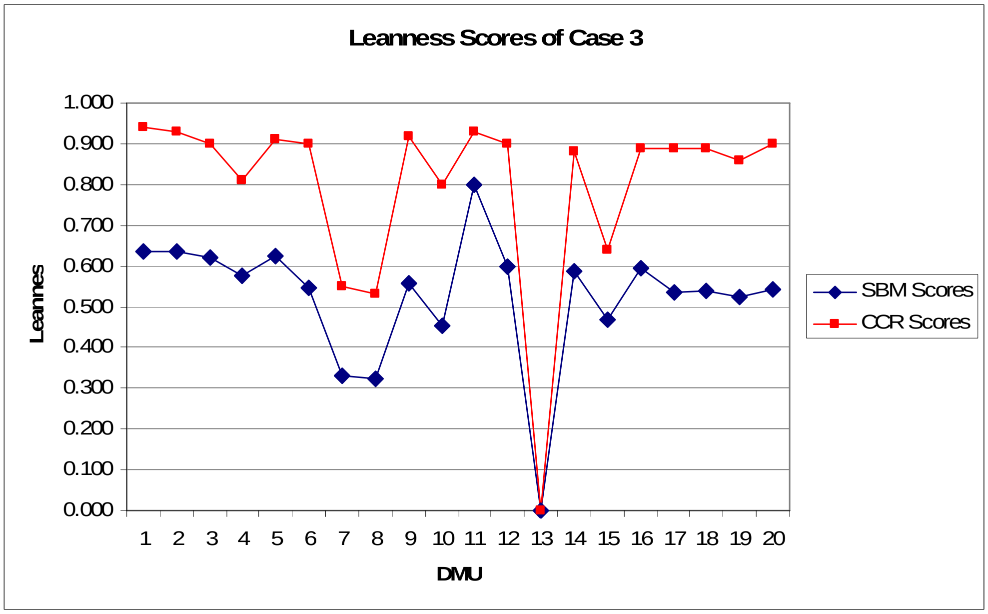


Figure 3.22 Leanness Scores of Case 3: SBM Model vs. CCR Model

In Case 3, the results from both models show a very similar pattern. The DMUs with problems embedded receive lower leanness scores (i.e., Part #4, #7, #8, #10, #13 and #15). Again, SBM model gives lower score for every DMU because of the existence of slacks in the CCR model. Among the DMUs, Part #11 receives significantly higher score in the SBM model, which is not seen in the CCR model. From Figure 3.16 in Section 3.2.2.3, Part #11 is the most efficient ADMU that locates near the cluster of IDMUs in the Cost-Time space. Therefore, the SBM model correctly reflects the situation, which is difficult to tell from the results of CCR model.

In summary, the hypothetical cases demonstrate the capability of DEA-Leanness Measure on capturing the wastes and evaluating the leanness level of manufacturing systems. CCR Model, the original DEA model, does not include the inefficiency caused by slacks in the leanness score. This weakness limits the effectiveness of CCR model on performing DEA-Leanness measuring since slacks are often found in general manufacturing cases. The SBM model provides a solution to include all sources of inefficiency into the leanness score and becomes a better choice for DEA-Leanness Measure. The SBM model is used in all the other analyses in this research.

3.4 Contributions and Limitations of DEA-Leanness Measure

The proposed DEA-Leanness Measure provides a way to quantify the leanness level of a manufacturing system based on a benchmark of ideal leanness obtained from historical data. For lean practitioners, the leanness scores answer the question, "how lean is the system?" Comparing to existing leanness assessment approaches, the development of DEA-Leanness provides following specific contributions.

Contributions:

1) **Integrated Index of Leanness:** The first contribution of this research is to apply DEA technique on measuring leanness. The leanness score derived by the DEA-Leanness Measure provides an integrated index of leanness level of manufacturing systems, which eliminates the need to interpret several lean metrics at the same time. The score captures various types of wastes and provides a broad picture of the level of leanness or waste of a system. The 0 to 1 unit-invariant scale is easy to understand and efficient to compare between different observations. It also provides the information of how much waste can be possibly removed from the current system in order to reach ideal leanness.
2) **Multiple Inputs:** Most of the existing lean metrics consider either time-based efficiency or cost efficiency only. The DEA-Leanness Measure considers the investments on *Cost* and *Time* simultaneously as well as the output value of the production effort.
3) **Variable Scope of Application:** For lean practitioners, different granulations of value stream map are of interests during different stages of lean implementation. Since the DEA-Leanness Measure utilizes the summations of cost, time and value, it can be applied to a selected portion of a value stream regardless of the configuration of the value stream. Measuring the leanness level of a complicated value stream is made possible.
4) **Self-contained Benchmark:** Traditionally, lean practitioners rely on predefined lean indicators or benchmarks from industrial group, published research or consultants to evaluate their leanness. Using the DEA-Leanness Measure, the

frontier of leanness can be identified using historical data. The self-contained benchmark eliminates the need to outsource for leanness benchmarks.

5) **Up-to-date Frontier:** The real frontier of leanness changes when technologies or management skills improve. The leanness frontier obtained from the DEA-Leanness Measure can be updated continuously when new data set is obtained.
6) **Performance Standard:** Comparing the DMUs having high or low leanness sore may shed light on the performance standard for repeating production activities.
7) **Directions of Improvements:** The projection point of each ADMU on the frontier provides a direction of possible improvement. The distance between an ADMU and its benchmark suggests the extent of potential improvement in cost, time and value (quality). Further investigation on the detailed processes is required to form an actual improvement plan.
8) **Tradeoffs between Competitive Strategies:** The measure provides a potential on helping decision makers to weight their competitive strategies. Improvements on one variable often contradict the performance on other variables (e.g., time vs. cost, value vs. cost, and time vs. value). The leanness measure provides quantitative indices on how well the improvements are, or which strategy works better.

In spite of the above contributions listed above, certain limitations associated with the DEA-Leanness Measure are as follows.

Limitations:

1) **Effectiveness of Leanness Frontier:** Since there are potentially some unidentifiable wastes (Figure 3.4), the frontier identified by DEA-Leanness Measure may not be representing the true ideal leanness. A detailed and accurate cost breakdown which identifies VA and NVA costs is required to improve the quality of the frontier. Also, the ideal leanness changes over time, the cost breakdown needs to be revaluated continuously.
2) **Determining the Scope of Measurement:** The scope of the leanness measurement can be determined by the user of the model. It can be a

measurement for a workstation, a cell, a department, or a supply chain. However, leanness of a section of a system does not represent the leanness of the whole system. The scope of the measurement should be determined based on the needs of the decision maker, and the results should be carefully interpreted based on the chosen scope.

3) **Leanness Target:** Improving the system to achieve 100% appears to be the ultimate goal for lean practitioners. However, there are some situations that make this goal infeasible. A leanness target considering the unavoidable wastes would be more reasonable. A methodology to identify a practical target can enhance the application of the DEA-Leanness Measure.
4) **Improvement of the Value Stream:** The leanness measurement presents the extent of potential improvements on cost and time investments of a current value stream. However, the practical tactics to achieve these improvements are not explicitly shown in the scores. Further investigations on the inefficiency of the ADMUs are required to identify the practical actions of improvements.
5) **Data Collection:** The DEA-Leanness Measure compares the process of producing each work piece in order to find the best leanness frontier. However, collecting the detailed data of the production activities can be difficult. Furthermore, large amount of data entry may lead to difficulty of solving the mathematical model.

The limitations of the proposed DEA-Leanness Measure present some challenges about the effectiveness of the measure, which nevertheless inspire more research ideas. The following chapters introduce the extensions of the DEA-Leanness Measure, including strategic tradeoffs, improvement identification, performance targeting, and the software programs to carry out the leanness measure.

Chapter 4 Extended Applications of DEA-Leanness Measure

DEA-Leanness Measure introduced in Chapter 3 provides a new, unique means of evaluating the leanness level of manufacturing systems. The hypothetical cases demonstrated the capability of the measure. Yet certain limitations exist. In order to enhance the usability of the methodology, extended applications of DEA-Leanness Measures are explored in this chapter, starting with the tradeoffs between strategic competitiveness.

4.1 Tradeoffs between Competitive Strategies

Various improvement initiatives have been developed and applied in manufacturing systems. Under the name of lean manufacturing, a large portion of the improvement initiatives focus on time-based competitiveness. Some of these JIT techniques, such as Single Minute Exchange of Die (SMED), actually incur additional costs to certain degree. Other initiatives which focus on the competitiveness of cost, quality or customer satisfaction may also undermine the other factors. As a result, tradeoffs should be made in every decision while improving the system.

Companies often select the initiatives that align with their competitive strategies. Some focus on reducing cost to grab the market, while others may want to enhance functionality or quality of the products to attract customers who are willing to pay for it. When implementing the initiatives, performance metrics are employed to evaluate the effectiveness. Conventional metrics monitors the improvements on focused areas without relating to each other. Balanced Score Card and similar methodologies monitor multiple areas of metrics to pursue a harmonic improvement based on user defined targets. These methods guide the improvements effectively, but there were no synthetic performance measure that is able to show the overall improvement towards perfection. The DEA-Leanness Measure offers the opportunity of using an integrated measure to quantify the overall performance comparing to perfection. Furthermore, the leanness measure can be weighted among cost, time and value variables to provide decision support information that is aligned with the company strategy. The impact of improvement initiatives and the weighted measure are introduced in the following subsections.

4.1.1 Impacts of Improvement Initiatives

Different competitive strategies for manufacturing systems, such as *Lean, Six Sigma or Agile*, often emphasize only part of the overall performance. Yet, the improvement initiatives may have positive impacts on one performance area but have negative impacts on the others. The DEA-Leanness Measure provides an opportunity to evaluate the impact of an improvement initiative in terms of leanness level. Based on cost, time and value, the leanness measure offers supporting information for decision makers to judge the total effectiveness of the improvement initiatives and pinpoint the best solution.

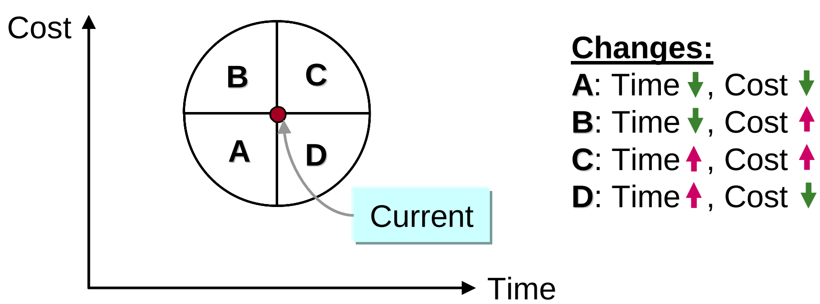


Figure 4.1 Changes from Current State in terms of Cost and Time

For a manufacturing system, the impacts of lean initiatives on cost and time can be categorized as in Figure 4.1. From the current status, a system can be improved by decreasing from one or both of the two dimensions. Therefore, sector A represents improvement; sector C represents deterioration; while the impact of section B and D depends on the amounts of the changes in the two axes. When the third axis, i.e., *Value*, is considered, the rules change. The *Value* includes profit and all customer satisfaction factors. Sector A can be deterioration if the value is decreased too much. On the other hand, sector C can be an improvement if the value increased enough to justify the increment in cost and time. As to B and D sectors, determination of the impact becomes more complicated since all three factors need to be compared. These conditions for improvements are summarized in Table 4.1.

Table 4.1 Conditions for Leanness Improvements

Direction	Requirements on Value	Example
A (Time↓, Cost↓)	Can be decreased to an acceptable level	- Use cheaper material with acceptable quality and fewer processes
Between A & B (Time↓, Cost~)		- Speed up some processes (e.g., heat treatment); decrease buffer size
Between A & D (Time~, Cost↓)		- Use cheaper material with acceptable quality
B (Time↓, Cost↑)	Must be large enough to justify the increment in Cost	- Invest on faster but more expensive equipment
Between B & C (Time~, Cost↑)		- Use expensive material, workforce, or equipment
C (Time↑, Cost↓)	Must be large enough to justify the increment in Time	- Use one operator to run multiple machines in a production cell
Between C & D (Time↑, Cost~)		- Produce at cheaper but distant facility
D (Time↑, Cost↑)	Must be increased to justify the increment in Cost and Time	- Use better material and complicated processes to enhance product value

The eight improvement directions with the value requirements in the table cover all the possible conditions of improvements in leanness level. Some examples are listed to illustrate these improvement directions but they are not the only possible cases. Impacts of the eight directions can be quantified by the proposed DEA-Leanness Measure. In Figure 4.2, nine DMUs are created in the Cost-Time space to represent the eight improvement directions.

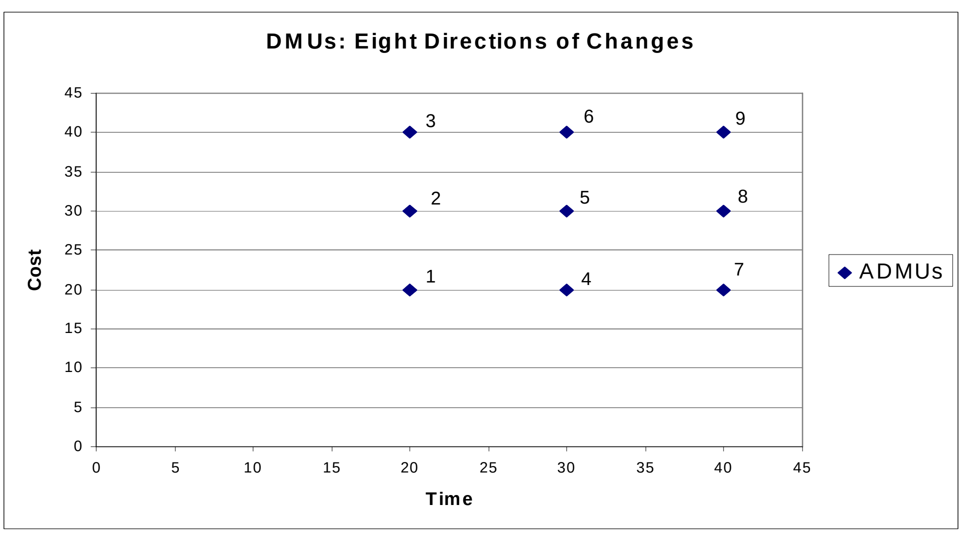


Figure 4.2 DMUs Representing Current State and Eight Directions of Improvements

From the current state (DMU#5), the leanness level would be decreased while moving to any other DMU. Three levels of output values (1.0, 0.75, and 0.5) are employed to demonstrate the requirements of value associated with each direction. The results are listed in Table 4.2 and also shown graphically in Figure 4.3.

Table 4.2 Leanness Scores of DMUs Representing Improvement Directions

DMUs	Value	Leanness Score	*Slacks*		
			Time	Cost	Value
1	**1.0**	1.000	0.000	0.000	0.000
2		0.833	0.000	10.000	0.000
3		0.750	0.000	20.000	0.000
4		0.833	10.000	0.000	0.000
5		0.667	10.000	10.000	0.000
6		0.583	10.000	20.000	0.000
7		0.750	20.000	0.000	0.000
8		0.583	20.000	10.000	0.000
9		0.500	20.000	20.000	0.000
1	**0.75**	0.750	0.000	0.000	0.250
2		0.625	0.000	10.000	0.250
3		0.562	0.000	20.000	0.250
4		0.625	10.000	0.000	0.250
5		0.500	10.000	10.000	0.250
6		0.438	10.000	20.000	0.250
7		0.562	20.000	0.000	0.250
8		0.437	20.000	10.000	0.250
9		0.375	20.000	20.000	0.250
1	**0.5**	0.500	0.000	0.000	0.500
2		0.417	0.000	10.000	0.500
3		0.375	0.000	20.000	0.500
4		0.417	10.000	0.000	0.500
5		0.333	10.000	10.000	0.500
6		0.292	10.000	20.000	0.500
7		0.375	20.000	0.000	0.500
8		0.292	20.000	10.000	0.500
9		0.250	20.000	20.000	0.500

Consider ***DMU#5 with Value=0.75*** as the original state, the other DMUs are the eight directions of improvement, and the Value associated with each DMU plays a critical role on its leanness level. From Figure 4.3, the current state receives a leanness score of 50% and is located at the middle of the chart. For the series with *Value=0.75*, DMU#6, #8, and # 9 deteriorated since the value is not increased to meet the requirements in Table 4.1. For the series with *Value=1*, the increment of value is large enough to justify the changes in cost and time in all DMUs including DMU#9. It can be seen that the increment of value just meets the minimum requirement for DMU#9 to receive the same score as the original state. As for the series with *Value=0.5*, only DMU#1 receives the same leanness score as the original state, which means the reduction in *Value* can only be justifiable if *Cost* and *Time* can be further reduced from DMU#1.

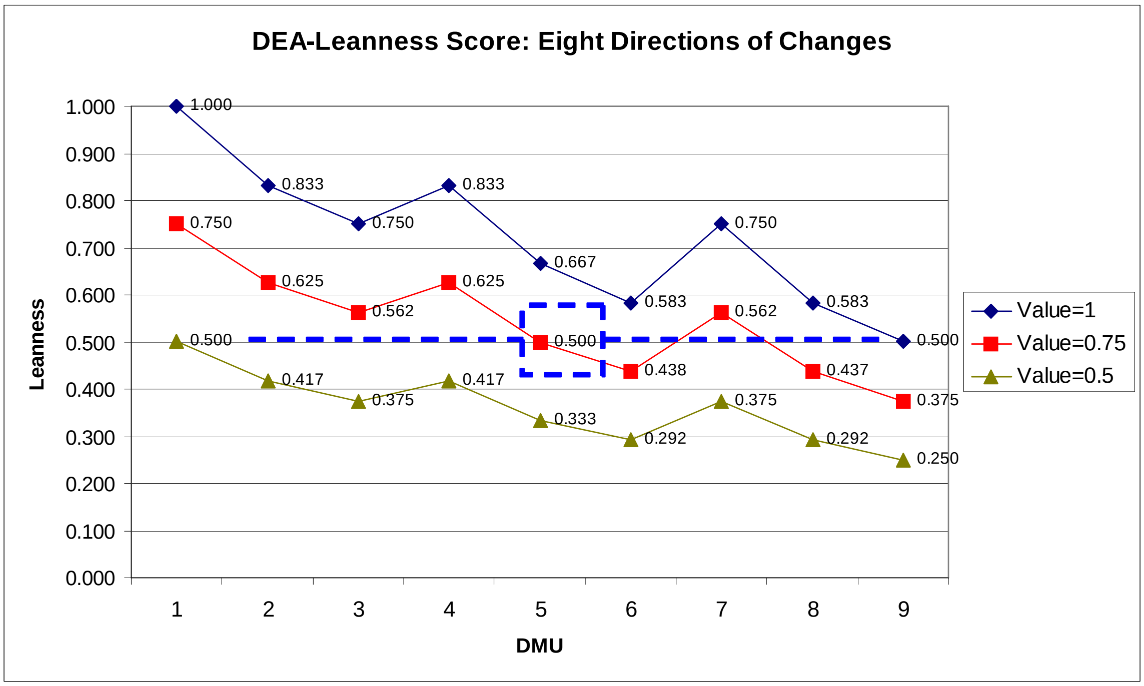


Figure 4.3 Leanness Scores of DMUs Representing Improvement Directions

In the series of *Value=0.75*, DMU #3 and DMU#7 both receives higher score than the original DMU although the increment and decline of cost and time variables should be balanced out. The reason for this result is implied by Equation (9) in Section 3.3. When the cost decreased from 30 to 20 and time increased from 30 to 40, the impact of these changes on the leanness score is the difference (-10 and +10) compared with the later value (20 and 40). Therefore, with the same percentage of increment and decrement on each factor, the decrement has greater impact. The same result applies to the output variable as well.

The example of improvement directions does not include IDMU to push the frontier. As discussed in Section 3.2.3, the IDMUs usually do not improve much after improvement initiatives since the VA cost and time normally do not decrease unless there are dramatic technology advances. If the new IDMUs do push the frontier forward, then the leanness scores of the original DMU need to be recalculated based on the new frontier. Hence, the original and improved DMUs are always compared with each other based on same standard.

In summary, the DEA-Leanness Measure provides a quantitative indication of the impacts of improvement initiatives in terms of leanness level. The measure includes cost, time and value as input/output variables and offers a synthesized, unit invariant leanness score. However, in some situations, cost, time and value may not be taken as equally important. Weighting the impacts of the changes of different variables allows calculation of a leanness measure that better reflects the strategic plan.

4.1.2 Weighted DEA-Leanness Measure

In attempting to build profitable and sustainable companies, various strategies have been developed and employed to keep a manufacturing system competitive. “Mass Production” strategy, developed in the early 20th century, increases market share by minimizing unit cost of a product. Time-based performance of the production and the customers’ individual needs are often ignored under this strategy. The “Six Sigma” methodology aims for preventing variability in a system to maximize quality of products. The results include not only improved quality but also more stable lead time and less unexpected costs. “Agile Manufacturing” stresses on rapid response to customers’ demand before competitors can react. Using this strategy, satisfying customers’ individual needs is most important, and higher unit cost or lead time is often justifiable. As to “Lean Manufacturing,” it helps companies remove various types of waste from the perspective of the customer’s viewpoint. Time-based performance is an important area of lean implementation, but lean practitioners also benefit from lower overall cost, increased product variety and more stable quality. All the abovementioned strategies have been successfully implemented, but tradeoffs between cost, time, and value are incorporated with every improvement initiatives. For a company implementing improvement initiatives, the performance measures should be aligned with the competitive strategy chosen by the company. Therefore, if different weights can be applied to the input/output variables of DEA-Leanness Measure, the leanness score can better reflect the company's need.

Since the DEA-Leanness Measure is a unit invariant index, applying a weight directly to the cost, time, or value data simply changes the scale of the numbers and has no effect on the resulting score. As mentioned in Section 3.3, the SBM model calculates the leanness scores based on input excesses and output shortfalls, i.e., slacks. Therefore, to develop a Weighted DEA-Leanness Measure, the weights must be applied directly to the slack variables in the model.

Weighted DEA-Leanness Measure (Fractional Program)

$$\text{Min.} \quad \rho_{lean} = \frac{1-(\frac{1}{2})(\frac{w_T s_T^-}{x_{T0}} + \frac{w_C s_C^-}{x_{C0}})}{1+\frac{w_V s_V^+}{y_{V0}}} \tag{19}$$

$$\text{Subject to} \quad x_{T0} = \sum_{i=1}^{n} x_{Ti}\lambda_i + s_C^- \tag{21}$$

$$x_{C0} = \sum_{i=1}^{n} x_{Ci}\lambda_i + s_C^- \tag{22}$$

$$y_{V0} = \sum_{i=1}^{n} y_{Vi}\lambda_i - s_V^+ \tag{23}$$

$$\text{Where } \lambda,\ s_T^-,\ s_C^-,\ s_V^+ \geq 0$$

<u>Notation:</u>

ρ_{lean}: Leanness Score	n: Number of DMUs
x_{T0}: Input Time of DMU_0	λ: SBM Weights for DMUs
x_{C0}: Input Cost of DMU_0	s_T^-, s_C^- and s_V^+: Slacks associated with Inputs/Output
y_{V0}: Output Value of DMU_0	w_T, w_C, w_V: Assigned weights for Inputs/Output

Similar to the original SBM model, the fractional program of the Weighted DEA-Leanness Model can be transformed into an equivalent linear program by introducing a multiplier *t* and defining the following relationships:

$S_T^- = t\, s_T^-$, $S_C^- = t\, s_C^-$, $S_V^+ = t\, s_V^-$, and $\Lambda = t\, \lambda$.

Weighted DEA-Leanness Measure (Linear Program)

$$\text{Min.} \quad \tau_{lean} = t - (\frac{1}{2})(\frac{w_T S_T^-}{x_{T0}} + \frac{w_C S_C^-}{x_{C0}}) \tag{24}$$

$$\text{Subject to} \quad 1 = t + \frac{w_V S_V^+}{y_{V0}} \tag{25}$$

$$tx_{T0} = \sum_{i=1}^{n} x_{Ti}\Lambda_i + S_T^- \tag{26}$$

$$tx_{C0} = \sum_{i=1}^{n} x_{Ci}\Lambda_i + S_C^- \tag{27}$$

$$ty_{V0} = \sum_{i=1}^{n} y_{Vi}\Lambda_i - S_V^+ \tag{28}$$

$$\text{Where } \Lambda,\ S_T^-,\ S_C^-,\ S_V^+ \geq 0, \qquad t > 0$$

As mentioned briefly in Section 3.3.1, Tone (2001) suggests that the optimal solution set of the SBM fractional program (ρ^*, λ^*, s^{-*}, s^{+*}) is equal to (τ^*, Λ^*/t^*, S^{-*}/t^*, S^{+*}/t^*). Based on this relationship, the transformation is deemed to be reversible (Cooper et al., 2004, p.99). However, this relationship is not always true. The condition $\lambda^*=\Lambda^*/t^*$ is not imposed in the model.

Consider the DMU#9 in Figure 4.2, the DMU consumes twice as much cost and time of those of reference DMU #1. When the two DMUs deliver the same level of output (let value=1), an optimal solution set of the SBM program can be derived:

Fractional Program: $\rho^*=0.5$, $s_T^{-*}=20$, $s_C^{-*}=20$, $s_V^{+*}=0$, and $\lambda_1^*=1$.

Linear Program: $\tau^*=0.5$, $S_T^{*-}=20$, $S_C^{-*}=20$, $S_V^{+*}=0$, and $\Lambda_1^*=1$, where multiplier $t^*=1$.

However, there exists another optimal solution set of the linear model that cannot be applied to the original fractional program.

Linear Program: τ*=0.5, S_T^-*=0, S_C^-*=0, S_V^+*=0.5, and Λ_1*=1, where t*=0.5.

Fractional Program: $\rho = (1-0)/(1+1) = 0.5$

Constraint #1 LHS: $x_{T9}=40$ RHS: $x_{T1}\lambda_1 + s_T^- = 20*0.5+0 = 10$

Constraint #2 LHS: $x_{C9}=40$ RHS: $x_{C1}\lambda_1 + s_C^- = 20*0.5+0 = 10$

Therefore, this particular optimal solution of the linear program is not applicable to the fractional program.

The second set of solution actually transforms the DMU#9 into a new DMU (let it be #9') that has the same level of inputs with its benchmarking DMU#1 (cost=20 and time=20), while the output of the new DMU is scaled down from 1 to 0.5. With this new profile, the leanness score of the new DMU#9' is still equal to the original DMU#9, but the slacks in *Cost* and *Time* has been transformed in to the slack in *Value*. If weights are applied to the linear program, then the results would be distorted since slacks of inputs can be transformed into slacks of output and vice versa. Using the DEA-Leanness Solver developed in MS Excel, the second solution set is picked up by the program constantly, and similar situations are found frequently in other examples and cases. Therefore, the transformation from fractional program to linear program needs to be revised.

In the transformation, the original idea should be letting $\Lambda_i = \lambda_i t$ for any i, so that $\Sigma\Lambda_i = t$ because $\Sigma\lambda_i = 1$. However, the SBM linear program proposed by Tone (2001) does not impose this condition, and the resulting solution may not be applicable to the original program. Therefore, a reversible linear program of the weighted DEA-Leanness Measure is developed by adding a new constraint as follows to ensure that $\Sigma\lambda_i = 1$ is always true.

Weighted DEA-Leanness Measure (Reversible Linear Program)

$$\text{Min.} \quad \tau_{lean} = t - (\frac{1}{2})(\frac{w_T S_T^-}{x_{T0}} + \frac{w_C S_C^-}{x_{C0}})$$

$$\text{Subject to} \quad 1 = t + \frac{w_V S_V^+}{y_{V0}}$$

$$tx_{T0} = \sum_{i=1}^{n} x_{Ti}\Lambda_i + S_T^-$$

$$tx_{C0} = \sum_{i=1}^{n} x_{Ci}\Lambda_i + S_C^-$$

$$ty_{V0} = \sum_{i=1}^{n} y_{Vi}\Lambda_i - S_V^+$$

$$t = \sum_{i=1}^{n} \Lambda_i \tag{29}$$

$$\text{Where } \Lambda,\ S_T^-,\ S_C^-,\ S_V^+ \geq 0, \quad t > 0$$

Another issue of the Weighted DEA-Leanness Measure is that the weights applied to the slacks cannot be assigned arbitrarily. In order to deliver a leanness score between 0 and 1, the weights for input slacks (w_T and w_C) must be summed up to 2, and the weight for output slack (w_V) must be adjusted accordingly. In other words, when a decision maker ranks the relative importance of the three variables into a number, certain calculation is required to translate the importance into applicable weights for the model. Let the importance of Time, Cost and Value be represented by P_T, P_C, and P_V, respectively. The actual weights applied to the model are:

$$w_T = \frac{2 \cdot P_T}{P_T + P_C} \tag{30}$$

$$w_C = \frac{2 \cdot P_C}{P_T + P_C} \tag{31}$$

$$w_V = \frac{2 \cdot P_V}{P_T + P_C} \tag{32}$$

The importance (P_T, P_C, and P_V) can be determined by surveys or individual judgments considering the strategic competitiveness. A simple solution is to assign a value scaled from 1 to 9 to each variable. For example, let P_T=1, P_C=3 and P_V=2, the resulting weights will be w_T=0.5, w_C=1.5, and w_V=1 for the DEA model.

Some more delicate methodologies can be applied to determine the importance level of the variables. For example, the Analytic Hierarchy Process (AHP) can synthesize pair-wise relative importance levels (i.e., importance of Cost to Time, Time to Value and Cost to Value) into a series of rationalized numbers between 0 and 1 with the sum equals to 1 (Saaty, 1980). However, the process is developed for a large number of qualitative decision variables. When few variables are involved, the conflicts between variables (e.g., P_T=2P_C, P_C=2P_V, and P_V=2P_T) can make the problem more complicated. In the DEA-Leanness Measure, only three variables are involved. Therefore, the delicate methodologies are not suggested for the determination of importance levels.

Using the DEA-Leanness Measure, the scores should be able to display the impact of initiatives on the performance considering the company strategy. Using the example of nine DMUs in Section 4.1.1again, the results of DEA-Leanness with different weights are shown in the following figures.

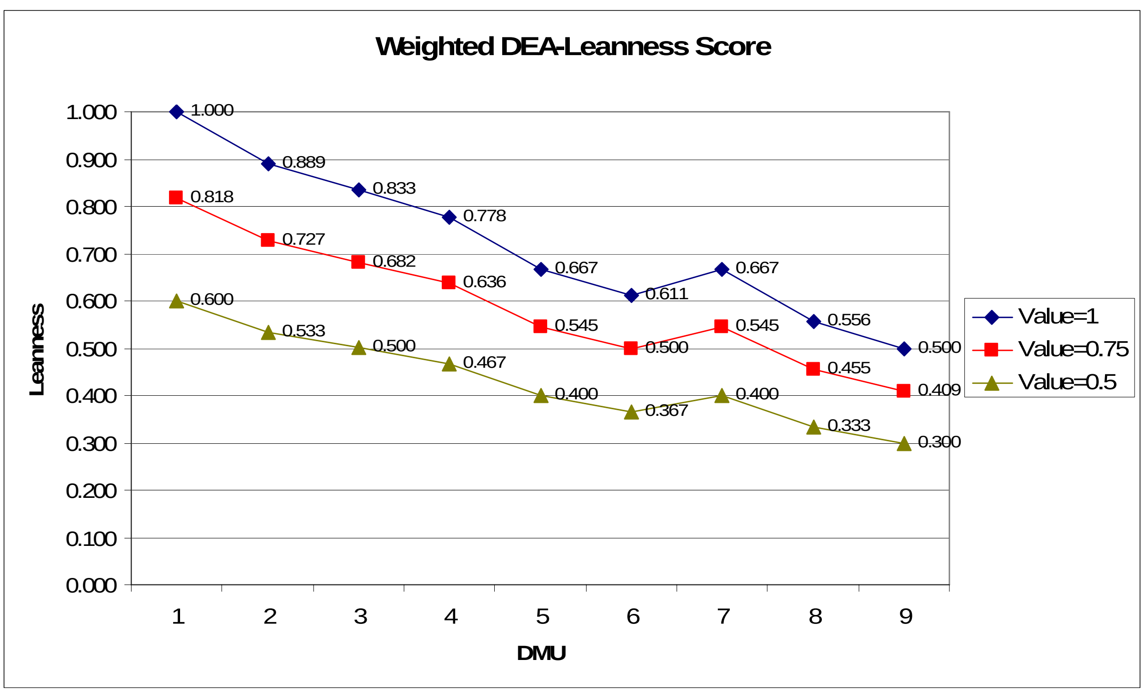


Figure 4.4 Weighted Leanness Scores with P_T=2, P_C=1 and P_V=1

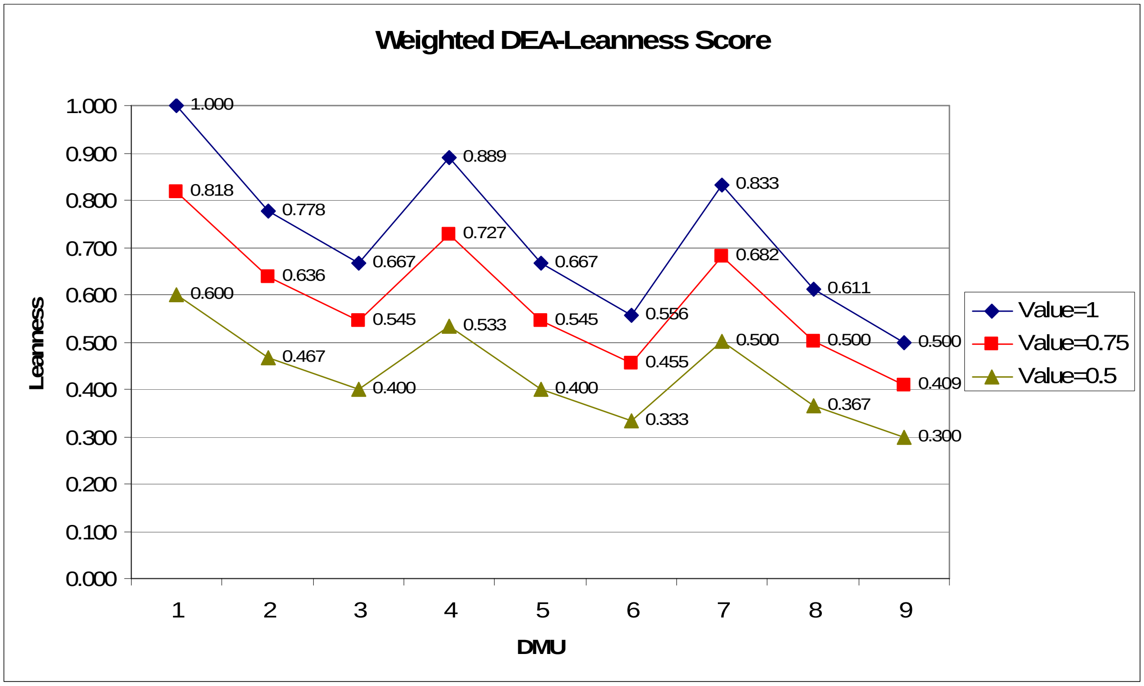


Figure 4.5 Weighted Leanness Scores with P_T=1, P_C=2 and P_V=1

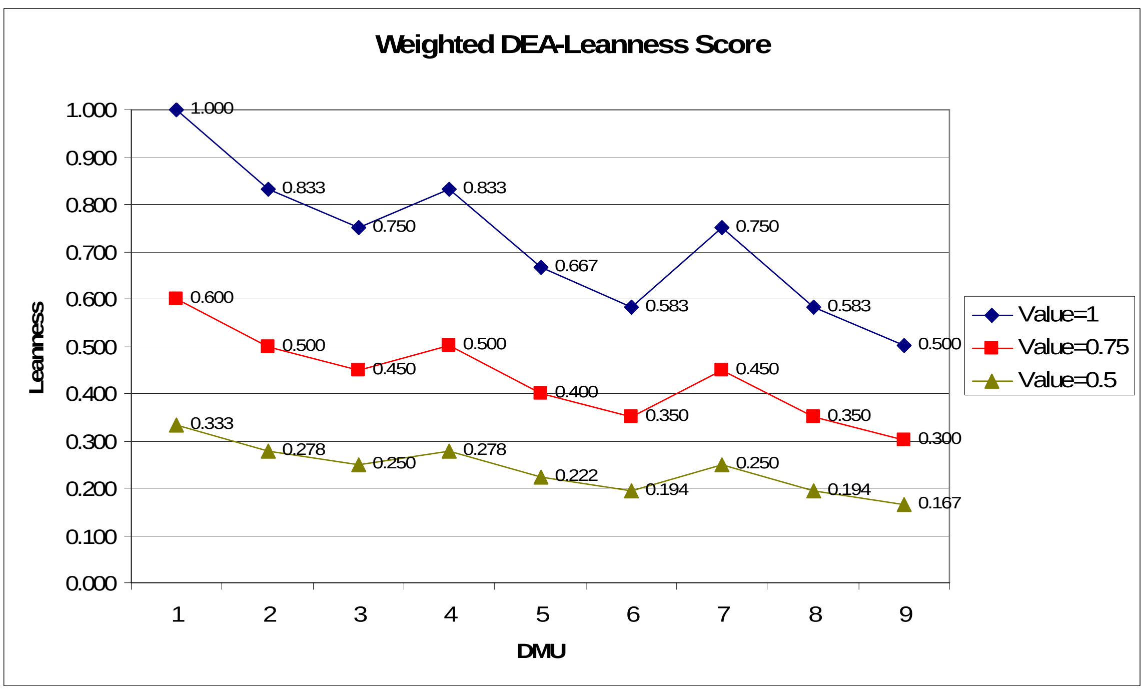


Figure 4.6 Weighted Leanness Scores with P_T=1, P_C=1 and P_V=2

From the results, when the DEA-Leanness Measure is weighted as P_T=2, P_C=1 and P_V=1 (Figure 4.4), the DMUs #4 to #9 receive lower scores than the original condition due to the time slacks of these DMUs. Similarly, when the measure is weighted as P_T=1, P_C=2 and P_V=1 (Figure 4.5), the DMUs containing more costs than DMU#1 receive lower score than original condition. Finally in Figure 4.6, increasing the weight of output *Value* affects the leanness score of DMUs in the second and third series, where full value was not delivered.

The DEA-Leanness Measure gives an indication of the current performance against perfection, and the weighted score aligns the performance measure with competitive strategies. Simplified examples are created to demonstrate the use of DEA-Leanness Measure and the weighted scores. In practice, the real cases may be much more complicated, but the concept remains the same. The DEA-Leanness Measure provides information to support decision makers in evaluating the improvement initiatives. When weights are properly assigned, the leanness score can be applied to various manufacturing strategies in addition to lean manufacturing.

4.2 DEA-Leanness Measure based on Existing Value Stream Maps

In the DEA-Leanness Measure, the whole production process of a work piece is selected to be the DMU. Using the data of each work piece, individual differences, which are ignored by average numbers, can be included. Thus, the virtual DMUs with the best possible configuration are able to push the frontier as close as possible to the ideal leanness. However, collecting data from all work pieces may require extra time and efforts. Although a Web-based Kanban system is developed in this research (see Chapter 6) to facilitate the automatic data collection and analysis, in some cases, it may not be practical to do so. One example is a large amount of work pieces flow through the production line with high speed. Long and complicated production process, such as products flowing through a long supply chain, is another example.

On the other hand, *Value Stream Mapping*, introduced by Rother and Shook (1998), has become one of the most popular tools supporting lean implementation. It maps out the VA and NVA activities with remarks of time-based performance that provide part of the information needed by the DEA-Leanness Measure. Although the information contained in a traditional *Value Stream Map* (VSM) is not quite enough for conducting the leanness measure, it should be a quick starting point if a few more information can be added to complete the requirement. Due to the popularities of this tool, many companies implementing lean manufacturing have built current state maps of their manufacturing systems. Therefore, it should be convenient for them to evaluate their leanness level by adding some extra data collected to their VSM instead of collecting hundreds of data points from the shop floor. In this section, the possibility of applying leanness measure based on VSM data is explored. The application in manufacturing systems is discussed, which lead to a potential extension of this application to measuring the overall leanness of a supply chain.

4.2.1 DEA-Leanness for Manufacturing Systems Using VSM

Value Stream Mapping has become one of the most popular techniques used by lean practitioners. The technique is simple and intuitive to use and is very effective on identifying wastes in the value stream. A typical VSM comes with time-based performance, such as time in process, waiting in buffer, time in inventory, etc. An example VSM of three VA activities is shown in Figure 4.7.

Unlike the Cost-Time-Value analysis (Chapter 3) where data is collected from every work piece, the numbers associated with a VSM can be derived from aggregated data. For example, the average *processing time* can be calculated as the total processing time of a machine divided by the number of pieces processed by the machine. Similarly, the amount of inventory divided by the daily demand represents the average *time in inventory*. Collecting the aggregated data is usually more convenient than timing every work piece. Therefore, obtaining the time averages for a VSM may require less effort than collecting data from individual work pieces, and the averages are capable of representing the general conditions of a value stream. However, an average value cannot display the variability of the actual conditions. The lost information may contain clues of the actual leanness level and potential improvements. If the DEA-Leanness Measure uses the data from a VSM directly, can the measure be accurate? Furthermore, the DEA-Leanness Measure requires more than time-based data. What are the additional data needed to be collected based on an existing VSM? Finally, the DEA-Leanness Measure needs virtual DMUs to push the frontier. Can IDMUs be created using an existing VSM? These questions are discussed in greater details as follows.

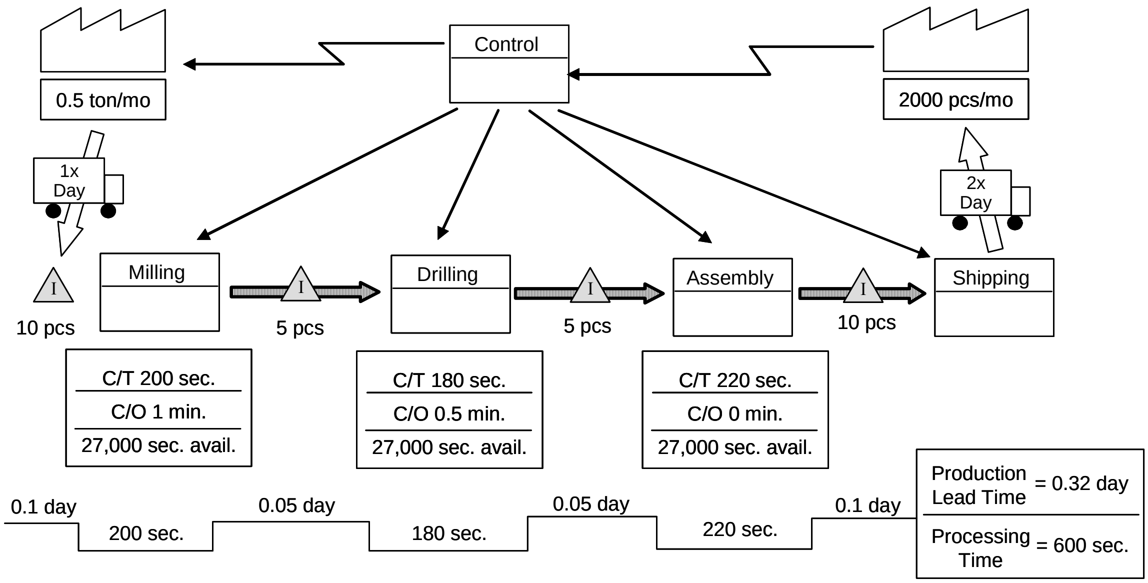


Figure 4.7 Example Value Stream Map with Three Value-added Activities

1. Preparing Data for DEA-Leanness Measure Using VSM

For the DEA-Leanness Measure, the data of input variables (*Cost* and *Time*) and output variable (*Value*) are needed to create an ADMU. From there, a corresponding IDMU can be created. The *Time* data can be collected directly from an existing VSM, but *Cost* and *Value* are not found in the map. Therefore, estimates are needed. To build the ADMU and IDMU, the following data entries are needed:

Time: The total time for one work piece to flow through the system is represented as "Production Lead Time" in the VSM. This number (0.32 day) can be used directly as the time variable of a DMU. The unit of the time needs to be consistent with the VA Time of the IDMU. In this example, the available work time is 27,000 seconds (or 7.5 hours) per day. Therefore, the production lead time 0.32 day is equivalent to 145 minutes or 8700 seconds.

Cost: A typical VSM does not show the information of costs explicitly. Therefore, the cost data need to be further analyzed. The average cost for a work piece to flow through the value stream can be calculated as the total cost of daily (or monthly) production divided by the quantity of product delivered per day (or per month). Here the total cost includes the material cost, direct processing cost, and indirect costs. Thus, all the VA and NVA costs can be included. The denominator uses the actual amount of finished products so that the costs of rework and scrap can also be included.

Value: The output value of a DMU is another type of information that cannot be found directly from a typical VSM. Same as the Cost-Time-Value analysis introduced in Chapter 3, the output value can be calculated as the retail price multiplied by customer satisfaction rate, where the satisfaction rate should reflect quality and functionality of finished product, on-time delivery, and other factors that affect the customers' perception of the experience of purchasing this product. The IDMU uses the same "Value" because the value of an IDMU cannot be assumed to be perfect when using the VA inputs obtained from the ADMU.

Value-Added Time: The "Processing Time" in the VSM is the VA Time of an IDMU. Therefore, the number can be used directly. In the example VSM, the VA time is 600 seconds (or 10 minutes).

Value-Added Cost: The VA Cost of an IDMU cannot be obtained directly from the VSM, and it should be analyzed for each VA process. For a VA process, the VA cost of daily (or monthly) production should include material cost and direct processing costs. To obtain the VA cost of one work piece, divide the daily (or monthly) VA cost by the total amount of work piece in that period including scrapped pieces. Therefore, the costs allocated to scrapped pieces are not value-adding any more.

The procedure of acquiring the *Cost, Time*, and *Value* data for the DEA-Leanness Measure is summarized in Table 4.3. A numerical example is given in the last column of the table to demonstrate the calculation. The resulting ADMU and IDMU are shown graphically in Figure 4.8.

Table 4.3 Preparing Data for DEA-Leanness Measure based on Existing VSM

	Variable	Procedure	Example
ADMU	**Time**	"Production Lead Time" from VSM	0.32 days = **145** minutes
	Cost	$\frac{\text{Daily Cost of Production}}{\text{Daily Amount of Delivered Products}}$	$1000.00 / 10 units per day = $**100.00** per unit
	Value	(Retail Price) x (Customer Satisfaction)	$120 x 95% = **114**
IDMU	**VA Time**	"Processing Time" from VSM	600 seconds = **10** minutes
	VA Cost	Sum ($\frac{\text{Daily VA Cost of a VA Process}}{\text{Delivered Amount x (1+Scrap Rate)}}$)	$500/(10x1.05) +$200/(10x1.02) +$100/(10x1.01) =$**77.13** per unit
	Value	(Retail Price) x (Customer Satisfaction)	$120 x 95% = **114**

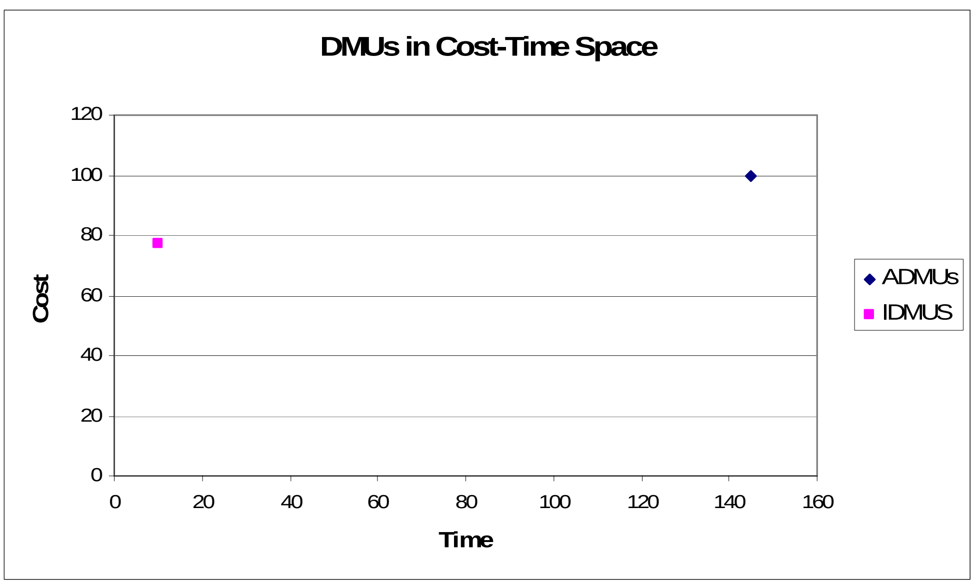


Figure 4.8 ADMU and IDMU Obtained from the VSM Example

2. Using One Pair of ADMU and IDMU for DEA-Leanness Measure

Based on the proposed procedure listed above, at least one ADMU/IDMU pair can be created. The DEA technique is developed to identify the frontier among multiple

DMUs as a performance benchmark. When very few DMUs and multiple inputs/outputs are considered, the original DEA model (i.e., CCR model) tends to form the frontier with as many DMUs as possible. Therefore, with the only two DMUs, both of them may receive a score of 100% lean. Fortunately, the SBM model is monotone increasing with regards to slacks (input excesses or output shortfalls). From the definition, *VA Time* and *VA Cost* cannot be greater than the *Total Time* and *Total Cost*. Therefore, unless the ADMU is really 100% lean, the DEA-Leanness Measure using SBM model can always capture the wastes of an ADMU and give a reasonable score. The results of the SBM model are listed below.

Table 4.4 Leanness Score Derived from the VSM Example

DMUs	Leanness Score	*Slack*		
		Time	Cost	Value
ADMU	0.420	135.000	22.870	0.000
IDMU	1.000	0.000	0.000	0.000

Actually, when only a pair of ADMU and IDMU is considered, the leanness score of the ADMU can be calculated directly using Equation (9) without going through the linear program. The calculation is listed below, which gives the same result as the SBM model. Consequently, Equation (33) can be applied whenever only one ADMU/IDMU pair is considered.

ADMU (x_{TA}, x_{CA}, y_{VA}) = (145, 100, 114)

IDMU (x_{TI}, x_{CI}, y_{VI}) = (10, 77.13, 114)

$$\text{Leanness Score} = \frac{1-(\frac{1}{2})(\frac{x_{TA}-x_{TI}}{x_{TA}}+\frac{x_{CA}-x_{CI}}{x_{CA}})}{1+(\frac{1}{1})(\frac{x_{VA}-x_{VI}}{x_{VA}})} \tag{33}$$

$$= \frac{1-(\frac{1}{2})(\frac{145-10}{145}+\frac{100-77.13}{100})}{1+(\frac{1}{1})(\frac{114-114}{114})}$$

= **0.420**

The pair of ADMU and IDMU is created based on the average time, cost, and value of a selected time period. Using the same procedure, different pairs of ADMU and IDMU can be created for different period of time. As a result, more than one pair of DMUs can be created, and the average leanness level of different time windows can be compared. However, the IDMUs are created using average number. The chance reaching the ideal leanness by the IDMUs declines since the best configuration of DMUs has been averaged out. The resulting leanness score may overestimate the actual leanness level since the benchmark may not be lean enough.

3. Pushing the Frontier Further towards leanness

Since the average numbers may not be able to represent ideal leanness, the leanness score may not be accurate. In order to ensure the quality of the frontier, the best historical IDMUs forming the frontiers in the previous analysis should be included. A rolling DEA approach is proposed in Section 4.4 to deal with the historical frontier DMU. In this approach, the historical frontier is replaced by the new frontier if the later one is leaner. Therefore, only the best DMUs of all time will be kept in the historical frontier database. Using this approach, the frontier is guaranteed to be as good as that created from previous DEA-Leanness analysis.

Beside historical data, leanness benchmark obtained externally can provide valuable information. If an external benchmark is available and can be translated into a DMU, it can provide an indication on how competitive the system can be in the market. The problem with this method is that external benchmark is not always available or trustworthy. This confirms an importance of using DEA technique that a self-contained benchmark can always be identified.

Another way to acquire good IDMUs is actually sampling from the manufacturing system. Although this section proposes a methodology to perform DEA-Leanness using existing VSM without collecting actual data, sampling is an activity that is important for all improvement techniques including VSM. The suggestion is to collect certain amount of IDMUs from actual production periodically and then, use these IDMUs to ensure the quality of the frontier in the later leanness analyses based on existing VSM.

Other than the abovementioned methods, statistical techniques can be used to identify a better frontier. It is much more complicated, since the distribution of the data and some required statistics are unknown. Nevertheless, the resulting frontier may not be reasonable if the estimates are incorrect. Therefore, the statistical techniques are not recommended for forming the frontier further. With DEA technique, at least the frontier is obtained from the data that are collected from real settings.

4.2.2 DEA-Leanness Measure for Supply Chain

The previous subsection discusses the potential use of DEA-Leanness Measure based on existing VSM when data of individual work pieces is difficult to obtain. Another situation where collecting individual data can be difficult is in the case of complicated systems, such as a supply chain. When a product goes through many distantly located facilities, collecting the detailed *Cost, Time,* and *Value* data becomes cumbersome, let alone separating the VA and NVA inputs. Jones and Womack (2002) apply the *Value Stream Mapping* technique on the *Extended Value Stream*, which is actually a supply chain. The map is similar to the VSM for manufacturing system but with wider scope and larger granulation. In the VSM for supply chain level, detailed processes within a manufacturing facility are replaced by an icon with aggregated time-based performance. Figure 4.9 shows a simplified example of the VSM for supply chain. Similar to a detailed VSM, the line segments on the bottom of the map displays the timeline of the whole supply chain operating process. The numbers above the upper lines represent “Transportation Time.” Numbers above the lower lines are “In-plant Time” with “Value Creating Time” in the brackets. Below the line segments, there are numbers of the “Steps” involved during that period. These numbers are summarized in the data boxes at both ends of the map.

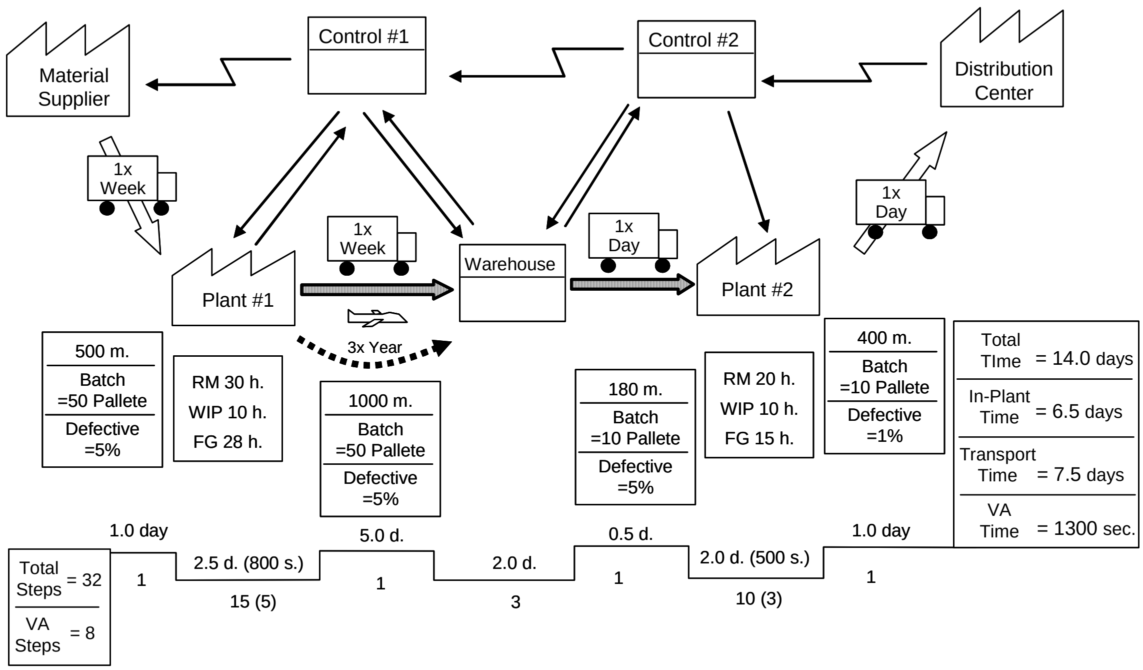


Figure 4.9 An Example of VSM for Supply Chain

For a product flowing through a supply chain, transportation and warehousing are typically the activities that make up most of the total time. In this example, the total time is 14 days, of which 7.5 days are transportation time and around 6.4 days are in-plant but NVA time. Only 1,300 seconds (=21.67 minutes) are processing time that actually adds value. It can be expected that the leanness level would be very low if these numbers are plugged into the DEA-Leanness Measure directly. However, whether the transportation time should be considered as non-value-adding is questionable?

According to Toyota Production System (Ohno, 1988), transportation is one of the seven types of waste that should be eliminated. The lean manufacturing concepts basically follow this rule and categorize transportation as non-value-added activity. Indeed, in-plant transportation is not adding value, and it should be eliminated or combined with value-added activities if possible. Outside the plant, scarce materials are normally found in certain areas in the world, and companies with different specialties are not necessarily located nearby. Without transportation, most industrial materials would not be available, and the companies with different specialties would not be able to work together. Therefore, transportation between different facilities may have to be considered as value-adding.

The DEA-Leanness Measure can be applied to the supply chain level based on the extended VSM by considering transportation as VA activity. The cost and time of different transportation methods may be dramatically different, which may also affect the output value. For example, delivery products by ship may be the cheapest way for international supply chains, but it takes weeks or even months. On the other hand, air delivery is the fastest, but it can cost several times more than regular delivery. From the customer's point of view, if time is the most important factor, than air delivery can mean better service or higher output "value." Otherwise, the regular delivery may be more welcomed. As a result, there are tradeoffs between different transportation methods. The DEA-Leanness Measure provides a way to evaluate the impact of using different transportation methods in terms of leanness level of the supply chain.

Based on the example of VSM for a supply chain (Figure 4.9), the data entries of *Cost*, *Time*, and *Value* variables can be obtained by using the procedure introduced in Section 4.2.1. Since two types of transportation (by truck or by air) are available between "Plant #1" and the "Warehouse," two pairs of AMDU and IDMU can be created accordingly. The data of the DMUs are listed in Table 4.5. Figure 4.10 shows the DMUs graphically in the Cost-Time space without considering the difference of output value.

Table 4.5 ADMUs and IDMUs Obtained from a VSM for Supply Chain

VSM	Transportation from Plant #1 to Warehouse	Cost	Time	Value
ADMU 1	By Truck	200	14	300
ADMU 2	By Air	300	9.5	320
IDMU 1	By Truck	180	7.6	300
IDMU 2	By Air	280	3.6	320

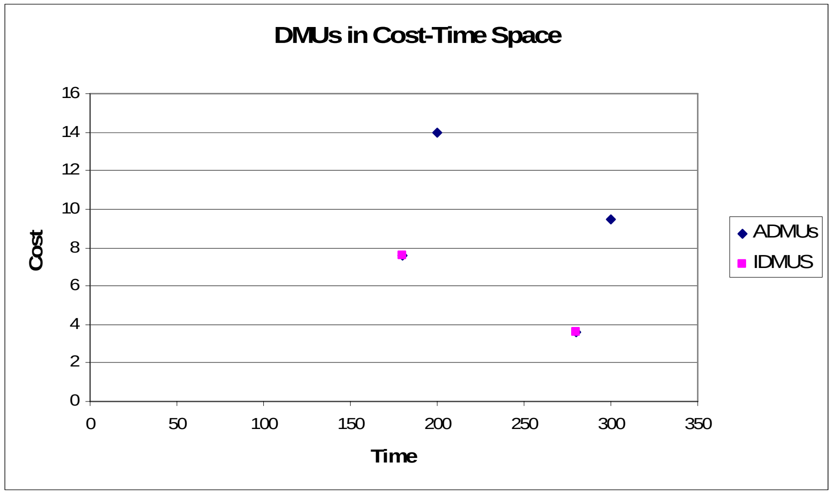


Figure 4.10 The DMUs from the VSM for Supply Chain

Table 4.6 Leanness Score Derived from the VSM for Supply Chain

DMUs	Leanness Score	*Slack*		
		Time	Cost	Value
ADMU 1	0.721	20.000	6.400	0.000
ADMU 2	0.656	20.000	5.900	0.000
IDMU 1	1.000	0.000	0.000	0.000
IDMU 2	1.000	0.000	0.000	0.000

Table 4.6 lists the results of the DEA-Leanness Measure for the example supply chain. From the leanness scores, the DMU delivered by truck receives higher leanness score than by air. Consequently, in this example, the delivery by air is not justifiable with the limited increment in output value.

In this section, the potential applications of DEA-Leanness Measuring using VSM are introduced. When the *Cost, Time,* and *Value* data can be acquired more conveniently for a VSM, this method provides a quick path to evaluate the leanness level of the target system. Two examples are employed to demonstrate the possibility of this application on manufacturing system and supply chain levels. Nevertheless the effectiveness of this application can be better verified using real cases in the future research.

4.3 Identifying Potential Improvements Based on DEA-Leanness

The DEA-Leanness Measure provides a way for lean practitioners to answer the question: "how lean is the system?" Knowing the leanness level, the next question would be "how to become leaner?" In other words, what are the wastes that can be removed from the current system? *Value Stream Mapping* is a powerful tool for lean practitioners to identify VA and NVA activities. A future state map created from the current condition provides guidance for improvement actions. However, cost is not explicitly shown in the map, and the time averages used in a VSM only display a general condition. The individual differences of the production of each work piece may contain clues for further improvement. In other words, if the DMU receiving the highest leanness score is compared with the one receiving lowest score, the difference between the two DMUs reveals the potential improvement directions. Yet, how to compare the DMUs becomes the core question to be answered. The answer lies in the Cost-Time-Value analysis that is proposed in Section 3.1.3 for data collection.

4.3.1 Cost-Time Profile (CTP) Analysis

The leanness level of a manufacturing system can be improved by decreasing cost or time consumed by the process, or by improving the output value. In order to identify the potential areas that can be improved, the cost and time consumed in the process and the output value need to be compared. In Section 3.1.3, a Cost-Time-Value analysis is introduced to prepare the input/output variables for each DMU. A Cost-Time-Value chart (Figure 3.5) is used to illustrate the relationships between the three variables. This very chart can be the tool to compare the cost, time and value data between DMUs and further identify potential improvement areas. Actually, a very similar tool has been developed and implemented a few decades ago. Before getting into the improvement identification, the original tool is introduced first.

The *Cost-Time Profiling* technique was developed by Westinghouse in the 1970s to "identify, understand, and quantify business process improvements" (Fooks, 1993). With this technique, a *Cost-Time Profile* (CTP) maps out the monetary investment over the timeline of a production process (Rivera and Chen, 2006). Figure 4.11 shows a sample CTP that demonstrates the components of a CTP.

In a CTP, the "Costs" are accumulated along the timeline of manufacturing processes. A vertical segment of the profile represents the time-invariant investment which happens all at once on a time spot, such as the arrival/addition of material or parts in a production line. A slope represents a time-based investment, such as labor costs, which increases over time. Horizontal segments are the waiting periods where no direct costs are added during that period.

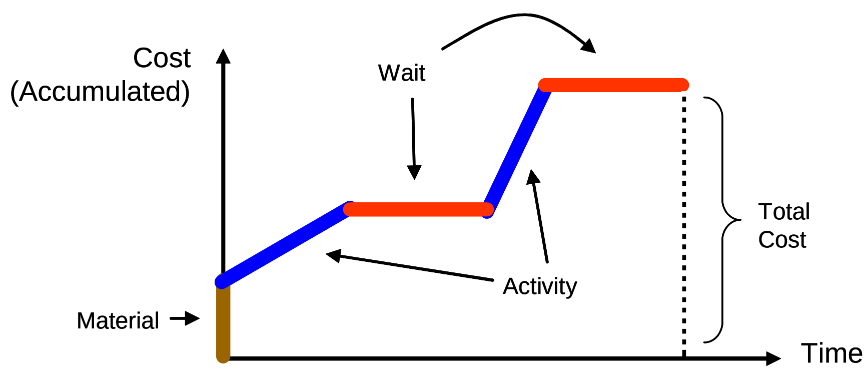


Figure 4.11 The Components of a Cost-Time Profile

When a CTP is built, the area under the curve, known as *Cost-Time Investment* (CTI), represents the time-value of working capital that has been locked in this process (Rivera and Chen, 2006). The CTI can be improved (decreased) by decreasing total cost, shortening lead time, or simply postpone an activity or the arrival of material. A smaller CTI value means more freedom of the working capital during that process, but it does not necessarily mean less total cost or shorter lead time. Similar to the tradeoffs between cost and time in the leanness measurement, when one of the two factors has been decreased to a certain level, the increment in the other factor can be justifiable within an acceptable range. As a result, the area under the curve can be decrease by cutting down from either or both axes. Thus, the CTI value can be used to evaluate the impacts and tradeoffs of improvement initiatives in terms of cost and time.

A CTP looks very similar to the Cost-Time-Value (CTV) chart in Figure 3.5, but there are fundamental differences between the two charts.

1) **Output Value**: The output value of the product is not included in the CTP. Therefore, using a CTP, tradeoffs between improvements are only compared by cost and time or the CTI without considering the impacts on value. The CTV analysis, on the other hand, includes the output value for the DEA-Leanness Measure. The resulting scores provide different information from the CTI area.
2) **VA vs. NVA**: The CTP does not differentiate VA and NVA activities explicitly. The horizontal segments represent waiting, but the other types of NVA activities, such as transportation, are not distinguished from the activities. The CTV chart distinguishes VA activities from NVA activities, and also separates the VA costs from NVA costs in order to create the IDMUs. The separated costs may provide more clues on potential improvement directions.
3) **Waiting Costs**: The CTP includes material costs and direct costs in the curve. Overhead is not included, so the waiting does not increase cost. In the CTV chart, waiting still increases NVA cost over time.

CTP is a useful tool for identifying the time-value of monetary investment. However, by separating VA and NVA costs, the charts may show more information of the potential improvements on leanness. Hence, the CTV chart is suggested to be the tool for DMU comparison.

4.3.2 Improvement Cycle Based on DEA-Leanness and CTV Chart

The leanness level of a manufacturing system can be improved by decreasing cost or time, or increasing output value. In order to identify the potential improvement directions, the CTV chart is employed to compare the three variables of DMUs. Figure 4.12 shows an example of a CTV chart that compares DMU#1 and #2. In the chart, VA Costs and NVA Costs of the two DMUs are plotted as curves accumulating across the production period. Leanness scores and output values are listed beside of the chart to provide necessary information for the comparison. According to the scores, DMU#2 is leaner than DMU#1, while the output values are similar. From the chart, DMU#2 uses apparently less time and a little less cost than DMU#1. Therefore, the second DMU receives higher leanness score. Assume that DMU#2 is the best DMU among a batch. The curves show that the DMU#1 spent more time on the first and last waiting period, so this is the first potential improvement for this system. Also, DMU#2 uses less time on the second process, which also leads to less time-based cost. This can be set as a performance target for the later production, which can bring the leanness level of the later DMUs closer to DMU#2. As such, the comparison of CTV charts between DMUs reveals potential improvement directions and future performance targets.

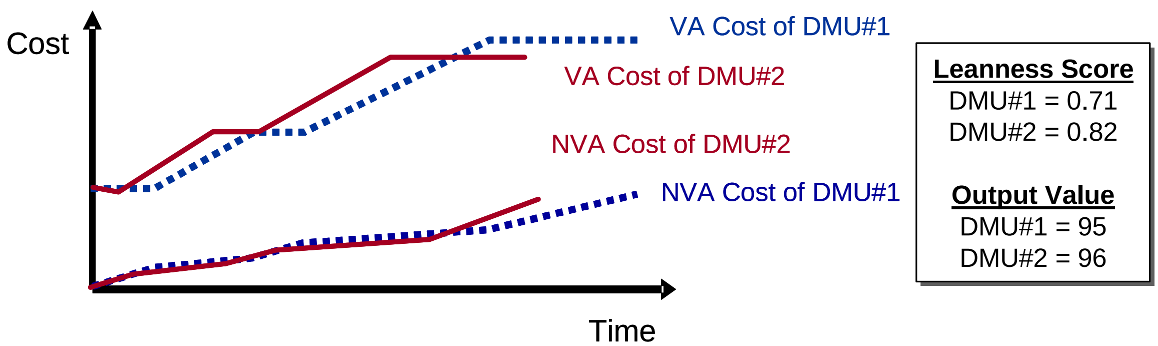


Figure 4.12 Comparing DMUs in a CTV Chart

After the improvement actions are carried out, the leanness scores should be monitored continuously to identify further improvement. The cycle of continuous improvement using DEA-Leanness Score and CTV chart is summarized as follows.

1) **Data Collection**: Collects *Cost, Time, and Value* data to create ADMUs and IDMUs for DEA-Leanness measurement.
2) **Leanness Scores**: Calculate leanness scores of the ADMUs and identify the ADMUs with highest and lowest leanness scores.
3) **CTV Comparison**: Compare the best and worst ADMUs in a CTV chart. Selected DMUs can be added to the chart for further comparison if necessary.
4) **Wastes Identification**: Identify the wastes by comparing the performance of DMUs based on the VA and NVA curves in the chart. Wastes can be found when a DMU

consumes more resources than the other DMUs during a particular activity. The best performance can be set as a performance target for the future activities.

5) **Root Cause**: Find the root cause of the identified waste. Further investigation on the manufacturing system is necessary to identify the root cause and improvement actions.
6) **Improvement**: Implement the improvement actions to enhance the leanness level of the system.
7) **Loop Back**: Start the improvement cycle all over again to carry out continuous improvement.

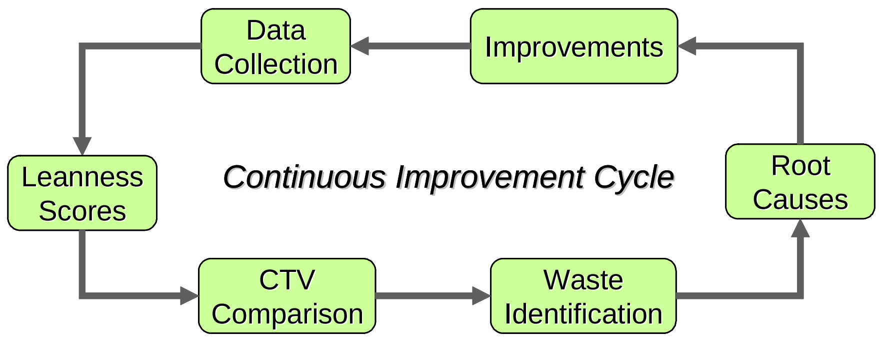


Figure 4.13 Improvement Cycle Based on Leanness Scores

Although the CTV chart is recommended as the tool for comparison, the CTP remains a useful tool for lean practitioners. The area under the curve (CTI) indicates the time-value of the monetary investments, which is not captured by the DEA-Leanness Level. It can help the lean practitioners understand the impacts of "postponement" of manufacturing activities, especially the process that differentiate product types from common material. Including the CTI in the DEA-Leanness Measure can be a direction of future research.

4.4 Rolling DEA Approach

The DEA-Leanness Measure evaluates leanness scores by comparing ADMUs with IDMUs. The more DMUs are included in the data set, the better leanness frontier can be established. However, including too many DMUs may lead to difficulty in solving the mathematical program. In reality, some types of products are produced in a cycle time as short as seconds. With this pace, thousands of ADMUs can be obtained from one day's production. Furthermore, creating corresponding IDMUs from ADMUs doubles the size of a data set. As a result, setting up and solving the mathematical model for the DEA-Leanness Measure may require a lot of extra efforts and time. In order to practically implement the leanness measure, a *Rolling DEA Approach* is developed.

In most cases, only a few of the DMUs within a data set lies on the frontier. The inefficient DMUs do not contribute to the formation of the frontier. Therefore, when any of the inefficient DMUs is removed from the data set, the frontier is not affected and the leanness scores of remaining DMUs also stay unchanged. On the other hand, if a new DMU introduced to a data set is leaner than any existing DMU, the frontier will be redefined by this new DMU. The leanness scores of all existing DMUs will then become lower. Therefore, no matter how many DMUs are considered, the leanness scores are determined by the most efficient ones of the whole data set. The following figure demonstrates different frontiers enveloping Data Set 1, Data Set 2, and the combination of the two data sets. *Frontier 1* covers all DMUs in Data Set 1 but fails to cover some of the DMUs in Data Set 2. Same situation happens to *Frontier 2*. The *Overall Frontier* is defined by the most efficient DMUs from both data sets, and consequently, all the DMUs are enveloped by this frontier.

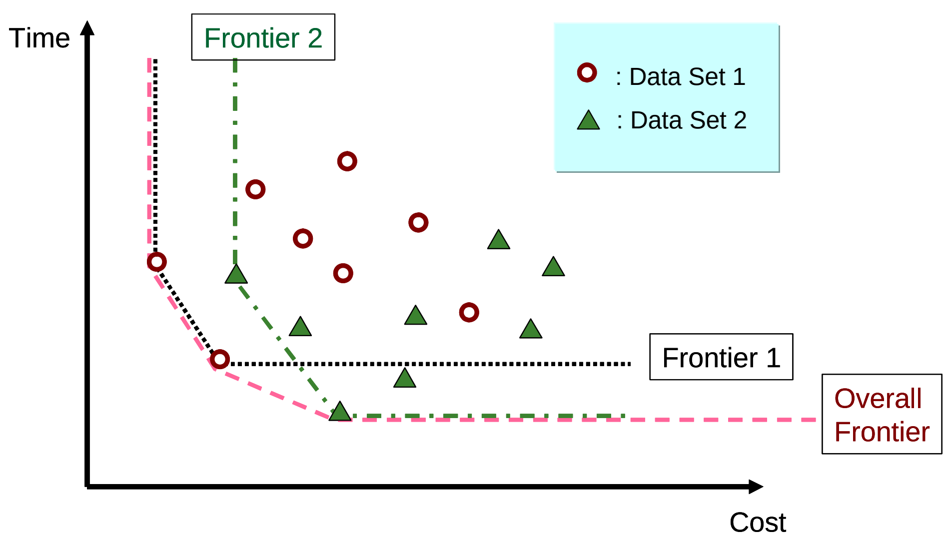


Figure 4.14 Frontiers Obtained from Different Data Sets

Based on this observation, a Rolling DEA approach is developed to ease the computation of a large number of DMUs. This approach maintains a group of *Historical Frontier DMUs* (the DMUs forming the previous frontiers) collected from previous DEA runs. As shown in Figure 4.15, every time a new data set is to be evaluated, the Historical Frontier DMUs are evaluated together with the new DMUs by the DEA-Leanness Measure. Therefore, the resulting frontier of the new data set is guaranteed to be as good as previous frontiers. If the new data set contains better DMUs than the Historical Frontier DMUs, the DMUs forming the new frontier are added to the database of Historical Frontier DMUs while the less efficient historical DMUs are removed from the database. Thus, whenever a data set is evaluated by the DEA-Leanness Measure, the resulting frontier is the closest one to the ideal leanness that can be defined from the existing knowledge.

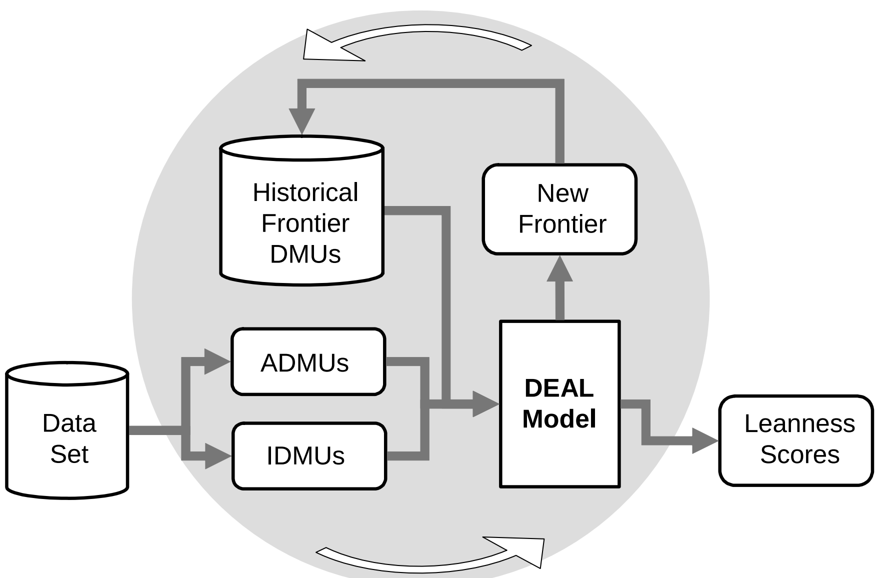


Figure 4.15 The Concept of Rolling DEA Approach

The Rolling DEA approach facilitates the process of DEA-Leanness measurement when new data sets are obtained from the manufacturing systems. Including the up-to-date Historical Frontier DMUs in every measuring process ensures the effectiveness of the leanness benchmark. In Chapter 5, it is shown that the Rolling DEA approach also makes the calculation of leanness target easier since only the DMU for leanness target is compared to Historical Frontier DMUs.

Another situation where Rolling DEA approach can be used is when a data set is too large to be solved at once. For example, the DEA Solver provided by *SAITECH* used in Section 3.2 can only handle 50 DMUs at once. Data set larger than 50 DMUs needs to be solved using the Rolling DEA approach. A large data set can be divided into smaller groups of data and solved separately. After solving all the data groups, the DMUs forming the frontier of each data group are all included in the Historical Frontier database. Following that, each of the data group is solved again together with the Historical Frontier DMUs. The resulting leanness scores are exactly the same as solving the whole data set all together.

The Rolling DEA technique is extremely important for tracking the progress of leanness improvement in a manufacturing system. When production technologies and management skills improve gradually, the benchmark of leanness should be updated accordingly. In order to compare the old data and new data on the same ground, the scores of old data sets need to be recalculated against the up-to-date frontier every time. Instead of including all data sets into a huge mathematical program, the Rolling DEA approach can recalculate the scores of every data set easily. This relaxes the requirement of computational power while keeping the same quality of output scores.

In the literature review of DEA in Chapter 2, a *Window Analysis* technique has been discussed. Similar to the Rolling DEA approach, this technique is developed to demonstrate the changes of efficiency over certain periods of time. Instead of computing efficiency scores against same frontier, the *Window Analysis* compares the performance of a set of systems observed in different time frames, which are the *Windows* of time. As a result, different frontiers are determined for different time frames. An efficiency score shows the performance of an observed system (i.e., a DMU) within a certain *Window*, and several *Windows* are compared to demonstrate the changes of comparative performance of a DMU over a period of time. Therefore the *Window Analysis* can be used to identify the leaders of DMUs (in terms of performance) over a time span and rank the rest of the DMUs. However, the efficiency scores in different time frames are not comparable since they are derived from different standard. As a result, the *Window*

Analysis cannot be used in the DEA-Leanness Measure due to the inconsistency of the standards. On the other hand, the *Rolling DEA* approach compares every data set using the same standard as long as the Historical Frontier is maintained appropriately. It supports the DEA-Leanness Measure on the comparison over time.

Chapter 5 An Integrated Lean-Agile Performance Index

For lean practitioners, pursuing perfection is the goal of lean implementation. The DEA-Leanness Measure indicates "*how much leaner*" the system can be. Yet, a "perfect" manufacturing system without any waste is not likely to exist in reality. 100% leanness may not be the answer to the question of "*how lean the system should be*." This chapter proposes a methodology to identify an appropriate leanness target for lean practitioners. The leanness level of current system can be compared with this target to determine whether it is "*lean enough*." Hypothetical cases are included in this chapter to verify the proposed methodology.

5.1 Ultimate Leanness versus Acceptable Leanness Level

The DEA-Leanness Measure provides an indication of perfection (continuous improvement). It shows how much a system can be improved from its current state to a near-perfect state. For a manufacturing system, the ideal leanness can be achieved by pull production with one-piece (or continuous) flow moving through a fully synchronized production line without any breakdown, quality problem or operational variability. Beside of the ideal condition within the system, the demand of product and supply of material must be extremely steady to avoid accumulating inventory in any stage of the system. Only if all the perfect conditions exist simultaneously can the system achieve this 100% leanness.

In reality, the above mentioned ideal situation is nonexistent. Various kinds of problems occurring in real life cause wastes in the system that lower the leanness score. Thus, the ultimate leanness may not be a practical target for real manufacturing systems.

In the development and implementation of lean manufacturing, various tools and methodologies have been developed to prevent the undesirable conditions from happening. For example, the Total Productive Maintenance (TPM) is developed to enhance productivity by avoiding wastes caused by failures of equipment; a "Poka Yoke" (mistake proof) design avoids human errors; one of the benefits of implementing "5S" in Toyota Production System is to prevent from wasting time on finding things when they are needed. These examples demonstrate how wastes can be prevented before they occur. If all sorts of waste can be eliminated from a manufacturing system, it can be perfectly lean. However, in reality, not all wastes can be fully prevented.

In the view of a manufacturing system, the leanness level is affected by two major sources of waste that can hardly be fully prevented. Internally, the design of the system confines the leanness level. Processes along the value stream may not be perfectly synchronized, and the irreconcilable imbalances lead to higher level of WIP. Externally, the batch sizes of materials and finished goods, and the pattern of demand are causing inventories of materials and finished goods. These accumulations of WIP, materials or finished goods represent delays of the production flow, which can be translated into NVA time and cost that lower the leanness level of the system. If the causes of these delays are unavoidable, then the delays cannot be fully eliminated. Therefore, a leanness score including the inevitable delays represents a minimum acceptable leanness level, if the system has not been redesigned significantly.

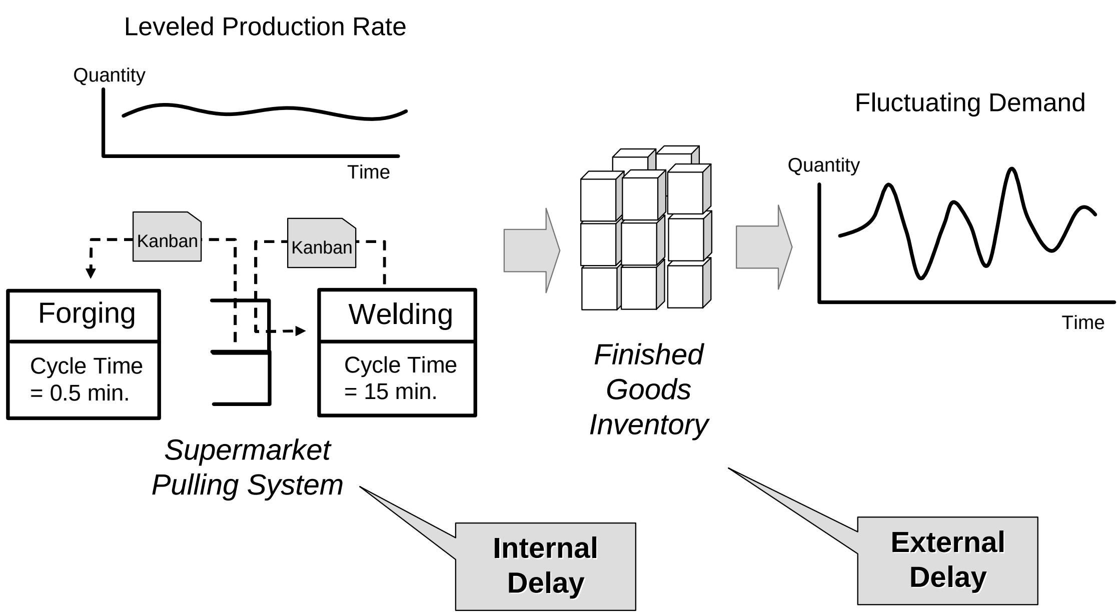


Figure 5.1 Internal Delay and External Delay of a Lean Manufacturing System

Among the causes of the delays, the imbalance and the batch sizes are determined by environmental conditions objectively. The imbalance between two production processes is caused by the difference of processing times, which are usually adjustable only within a limited range. Processes cannot be synchronized when the difference falls beyond the adjustable range. As to the batch arrivals and shipments, the size of a batch is determined by economical factors when one-piece flow is not justifiable. On the other hand, although demand pattern is determined by the customers, the production rate and safety inventory level to satisfy the demand are decisions made by the supplier. The fluctuation of demand can be coped with adjustable production rate and a low inventory level, or it can be met by a steady production rate with higher level of safety stock. When the demand fluctuates beyond the adjustable range of the system capacity, the supplier may even choose to drop some of the demand or outsourcing for extra capacity.

For a manufacturing system, leanness level represents the efficiency and effectiveness of the activities transforming inputs into desirable outputs. Less waste involved means the system is leaner. However, when the demand fluctuates, changes to the system are needed to meet the demand, such as adding operators, increasing inventory, working overtime, etc. As a result, consumptions of cost and time are increased, and the leanness level is lowered. The ability to meet different demand patterns is the agility level of the system. Satisfying volatile demand patterns requires higher level of agility, but the leanness level would be compromised. Although enhancing leanness and agility levels simultaneously would be an ideal goal, it cannot be achieved without dramatic improvements in the design of the system. Therefore, when a customer's demand is taken by a supplier, the minimum level of agility is determined by the demand pattern, and the supplier would need to enhance its leanness level as much as possible to win the market continually. The tradeoffs between leanness and agility provide a way to set an acceptable level of leanness that considers desirable level of agility.

5.2 Leanness Target Identification

The DEA-Leanness Measure quantifies the leanness level of manufacturing systems to demonstrate "*how lean the system is*", but it is not equal to "*how lean the system should be*." The ultimate leanness may not be reachable due to unavoidable conditions associated with the system, and the tradeoffs between leanness and agility should be considered.

In this section, a leanness target considering sufficient level of agility to cope with certain demand pattern is proposed. The leanness target is composed of an *Online-Delay Target* and an *Offline-Delay Target*, which correspond to irreconcilable internal and external conditions respectively. Combining the two delay targets, the *Lean-Agile Target* can be represented by a Target DMU in the Cost-Time-Value space. The corresponding score can then be derived as the acceptable leanness level for the desired agility. The methodology to identify the two delay targets are introduced in this section. Following that, a *Lean-Agile Performance Index* is introduced to compare the current state of a system against the Lean-Agile Target. The performance index shows whether the current leanness level is sufficient or not. If the index number is scored less than 1, the system needs to be improved to remain competitive in the marketplace.

5.2.1 Online-Delay Target

Within a production line, the imbalance between workstations may not be fully eliminated when the cycle times of two subsequent operations vary too much. As a result, the operations are not synchronized, and the work pieces cannot flow smoothly through the production line. In order to maintain an acceptable leanness level, the imbalance between workstations can be buffered by the *Supermarket Pulling System* invented by Toyota. An Online-Delay Target is proposed in this research to represent the minimum acceptable waiting time of the work pieces when a supermarket is installed. The target aims for a highest level of achievable leanness when imbalance cannot be fully removed. Therefore, only a minimum space of the supermarket is considered. In other words, the Online-Delay Target is the delay in a supermarket buffer that holds only one work piece.

Consider a two-station pull production system as shown in Figure 5.2. The upstream workstation, WS1, operates in a cycle time CT1. The downstream workstation, WS2, operates in the cycle time CT2. When the system runs continuously, the time for a work piece to flow through the system can be categorized in three scenarios as follows.

a) **CT1 > CT2**: When the downstream station works faster than the upstream, the downstream workstation does not block the upstream. For a pull system, the work piece leaving WS1 can be processed by WS2 right away. Therefore, no buffer is needed, and no delay is expected. The total time for a work piece to flow through is (CT1+CT2).

b) **CT1 = CT2**: When the two workstations are fully synchronized, the balanced line does not require a buffer in between. Therefore, no delay is expected. The total time for a work piece to flow through is still (CT1+CT2).

c) **CT1 < CT2**: When the downstream station works slower than the upstream, the upstream workstation would need to wait for the downstream workstation to finish. In a *Supermarket Pulling System* with a buffer spaced for one piece, WS1 starts a job when the buffer is emptied by WS2. Therefore, when the system runs continuously, the two workstations starts at the same time, and the WIP between the two stations would be delayed for a time of (CT2 – CT1). The total time for a work piece to flow through is determined by the down stream, which is (CT2 x 2).

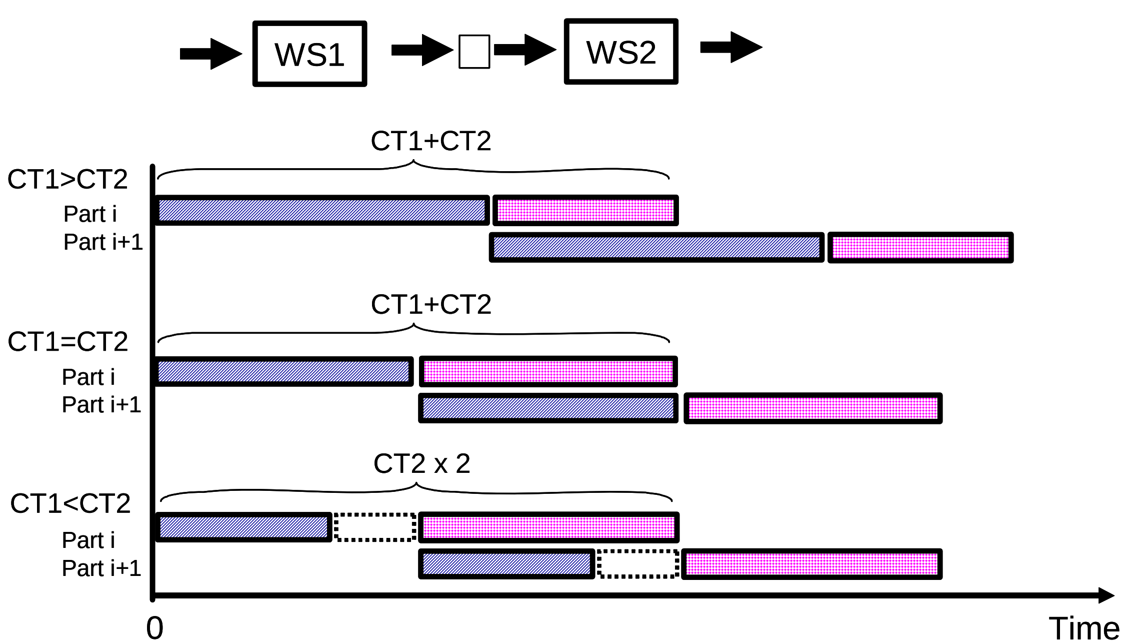


Figure 5.2 Timelines of Three Scenarios of a Two-Station Pull System

When more than two workstations are involved in a production line, the Online-Delay Target can be identified based on the three scenarios. The downstream workstations with longer cycle time confine the cycle time of their upstream workstations. Therefore, for any workstation, the cycle is constrained by the maximum cycle time among the later workstations. Consider an example of four workstations with processing time (4 min, 5 min, 3 min, 4 min). The resulting time for work piece to flow through the system will be (5 min, 5 min, 4 min, 4 min). If the last process requires 6 minutes instead of 4 minutes, then the resulting total time will be (6 min, 6 min, 6 min, 6 min).

The delays increase not only the time, but also the cost of a work piece. Based on the cost breakdown derived from CTV analysis, the increased costs are the NVA costs associated with the waiting periods. The extra time and cost associated with the delays caused by imbalances are summarized in Table 5.1.

Table 5.1 Cost and Time of the Online Delay Caused by Imbalances

Variable	Formula
Time of Delay	$\sum_{i=1}^{n}\left(\max\left(CT_i, CT_{i+1}, \ldots, CT_n\right) - CT_i\right)$
Cost of Delay	$\sum_{i=1}^{n}\left(Cost_i \times \left(\max\left(CT_i, CT_{i+1}, \ldots, CT_n\right) - CT_i\right)\right)$
Notation:	*n*: Number of processes CT_i: Cycle time of process i $Cost_i$: NVA cost rate of delay after process i

The "Online Delay" listed in the table is unavoidable when the imbalances are irreconcilable. Therefore, the Time and Cost of the delay cannot be eliminated either and should be considered as "Acceptable." Using the acceptable time and cost of the expected delay, the Online-Delay Target can be established. The procedure of establishing the target DMU is introduced in Section 5.2.3.

5.2.2 Offline-Delay Target

Beside the Online Delay, external conditions also cause delays off the production line. Three conditions are considered in this research (Figure 5.3). First, if materials arrive in batches, only the first work piece has the chance to enter the system directly. The other work pieces have to wait before entering the system. Similarly at the other end of the production line, finished goods (except for the last piece in a batch) cannot avoid waiting after leaving the last process if the final products are shipped in batches. Therefore, batch arrival and shipment cause unavoidable delays. In addition, finished goods may also spend time in inventory when safety stock exists for coping with fluctuations in demand. The cost and time of the three types of delays are discussed in detail as follows.

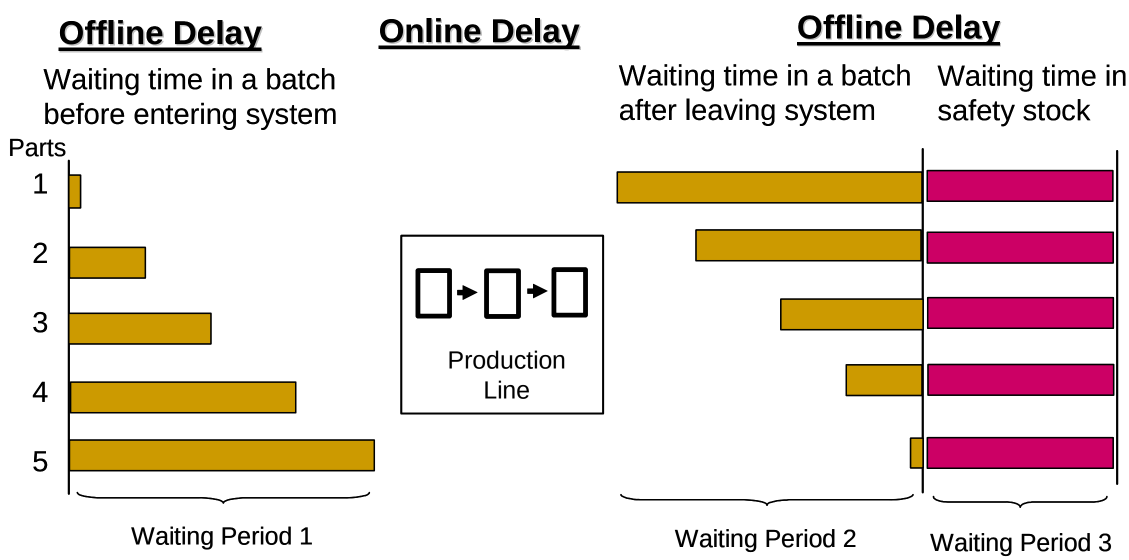


Figure 5.3 Three Types of Offline Delays

For the Offline Delay caused by batch arrival, the average waiting time of the batch is simply a half of the longest waiting time. Ideally, the production line should run in a steady rate with a system cycle time of CT_{system}, which is the longest cycle time among all the operations. Assuming that the batch size of input material is M_I, the waiting time for the last work piece before entering the system is the system cycle time CT_{system} multiplied by the number of previous work pieces in the batch (M_I-1), and the average waiting time is half of this number. The time and cost of the Offline Delay caused by batch arrival is summarized in Table 5.2.

Table 5.2 Cost and Time of the Offline Delay Caused by Batch Arrival

Variable	Formula
Time of Delay	$\frac{CT_{system} \times (M_I - 1)}{2}$
Cost of Delay	$Cost_{waiting\ \ period\ \ 1} \times \frac{CT_{system} \times (M_I - 1)}{2}$
Notation:	M_I: Batch size of the input material CT_{system}: Cycle time of the system, which is the longest cycle time of all operations. $Cost_{waiting\ period\ 1}$: NVA cost rate of waiting before entering the system

Similar to the Offline Delay before entering the system, the wait in the batch after leaving the system is also the half of the longest waiting time, which occurs at the first work piece of the batch. Calculations of the time and cost are listed in Table 5.3, which resemble the previous table, but the batch size and the cost rate can be different.

Table 5.3 Cost and Time of the Offline Delay Caused by Batch Removal

Variable	Formula
Time of Delay	$\frac{CT_{system} \times (M_O - 1)}{2}$
Cost of Delay	$Cost_{waiting\ \ period\ \ 2} \times \frac{CT_{system} \times (M_O - 1)}{2}$
Notation:	M_O: Batch size of the output product CT_{system}: Cycle time of the system $Cost_{waiting\ period\ 2}$: NVA cost rate of waiting before entering the system

The third type of Offline Delay is caused by safety stock that is used to maintain desired level of agility. Finished goods inventory is necessary when the system produces in a leveled production rate but demand is not stable. The Offline Delay in inventory is the average waiting time of the finished goods stored in the inventory before they are shipped to customer. A linear program is constructed to determine the minimum average inventory level during a period of time. Daily production rate is also determined by the linear program. After solving the linear program, the average inventory level necessary for this period of time is derived. Dividing the average inventory level by average demand rate generates an estimate for the average time spent in the finished goods inventory.

The linear program and the calculation of the acceptable Offline Delay are discussed as follows.

Linear Program for Minimum Average Inventory

$$\textit{Min.} \quad z = \frac{\sum_{i=1}^{k} I_i}{k} \tag{34}$$

$$\textit{S.T.} \quad P + I_{i-1} = D_i + I_i \qquad \textit{for } i = 1 \textit{ to } k \tag{35}$$

where, z is the minimum average inventory level;

I_i is the daily inventory level;

k is the number of days being considered for a leveled production rate;

P is the daily production rate;

D_i is the daily demand.

In the program, the number "*k*" is the time span being considered for a fixed production rate. For a certain level of demand fluctuation, the choice of "*k*" determines the inventory level and the production rate. For example, the production rate can be chosen to be changed daily to meet the demand without inventory, or it can be changes every week with an inventory level to satisfy the maximum demand of the week. If the demand is not stable, a smaller k makes the production rate change frequently, but lower safety stock level is needed. On the contrary, a larger k leads to stable production rate over longer period of time, but higher inventory level is necessary to meet the changing demand. There, the number k determines the agility level chosen by the decision maker. If the daily production rate exceeds the capacity of the system, the demand can be met by working overtime or outsourcing for extra capacity. Or the company may need to give up on the extra portion of the demand if it cannot be back logged.

With the results of the linear program, the Offline Delay caused by finished goods inventory can be calculated as shown in Table 5.4.

Table 5.4 Cost and Time of the Offline Delay Caused by Finished Goods Inventory

Variable	Formula
Time of Delay	$\frac{Average\ Inventory\ Level\ z}{Average(Daily\ Demand)} \times Available\ Munites\ per\ Day$
Cost of Delay	$Cost_{inventory} \times \frac{Average\ Inventory\ Level\ z}{Average(Daily\ Demand)} \times Available\ Munites\ per\ Day$
Notation:	z: Average Inventory Level of Selected Time Span $Cost_{inventory}$: NVA cost rate of waiting in inventory

Based on the cost and time data derived for various types of unavoidable delay, a Target DMU can be generated to form the Lean-Agile Performance Target as to be discussed in the next subsection.

5.2.3 Lean-Agile Performance Target

Combining the all expected online and offline delays, a leanness target can be identified which considers sufficient level of agility to cope with certain product demand. The procedure to identify the Lean-Agile Performance Target is illustrated below. Figure 5.4 shows the formation of the Target DMU graphically.

Step 1: Identify the expected cost and time investments of the Online-Delay Target.

Step 2: Identify the expected cost and time investments of the Offline-Delay Target.

Step 3: Identify the dominant reference DMU from the data set. The dominant reference DMU is the DMU that appears in other DMUs' reference set most frequently. This DMU serves as a base of the leanness standard before the delays are included.

Step 4: Add the expected cost and time investments of Online and Offline Delays to the dominant reference DMU to create the Target DMU.

Step 5: Calculate the leanness level of the Lean-Agile Performance Target using DEA-Leanness Measure and the Rolling DEA technique. The resulting leanness score is the target of appropriate leanness level considering the inevitable internal and external conditions.

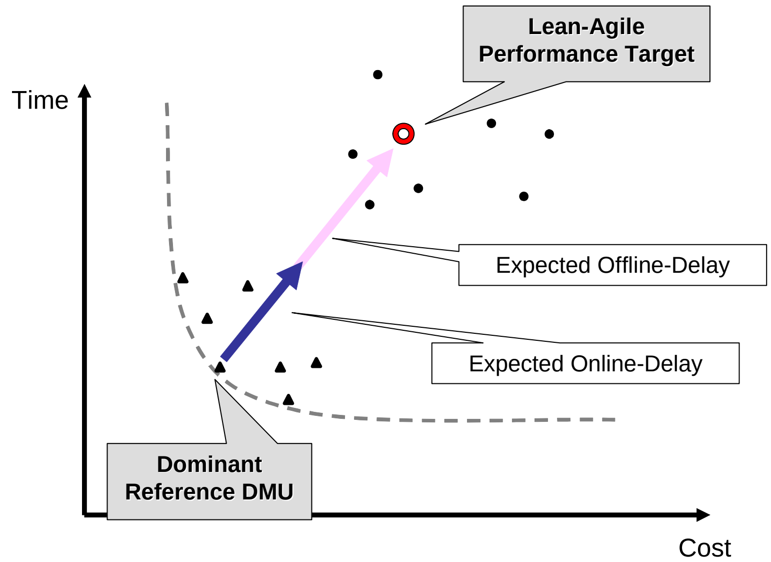


Figure 5.4 Identification of Lean-agile Performance Target DMU

5.3 Lean-Agile Performance Index

The Lean-agile Performance Target indicates a leanness level of a manufacturing system that is sufficient to handle the customer demand with current configuration. For a manufacturing system, the leanness score derived by the DEA-Leanness Measure need to be higher than the performance target. If not, improvement actions must be deployed in order to achieve the sufficient leanness. To provide an overview of the performance of a system, a *Lean-Agile Performance Index* is proposed as follows.

$$\textit{Lean-Agile Performance Index} = \frac{\textit{Average Leanness Score}}{\textit{Lean-Agile Target Score}}$$

Index ≥ 1 => *The system is lean enough.*

Index < 1 => *The system is not lean enough; improvement is required.*

The index provides a broad picture of the overall performance of the system. However, the average numbers may deceive the difference between individual DMUs. Further investigation of the lean-agile performance of individual DMUs is necessary. When the data set contains a large number of DMUs, reading the scores becomes difficult. A graphical evaluation as shown in Figure 5.5 is more convenient for decision makers to identify the best practices, worst practices, and the pattern of the individual performance in leanness. Potential improvements can be identified by comparing the CTP and CTV charts of the Lean DMUs and Un-lean DMUs. This graphical evaluation is used in the hypothetical case study.

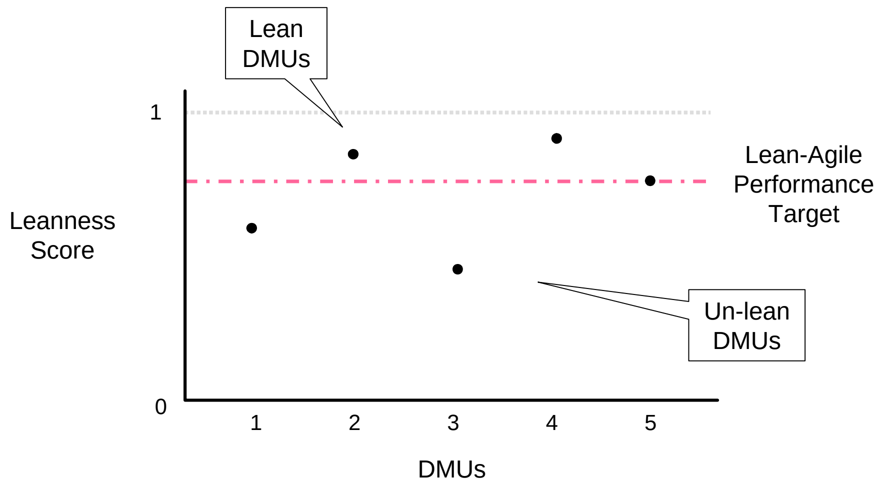


Figure 5.5 Graphical Evaluation of Lean-Agile Performance

5.4 Hypothetical Cases for Lean-Agile Targets

In this section, hypothetical cases are created to demonstrate the Lean-Agile Targets identified by the DEA-Leanness Measure. The basic settings of the hypothetical cases are the same as the cases discussed in Chapter 3 but different conditions are added to demonstrate the needs of Lean-Agile Targets.

5.4.1 Case 4: Dedicated Flow Line with Imbalanced Workstations

In this hypothetical case, processing time of each workstation is set to be different. The purpose of this setting is to demonstrate the leanness target for imbalanced line to allow certain level of WIP in between workstations. As proposed in Section 5.2, when the workstation in downstream runs faster than the upstream station, no WIP is accumulated. When the downstream workstation runs slower than upstream station, then the difference between the cycle times of the two stations is used to set the Online-Delay Target. In this case, the processing time of first operation is set to be 1/4 of the time of OP1 in Case 1.

The second operation uses the same amount of time as the OP2 in Case 1. The last operation use 1/2 of the processing time of OP3 in Case 1. It is assumed that the imbalance between workstations is difficult to be eliminated in the current system design. Therefore, a supermarket buffer is placed between WS1 and WS2 to facilitate the pulling process. Figure 5.6 shows the layout of the system in Case 4.

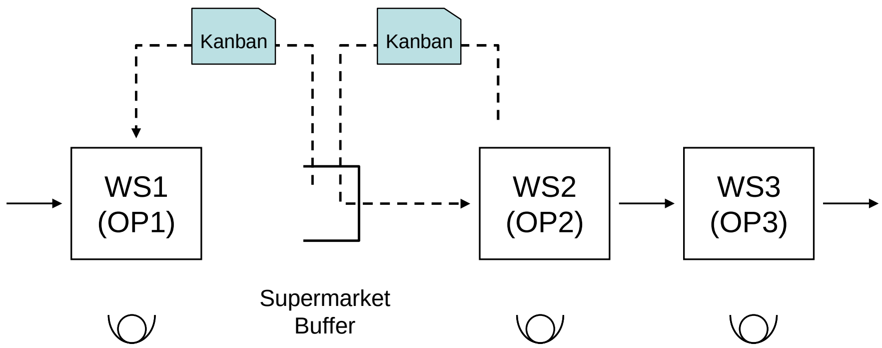


Figure 5.6 System Layout in Case 4

<u>Background Information of Case 4</u>:

Processing time:	*OP1*	*5 min. ± 0.5 min. (uniformly distributed)*
	OP2	*20 min. ± 2 min. (uniformly distributed)*
	OP3	*10 min. ± 1 min. (uniformly distributed)*

<u>Experimental Conditions:</u>

- Raw materials are pulled by WS1.
- Finished goods are removed immediately from the last workstation when the process is finished.
- WS3 is always available for parts from WS2.
- All other system settings are the same as in Case 1.

<u>Note:</u> Detailed numerical data can be found in Appendix A.

Before the online-delay target can be identified, the leanness scores must be calculated first. Following the steps in Chapter 3, the data and leanness scores are obtained as follow. Since the supermarket system is installed between WS#1 and WS#2, the waiting only occurs there.

Table 5.5 Time Stamps of Case 4

DMU	Material Arrive	Enter WS1	Leave WS1	Enter WS2	Leave WS2	Enter WS3	Leave WS3	Leave System
Part 1	0.00	0.00	4.60	4.60	23.40	23.40	33.00	33.00
Part 2	4.60	4.60	9.35	23.40	42.47	42.47	52.03	52.03
Part 3	23.40	23.40	28.72	42.47	64.43	64.43	73.75	73.75
Part 4	42.47	42.47	47.40	64.43	85.56	85.56	94.83	94.83
Part 5	64.43	64.43	68.98	85.56	106.85	106.85	117.04	117.04
Part 6	85.56	85.56	90.25	106.85	124.96	124.96	135.69	135.69
Part 7	106.85	106.85	111.59	124.96	143.86	143.86	153.28	153.28
Part 8	124.96	124.96	130.11	143.86	163.13	163.13	174.10	174.10
Part 9	143.86	143.86	148.57	163.13	181.56	181.56	190.56	190.56
Part 10	163.13	163.13	167.94	181.56	202.30	202.30	211.43	211.43
Part 11	181.56	181.56	186.72	202.30	220.91	220.91	231.18	231.18
Part 12	202.30	202.30	207.00	220.91	241.09	241.09	251.87	251.87
Part 13	220.91	220.91	226.07	241.09	260.23	260.23	271.05	271.05
Part 14	241.09	241.09	246.55	260.23	281.89	281.89	292.63	292.63
Part 15	260.23	260.23	265.61	281.89	300.41	300.41	310.17	310.17
Part 16	281.89	281.89	287.00	300.41	321.29	321.29	331.96	331.96
Part 17	300.41	300.41	305.60	321.29	339.74	339.74	349.81	349.81
Part 18	321.29	321.29	325.88	339.74	359.29	359.29	369.66	369.66
Part 19	339.74	339.74	345.20	359.29	380.61	380.61	391.01	391.01
Part 20	359.29	359.29	364.16	380.61	399.73	399.73	409.12	409.12

Unit: Minute

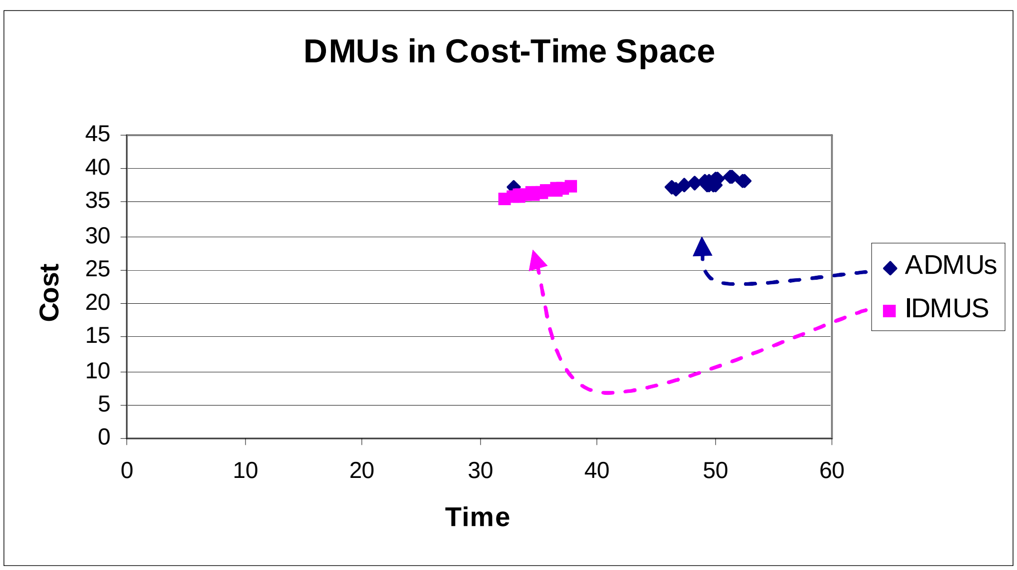


Figure 5.7 ADMUs and IDMUs of Case 4

Table 5.6 Data and Results of Case 4 Using SBM Model

DMU	*Inputs*				*Output*	*Leanness Score*	
	Total Time	VA Time	Total Cost	VA Cost	Value	ADMU	IDMU
Part 1	33.003	33.003	37.211	35.711	1.000	**0.963**	**0.983**
Part 2	47.430	33.379	37.466	35.826	1.000	**0.811**	**0.976**
Part 3	50.351	36.606	38.451	36.814	1.000	**0.780**	**0.920**
Part 4	52.366	35.331	38.087	36.416	1.000	**0.772**	**0.941**
Part 5	52.613	36.029	38.345	36.679	1.000	**0.767**	**0.929**
Part 6	50.128	33.534	37.598	35.932	1.000	**0.792**	**0.972**
Part 7	46.429	33.054	37.351	35.718	1.000	**0.820**	**0.982**
Part 8	49.142	35.397	38.159	36.522	1.000	**0.791**	**0.939**
Part 9	46.700	32.139	37.059	35.413	1.000	**0.822**	**1.000**
Part 10	48.293	34.678	37.842	36.206	1.000	**0.801**	**0.952**
Part 11	49.623	34.044	37.723	36.068	1.000	**0.793**	**0.963**
Part 12	49.569	35.666	38.235	36.595	1.000	**0.787**	**0.934**
Part 13	50.141	35.117	38.078	36.427	1.000	**0.785**	**0.944**
Part 14	51.543	37.867	38.913	37.276	1.000	**0.767**	**0.899**
Part 15	49.940	33.653	37.583	35.920	1.000	**0.793**	**0.970**
Part 16	50.062	36.649	38.529	36.895	1.000	**0.781**	**0.918**
Part 17	49.396	33.714	37.611	35.955	1.000	**0.796**	**0.969**
Part 18	48.371	34.513	37.856	36.217	1.000	**0.800**	**0.954**
Part 19	51.271	37.177	38.686	37.045	1.000	**0.771**	**0.910**
Part 20	49.830	33.375	37.480	35.816	1.000	**0.795**	**0.976**
Average						**0.799**	

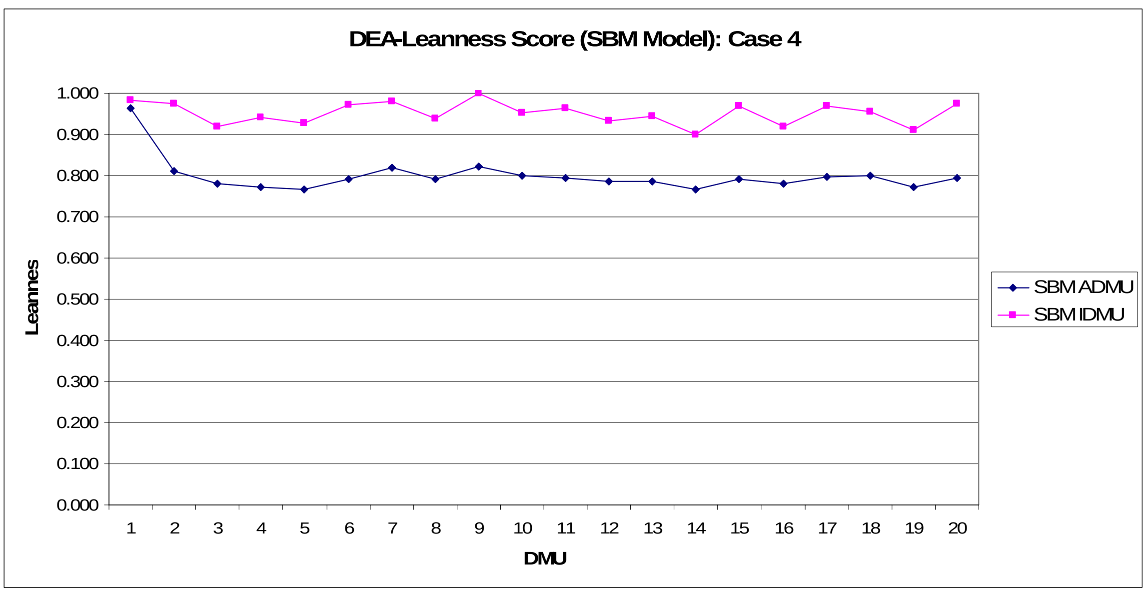


Figure 5.8 Leanness Scores of Case 4 Using SBM Model

From the leanness scores listed in Table 5.6, IDMU 9 is identified as the most efficient IDMU in the frontier reference set. Therefore, IDMU 9 is used to calculate the Lean-Agile Performance Target considering the imbalance in the line. Since the daily demand is still assumed to be 20 units per day, only Online-Delay Target needs to be considered. After the cost and time of the delay target are identified, the DEA-Leanness model is performed again with the lean-agile delay as a DMU. The leanness score of the delay target is the lean-agile performance target. All the numbers are listed in the following tables together with the graphical comparison.

Table 5.7 Online-Delay Target in Case 4

Average Processing Time of Operations	**OP1**	**Imbalance**	**OP2**	**Imbalance**	**OP3**
	Processing Time	= OP2 – OP1	Processing Time	= OP2 – OP1	Processing Time
	4.967	**14.790**	**19.757**	**-9.734**	**10.023**
Online Delay		**14.790**		**0**	

Unit: minutes

Table 5.8 Lean-agile Target and Performance in Case 4

IDMU 9	Time (min.)	32.193
	Cost ($)	35.413
	Value	1.000
Lean-agile Target	**Time (min.)**	46.928
	Cost ($)	35.561
	Value	1.000
	Target Score	**0.840**
Average Leanness Score		**0.799**
Lean-agile Performance Index		**0.951**

From Table 5.8, the target leanness score considering online delay is 0.840. However, the average leanness score is only 0.799. The leanness level of this system cannot reach the target because of the variations of the processing time. The results of leanness scores and leanness target are shown graphically in Figure 5.9. It can be observed that only DMU #1 is leaner than the target, because the first DMU is not affected by any other activities. Variations of the processing time at each workstation need to be eliminated in order to achieve a satisfying leanness level.

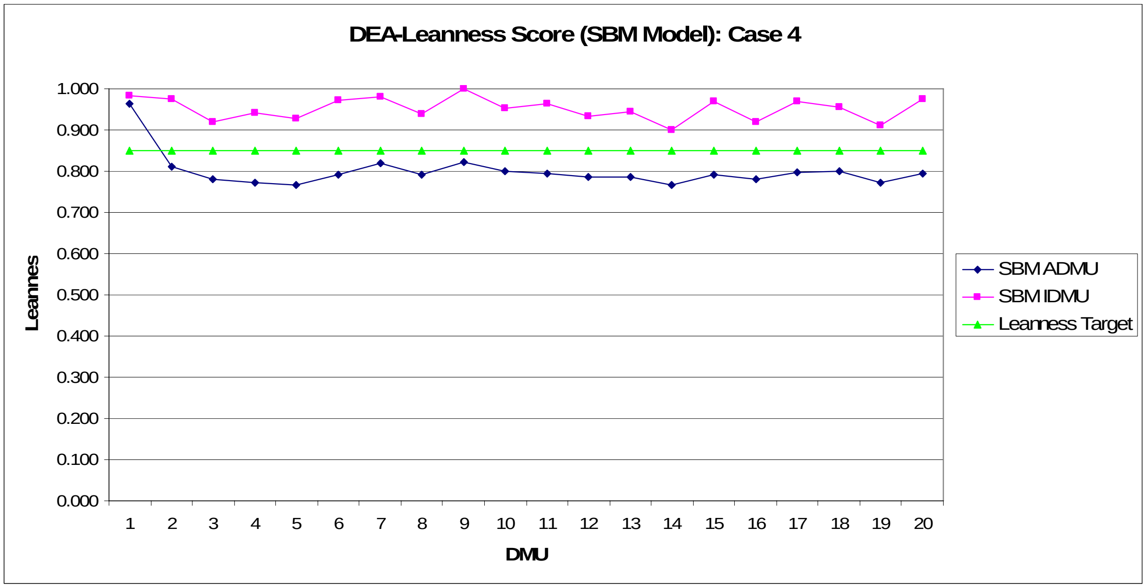


Figure 5.9 Lean-Agile Target and Performance in Case 4

5.4.2 Case 5: Dedicated Flow Line with Fluctuating Demand

In this hypothetical case, fluctuation in demand quantity is introduced to demonstrate the identification of Offline-Delay Target. The settings of this case are created based on Case 1, but five days of production is considered. The detailed settings of this case are listed below. Overtime will be used when the daily demand cannot be met by the regular working time.

Background Information of Case 5:

Weekly Schedule:	*Day 1*	*20 units of Product A*
	Day 2	*15 units of Product A*
	Day 3	*30 units of Product A*
	Day 4	*10 units of Product A*
	Day 5	*25 units of Product A*
Regular Working Time:		*8 hours/day = 480 minutes/day*
Daily Production Rate:		20 units/day
Takt Time:		*24 minutes/unit*
Processing time:	*OP1*	*20 min. ± 2 min. (uniformly distributed)*
	OP2	*20 min. ± 2 min. (uniformly distributed)*
	OP3	*20 min. ± 2 min. (uniformly distributed)*

Experimental Conditions:

- The system starts with no inventory.
- The system produces at a daily production rate that meets the average of demand quantity. If the amount produced together with inventory exceeds the demand on that day, excessive finish goods go to inventory. If there is a shortage, the system runs on overtime to meet the balance.
- For regular production time, cost breakdown is the same as in Case 1. For overtime, all costs increase 50%, except for material cost.
- Raw materials are pulled by WS1 one piece at a time.
- Finished goods are shipped once a day. Batch size equals to the daily demand. The batch is shipped when the last piece of the batch is finished. Products produced after the daily shipment are included in the batch of the next day.

Note: Due to the large sample size, the original data of Case 5 is not listed in this section. The detailed numerical data can be found in Appendix A.

In this case, the materials are pulled one piece at a time. Therefore, there should be no delays caused by batch arrival. Only the delay caused by batch removal and demand fluctuation should be considered in the Offline-Delay Target.

Table 5.9 summarizes the actual production and inventory from Day 1 to Day 5. The other numerical data is not listed in this section due to the large size of the data set. Only the scatter diagram and line charts are included to present the data graphically. Based on the production/inventory balance, a total of 105 parts were processed in this system during the 5 days. From the scattered diagram of the Cost-Time data (Figure 5.10), it can be observed that most of the parts were produced in similar conditions in terms of cost and time investments. However, some parts stayed in the system for much longer time, and a few others required extra costs. The extra costs were caused by the extra expenditures in overtime production. As to the extra waiting time, it is resulted from finished good inventory. The resulting leanness scores of the 105 ADMUs are listed in Table 5.10 and graphically shown in Figure 5.11.

Table 5.9 Actual Demand, Inventory and Overtime of Case 5

	Daily Demand	Inventory	Unit Produced in Overtime
Initial		0	
Day 1	20	0	0
Day 2	15	5	0
Day 3	30	0	5
Day 4	10	10	0
Day 5	25	5	0

Daily Production: 20 units

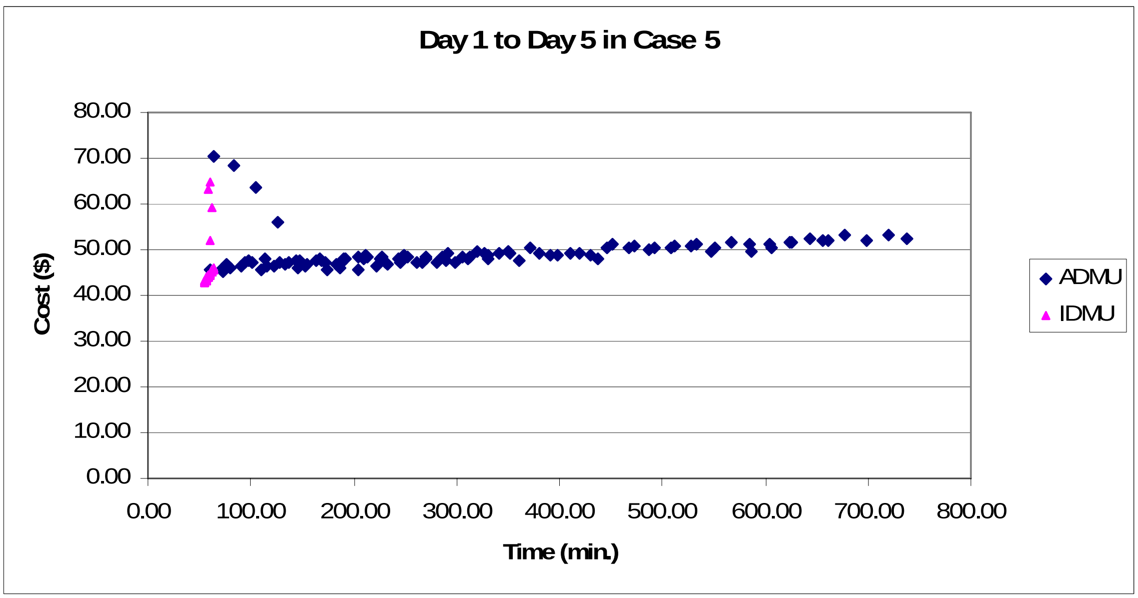


Figure 5.10 ADMUs and IDMUs in Case 5

Table 5.10 Summary of DEA-Leanness Measurement of Case 5

Average Leanness Score of ADMUs:	**0.570**
DMUs on Frontier	**IDMU 1** (referred frequency: 5/105) **IDMU 13** (referred frequency: 100/105)

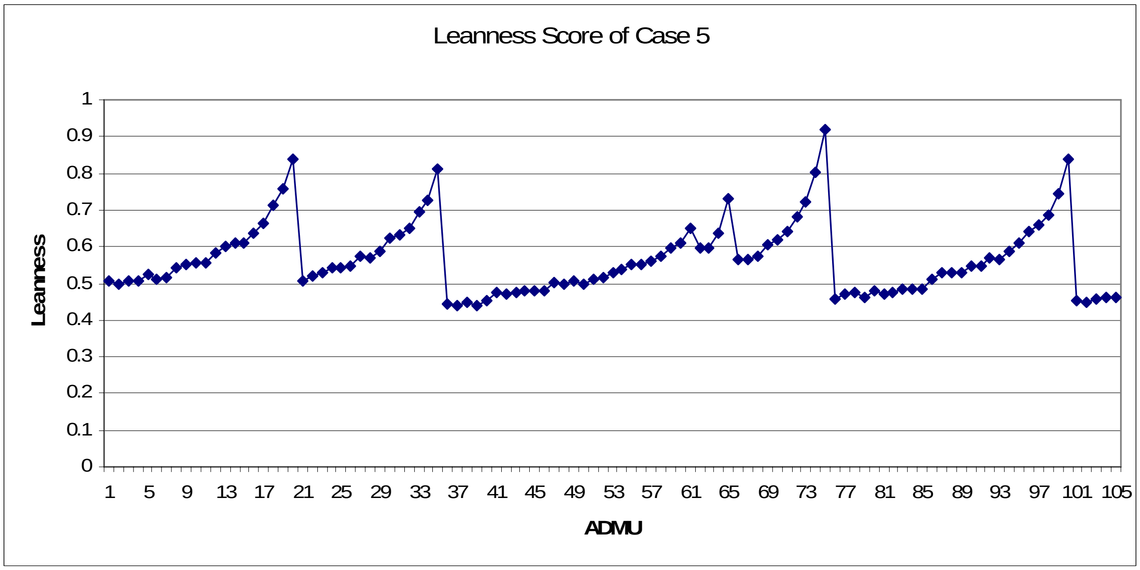


Figure 5.11 Leanness Scores of Case 5

From Table 5.10, IDMU 13 is clearly the dominant DMU on the frontier. Therefore, the Offline-Delay Target DMU can be constructed using the Cost/Time/Value data of IDMU 13. First, the Offline Delay caused by batch removal is calculated. The average cycle time is 20 minutes. Since the demand changes daily, an average of the five days' data is calculated.

Table 5.11 Offline Delay of Case 5

Variable	Offline Delay Caused by Batch Removal
Time of Delay	Average ($\frac{CT_{system} \times (M_O - 1)}{2}$) = 190 minutes
Cost of Delay	$Cost_{waiting\ \ period\ \ 2} \times \frac{CT_{system} \times (M_O - 1)}{2}$ = \$1.90

The next step is to calculate the minimum average inventory level with a constant production rate. A mathematical program is developed to determine the minimum value.

$$\begin{aligned}
\text{Min.}\quad & Z = (I_1 + I_2 + I_3 + I_4 + I_5)/5 \\
\text{S.T.}\quad & P + 0 = D_1 + I_1 \\
& P + I_1 = D_2 + I_2 \\
& P + I_2 = D_3 + I_3 \\
& P + I_3 = D_4 + I_4 \\
& P + I_4 = D_5 + I_5
\end{aligned}$$

All variables are non-negative.

In the linear program, I_i represents daily inventory, D_i represents daily demand, and P represents the constant daily production rate. Substituting the D_i's with the values from Table 5.9, the results are obtained as shown below.

$P = 21.667$ *(daily production rate)*

$Z = 6$ *(minimum average inventory)*

Then,

Expected Time in Inventory = *Z / Average Daily Demand * Available Time*

= *6/20*480*

= *144.00 (min.)*

Therefore, the Offline Delay caused by fluctuation demand is:

Offline-Delay Target: *Cost = $1.44,* *Time = 144.00 min.*

Combining the two types of Offline Delays, the Target DMU and the leanness score is listed in Table 5.12.

Table 5.12 Lean-agile Target and Performance in Case 5

IDMU 13	Time (min.)	54.283
	Cost ($)	42.731
	Value	1.000
Lean-agile Target	**Time (min.)**	388.283
	Cost ($)	46.071
	Value	1.000
	Target Score	**0.534**
Average Leanness Score		**0.567**
Lean-agile Performance Index		**1.062**

Figure 5.12 compares the leanness scores against the performance target. As a result, the system appears to be lean enough considering the Offline Delays. The main reason is that overtime production (DMU 61 to 65) is used to avoid accumulation of final product inventory. It turns out that the cost increments in the overtime production are justifiable.

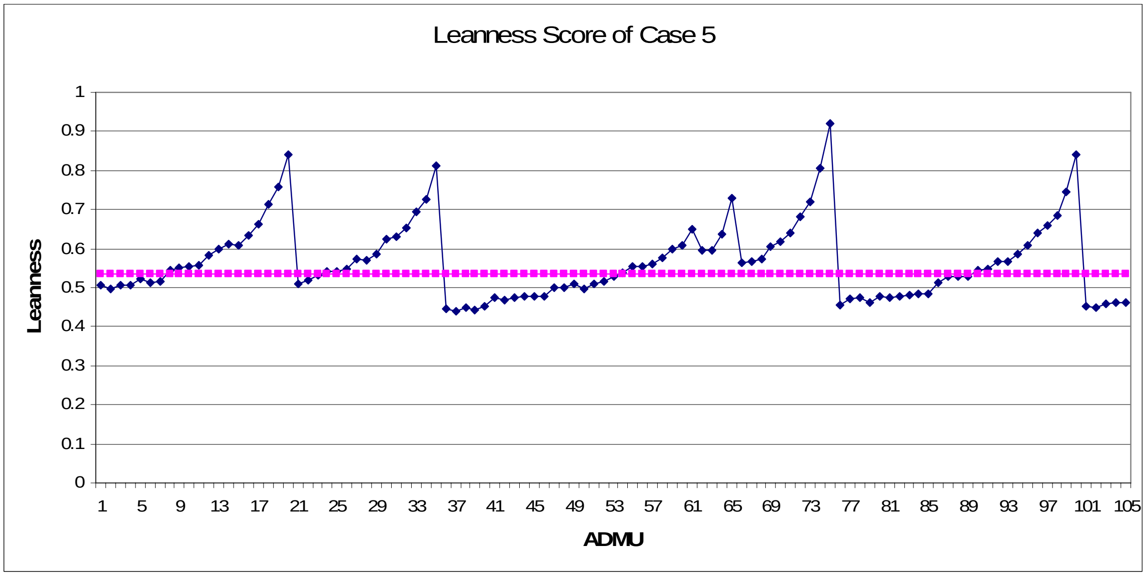


Figure 5.12 Leanness Scores and Lean-agile Target in Case 5

In summary, the hypothetical cases demonstrated the use of the Online-Delay Target and Offline-Delay Targets. The methodology proposed in this section captures one scenario of Online-Delay and three scenarios of Offline-Delay. In reality, the system can be much more complicated, and the cost and time breakdown may not be as simple as the approach introduced in this chapter. In the future, various cases of the delays should be investigated in order to further improve the effectiveness of this methodology.

Chapter 6 Software Implementation of DEA-Leanness Measure

The proposed methodology of DEA-Leanness Measure evaluates the leanness level and lean-agile performance of manufacturing systems by comparing the production activities of every work piece. To evaluate the leanness level, cost and time investments of all activities on the value stream need to be recorded in detail, and the VA investments need to be distinguished from the NVA investments. In order to handle the huge amount of data, two computer programs have been developed to realize this methodology. First, a Web-based Kanban System is developed to collect the time stamps of production activities. This data can be transformed into VA and NVA intervals, and then, *Cost* and *Value* data can be added to generate ADMUs and IDMUs for the DEA-Leanness Measure. Another software program developed in this research is an Excel-based DEA Solver that solves the SBM model and provides leanness scores. The CTV Charts of DMUs are also generated for the users to identify wastes from the production processes. With the two software programs, the cumbersome processes of data collection and analysis can be carried out by computers. This chapter discusses the two software programs starting with the Web-Kanban System.

6.1 A Web-based Kanban System

As introduced in the previous chapters, various approaches, such as *Rolling DEA*, have been developed to address potential barriers of applying the DEA-Leanness Measure. However, the methodologies and mathematical models introduced previously have not addressed the potential difficulty on data collection for the leanness measure. If a delicate computer system, such as *Enterprise Resources Planning* (ERP) system, is already in place and can provide detailed information on *Time, Cost* and *Value* required by the model, the data collection process should not a problem. Nevertheless, the investment on installing an ERP system is known to be enormous and many small and medium sized companies cannot afford ERP. In that situation, the *Cost* and *Value* data can be identified later when the processes are finished. However, time stamps of each activity need to be recorded while it is progressing via various steps. The *Time* data can be collected manually by operators or a dedicated observer on site. However, when the products flow through the system with a relatively fast pace, manual timing would be a burden for the online operators. On the other hand, timing each production activity by an observer may be difficult if multiple products are processed in a production line by different workstations. The observer will not be able to keep detailed track of each product. Consequently, a computerized system that keeps the timing records of all production activities is in need. A Web-based Kanban System developed in this research is to facilitate the automated data collection for DEA-Leanness Measure.

6.1.1 Background of Web-Kanban System Development

Kanban is known to be one of the most important tools of the Toyota Production System (TPS). The Japanese word, Kanban, means a card with visual information that conducts the information flows in the TPS (Monden, 1998). Because of the simplicity and effectiveness of the Kanban system in shop floor control, it has become one of the most powerful tools for implementing lean concepts. However, lacking of the capability to track and monitor physical Kanbans is the weakness of the traditional Kanban system. In a conventional Kanban system, the Kanbans are not tracked, and the performance of executing a task triggered by a Kanban is not monitored or recorded. A computerized Kanban system can effectively address this weakness.

Among various programming environments, web-based programming owns several features that facilitate the computerized Kanban system. A web-based Kanban system can be simple, effective and easy to use. The reasons to integrate Kanban systems with web-based technology are listed as follows.

1) **Standard User Interface:** Web browser has become a standard feature of every operating system in computers. Various web browsers (e.g., *Explorer* by Microsoft, *Firefox* by Netscape, etc.) have been developed, and all of them interpret the standard

HyperText Markup Language (HTML) in the same way even in different operating systems, such as *Windows*, *Apple*, or *UNIX*. Even some handheld devices, such as *Personal Digital Assistant* (PDA) and cell phone, can browse web pages. Therefore, the web browsers provide a standardized user interface regardless the type of computer system. The cross-platform compatibility makes web-based programs accessible to any users connected to the server.

2) **Easy Connections:** In the past decade, web connection has become readily available in most of the working environments. Web services can be accessed by computers or handheld devices through wired or wireless network. Implementing a web-based Kanban system does not require additional investment on hardware if Internet or Intranet service is available at workstations in the shop floor.
3) **Improved Web-based Program Capability:** The computational capacity of web-based program has been improved dramatically in the past decade. Traditional HTML files provide only static contents to the users. In contrast to the static web pages, the newly developed web-based programming environment supports “dynamic” web pages which facilitates interactive web browsing and computational capabilities. Together with web-based databases, the servers can provide functional web pages for various purposes. For manufacturing systems, the functions, such as *Real-time tracking*, *Performance measurement*, *Interactive input/output*, *Dynamic display*, etc., can all be achieved by web-based programs now.

Based on the aforementioned features, developing a Kanban system using web-based technology is a solution to address the weakness of the TPS tool. Following improvements on functionality are expected when upgrading a physical Kanban system to a web-based system.

1) **Real-time Kanban Tracking**: Improved capability on Kanban tracking and monitoring can be achieved by web-based services. The time stamps of all movements of a Kanban can be recorded in real time for performance analysis.
2) **Higher Capacity of Information Flow**: More information can be embedded and delivered by a web-based Kanban than that of a physical Kanban. Not only the size of

information carried by the Kanbans can be increased, the web-based Kanban can also deliver different formats of information, such as *electronic CAD/CAM files*, *audio streams*, *video clips*, etc., which dramatically improves the capability of conducting the information flow. Furthermore, other online information can always be linked from a web-based Kanban, which eliminates the limit of the size of information a Kanban can carry.

3) **Wide Range of Application**: The web-based system can be applied to different settings, including *Pull Production System, Push Production System, Project-Oriented Production, Project Management, Documentation System,* etc.
4) **Performance Monitoring**: Most importantly for this research, the web-based Kanban system can evaluate the performance of the system in real time. Since all Kanbans are dispatched and monitored by the web server, the data of cost and time can be generated accordingly. Therefore, the leanness measurement can be implemented through the web-based Kanban system. Functionality extensions, such as integration with sensors, barcode and RFID systems, are foreseeable to increase the efficiency of leanness measurement.

With the abovementioned expectations, a Web-Kanban System is established using server-executed web-based program together with Internet database. In this research, the Web-Kanban System serves as an implementation of the DEA-Leanness measure. It can also be a starting point for the construction of a web-based manufacturing system. Eventually, a *Performance-Oriented* web-based manufacturing system can be carried out (Wan and Chen, 2004). Details of the Web-Kanban System are introduced in the following subsections.

6.1.2 Framework and Functionality of Web-Kanban System

In this research, a web-based program is developed to run a computerized Kanban system which is capable of collecting time-based performance data for the DEA-Leanness Measure. In addition to network connections, the Web-Kanban System developed in this research contains the following components:

1) **Web Service Platform**: The web service infrastructure that supports dynamic web-pages with computational power.
2) **System Configuration Module**: The program and interfaces for administrators to configure the Web-Kanban system.
3) **Kanban Operating Module**: The program and interfaces for shop floor operators to receive, process, and fulfill the Kanbans on computers.
4) **Performance Monitoring Module**: The program and interfaces for managers to analyze and monitor the time-based performance of the manufacturing system.

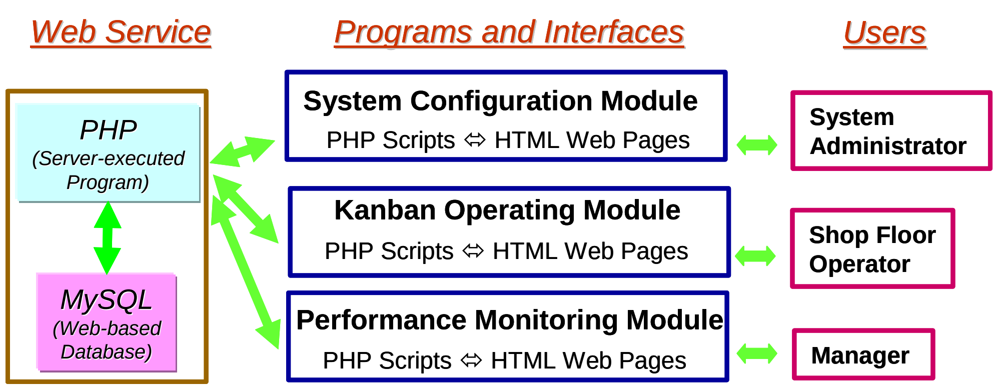


Figure 6.1 Framework of Web-Kanban System

Figure 6.1 portrays the framework of the Web-Kanban System. The three modules of program and interface run on the web service platform. Users access the system through the interfaces which provides standard HTML files. Details of the components are introduced respectively as follows.

6.1.2.1 Web Service Platform

The Web-Kanban System is developed using the web-based programming language, PHP, and the web-based database, MySQL. Both programs are open source programming tools developed with the Linux development group. Due to the close relationships, the combination of web-service environment of *Linux, Apache, MySQL* and *PHP* is often mentioned as the *LAMP* (Stopford, 2002). Since this environment is constructed with all open source packages, this combination is economically advantageous. Also, the reputation of Linux group helped the wide acceptance of this combination.

"PHP" is a recursive acronym for "PHP: Hypertext Preprocessor" (Achour et al., 2006). It is an open source scripting language that can be embedded into HTML. Unlike some other web-based scripting languages (e.g., Java Script), PHP programs are fully server-executed web-based program. The software programs written in PHP deliver standard HTML files to the users when a web page is requested by web clients. Scripts are sent to the server with the user-requested parameters, and a responding HTML web page is sent back to the user. Minimum amount of information is generated in response to user's requests every time. Therefore, a minimum increase in the load to the network can be maintained together with high security level. A simple example of PHP program is the online photo albums. In an album written in PHP, the background layout is fixed while the photo is displayed dynamically according to user's request. Therefore, all photographs in an album can be displayed by the same web page, one at a time, according to the parameter that controls the selection. Other examples include news pages, online bulletin, etc.

The Web-Kanban System cannot be completed by using only the PHP program. Online database is a critical part of the web service that supports the dynamic web pages. Various types of data need to be stored, managed and related in the system, which cannot be done merely by PHP server. MySQL is a open source web-based database for this purpose. It is a relational database managed by *Structured Query Language* (SQL) (Atkinson, 2002). In the Web-Kanban System, all types of data are stored in the MySQL database, including system configuration (e.g., Bill of Material, Kanban routing), operating data (e.g., job details, Kanban status), and performance data (e.g., time stamps). The SQL scripts are sent by the PHP web server to the MySQL server to fulfill every request from the clients. Therefore, the Web-Kanban runs on the PHP+MySQL platform records and provides data in real time.

In this research, the Web-Kanban System is developed on the PHP+MySQL platform provided by Computing Center at Virginia Tech. The development of the software program is supported by *Center for High Performance Manufacturing* at Virginia Tech.

6.1.2.2 System Configuration Module

Based on the PHP+MySQL programs, three functional modules are developed to perform the functions of the Web-Kanban System. These modules are the actual PHP programs that are executed by the web server. The first module is developed for *System Configuration*. It provides web pages for administrators to define the system configurations, such as *materials, operations, bill of material (BOM), routings of material and Kanban, buffer size and reordering point*, and *user groups*. The Web-Kanban system is configured based on the actual manufacturing system and can be modified in response to any changes of the system. Figure 6.2 is a screen shot of the web interface for configuring materials. Similar web interfaces are available for the specifying other system configurations.

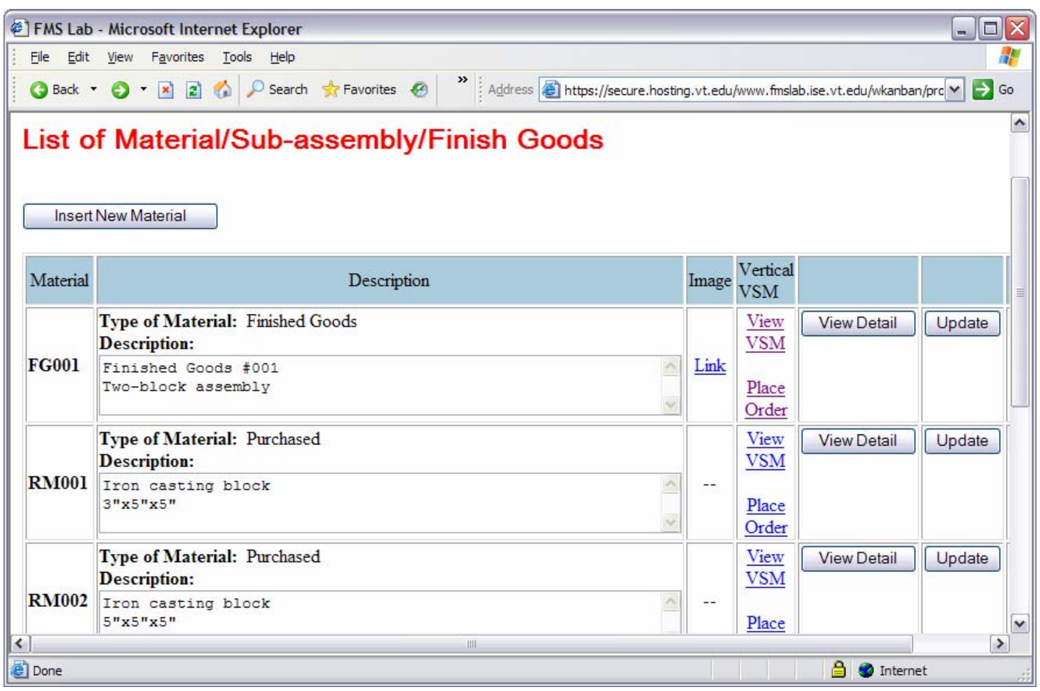


Figure 6.2 Interface of System Configuration Module: Material List

After the materials, processes, and workstations are coded in the software program, the system administrator is then able to view the *Vertical Value Stream Map* of each material or product type in the list. As shown in Figure 6.3, the map combines Bill of Material (BOM) with the process names and workstations performing the tasks.

Authorized users can place orders of selected material by using this interface. With specified quantity and duedate, the order will be transformed into Kanbans (one for each unit) to trigger the jobs. A pull system is embedded in the design, and materials are pulled from upstream workstations when needed. The orders can be placed in *Batches* (pulling multiple units all at once) or *Leveled Pulling* (evenly spreads the order amount over a period of time) to the selected workstation. When the demand is leveled, the Kanban will be dispatched automatically over the specified period, and thus the chance of human errors on timing can be minimized.

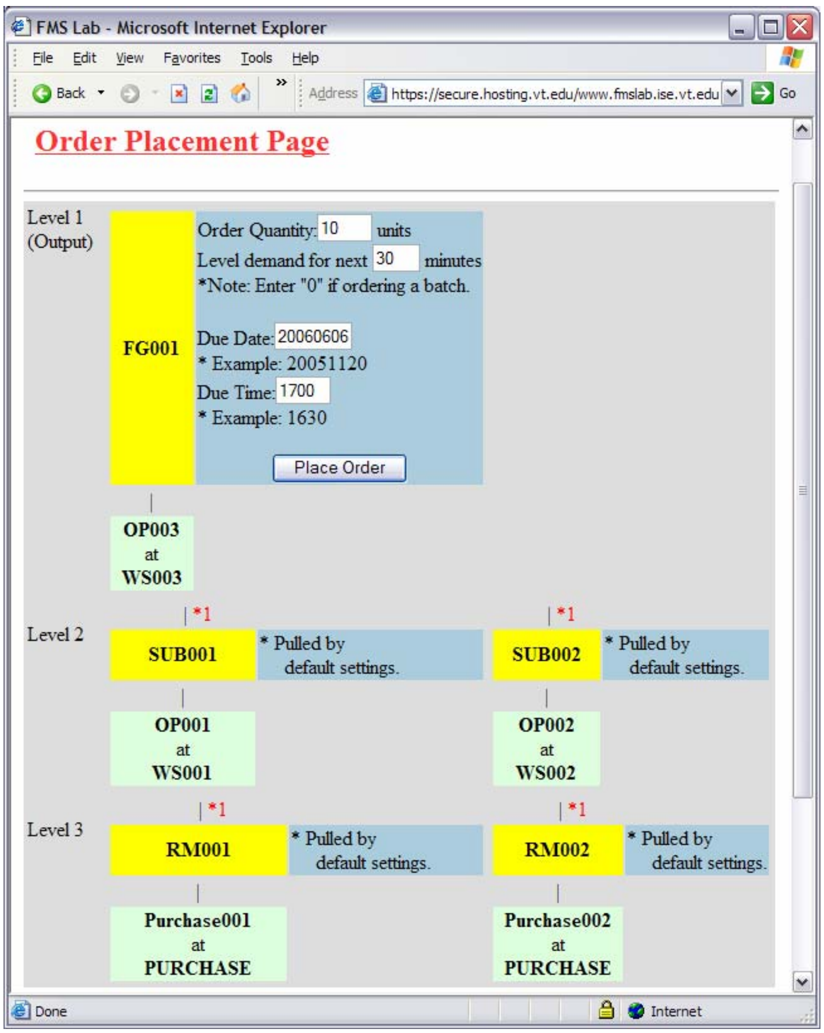


Figure 6.3 Interface of System Configuration Module: Order Placement

6.1.2.3 Kanban Operating Module

Following the system configuration module is the Kanban Operating Module. It provides interfaces for operators at the workstations to receive, process, and fulfill the Kanbans. When the system configuration is completed, users at each workstation can log on to the system to view the designated Kanbans. Based on the predefined user groups and authority levels, only the authorized user can see the designated Kanbans and information from the operating page.

After logging into the system, a job list will be provided to the user. As shown in Figure 6.4, new jobs, in-process jobs, pending jobs, and completed jobs are listed for the user to view or execute. An orange "►" button is displayed on every Kanban operating page to identify the task of highest priority. Therefore, the operator can follow the button to execute the jobs in the order of urgency.

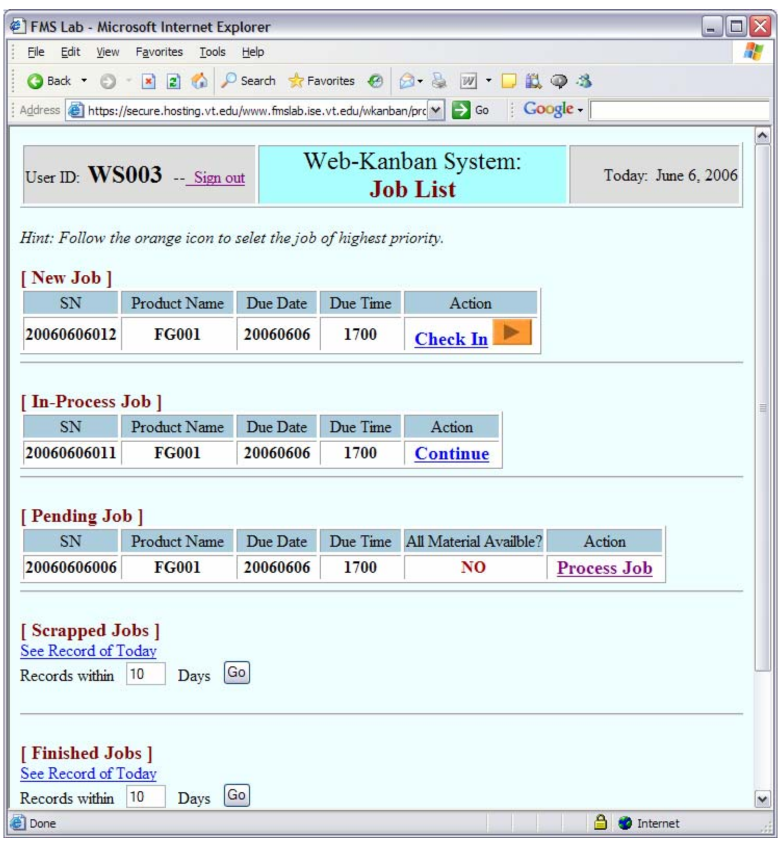


Figure 6.4 Interface of Kanban Operating Module: Job List

When a Kanban (job) is selected, a web page showing the details of the job will be brought up. The *Job Processing Page* displays the detailed information of the job, the required materials, and the work instruction. Graphical, audio, or video instructions can be linked if specified previously. Again, users can follow the orange button to perform the task in priority. The user must click on the corresponding link whenever a task is finished. For example, the Kanban in Figure 6.5 requires one unit of material RM002 from the upstream workstation. After retrieving the material, the user must click on the orange button (or the link next to it) to move on. This action also records a time stamp in the web server for later use.

After fulfill the job description, the user will need to send the product to designated location and click on the orange "►" button to fulfill the Kanban. It will then be categorized as "finished" in the job list.

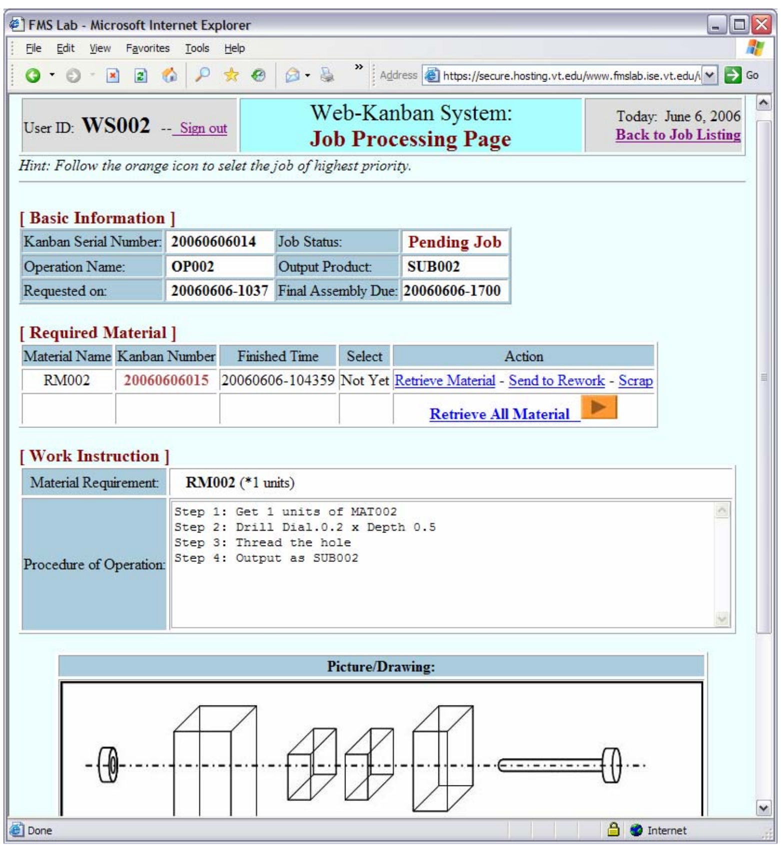
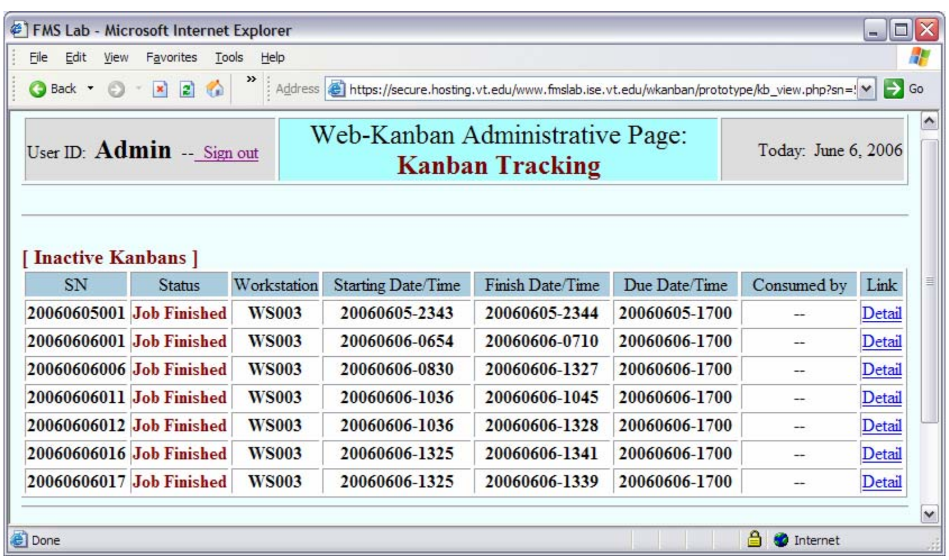


Figure 6.5 Interface of Kanban Operating Module: Job Processing Page

6.1.2.4 Performance Monitoring Module

The last functional module of the Web-Kanban System is for managers to monitor and analyze the performance dispatched jobs. Currently, this module offers the functions of *Kanban Tracking*, *Work-in-Process (WIP) Level Monitoring*, and *Time-based Performance Analysis*. Also, the time stamps can be output to the Excel-based DEA Solver for leanness measurement. Extensions of the functionality are discussed in the next section.

In the Kanban Tracking interface, the quantity, status and timing of the Kanbans are listed for the system manager. As shown in Figure 6.6, the managers can view the list of Inactive (finished or scrapped) or Active (new, in-process, or reworking) Kanbans. Details of each can be can also be found by following the links provided in the web page. Figure 6.7 demonstrates the *Vertical Value Stream* that shows the WIP level of each material involved. Managers can identify problematic areas of the value stream where high WIP level is shown. In Figure 6.8, the time-based performance of each Kanban is displayed. Accumulated time and accumulated VA time are listed together with a graphical display of the VA time versus NVA time of each job. The time stamps of VA and NVA activities are recorded in the web server, which are used to build ADMUs and IDMUs for the DEA-Leanness Measure.



SN	Status	Workstation	Starting Date/Time	Finish Date/Time	Due Date/Time	Consumed by	Link
20060605001	Job Finished	WS003	20060605-2343	20060605-2344	20060605-1700	--	Detail
20060606001	Job Finished	WS003	20060606-0654	20060606-0710	20060606-1700	--	Detail
20060606006	Job Finished	WS003	20060606-0830	20060606-1327	20060606-1700	--	Detail
20060606011	Job Finished	WS003	20060606-1036	20060606-1045	20060606-1700	--	Detail
20060606012	Job Finished	WS003	20060606-1036	20060606-1328	20060606-1700	--	Detail
20060606016	Job Finished	WS003	20060606-1325	20060606-1341	20060606-1700	--	Detail
20060606017	Job Finished	WS003	20060606-1325	20060606-1339	20060606-1700	--	Detail

Figure 6.6 Interface of Performance Monitoring Module: Kanban Tracking

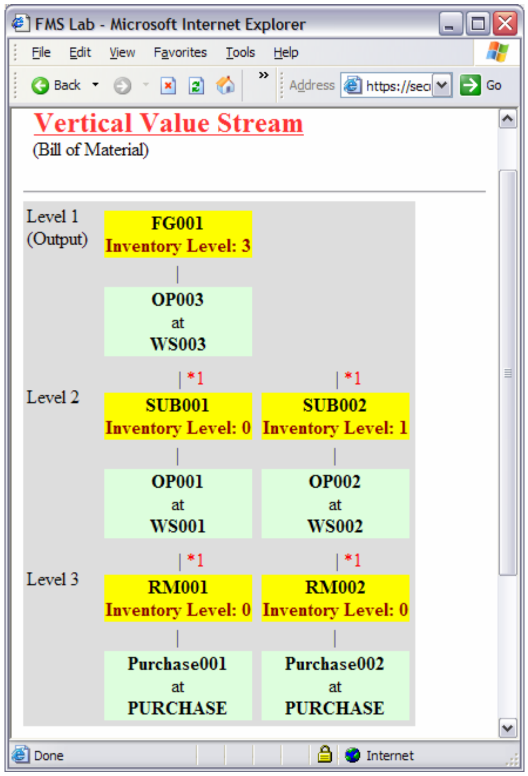


Figure 6.7 Interface of Performance Monitoring Module: WIP Level Monitoring

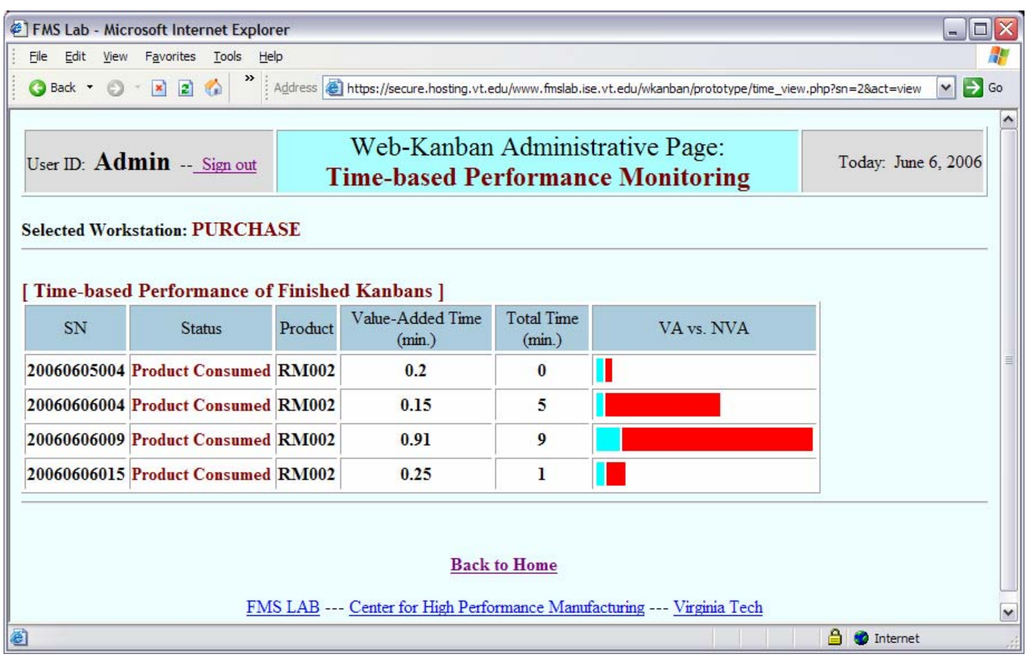


Figure 6.8 Interface of Performance Monitoring Module: Time-based Performance

6.1.3 Discussions on Web-Kanban System

The Web-Kanban System provides a way to collect time-based data automatically. It is designed to be applicable to various environments; however the scope of application is still limited. First, it is not necessary to implement the Web-Kanban System if a computer-based system (such as ERP system) is already in place that can monitor and record the time-based performance. Furthermore, the Web-Kanban is not applicable if network connection is not available at the workstations. Besides, when the cycle time of a process is short, clicking on the web pages may become a burden for the operators. Therefore, the Web-Kanban is suitable for manufacturing systems where delicate computer system is not available; network is accessible at workstations; and the work pieces flow through the system in a moderate pace. Comparing to manual data collection, when multiple products are in the system simultaneously, a dedicated observer may not be sufficient. In that situation, the Web-Kanban System provides a solution.

Beside the scope of application, the functionality of the Web-kanban System is limited in the following areas:

1) **Model Solving**: The web-based technology provides certain level of computational power, but the capability of solving mathematical programs is limited. Although the SBM model can be transformed into a linear program and solved by using *Simplex Method*, the solver needs to be programmed from scratch. The solution in this research is to feed the data collected by Web-Kanban to the Excel-based program, which provides various built-in features for data analysis.
2) **Graphical Display**: The standard HTML web pages are capable of displaying various types of data, such as text, image, audio, and video. However, the charts of data analysis, which can be easily generated by spreadsheet packages, are not included. Advanced web-based programming tools, such as *Macromedia Flash*, can be the solution in the future.
3) **Interface**: Current version of the Web-Kanban System cannot work with other software packages due to lacking of interfacing programs. If the interfaces can be built to link the Web-Kanban with other shop floor control programs or data analysis programs, it would improve the applicability of the system dramatically. More

importantly, connecting with data collection equipment, such as sensors, barcode and RFID systems can automate the process and avoid the frequent clicking on web pages.

4) **Modification**: The Web-Kanban System is designed to be configurable according to the user's actual manufacturing system. However, modifying the functions of the system requires knowledge of programming on the *PHP+MySQL* platform.

In summary, the functionality and applicability of the Web-Kanban system can be further improved by more programming efforts in the future. On the other hand, web-based technology has been enhanced continuously. More and more web-based programs are developed for various purposes. ERP system providers have all announced web-based features of their products (Bell, 2006). Web-based programs will become more and more important in the future.

6.2 An Excel-based Solver for DEA-Leanness Measure

At the proposal stage of this research, an Excel-based DEA-Leanness Solver was developed to be a temporary software tool for solving the DEA models before the solver function is built in the Web-Kanban System. The software tool then demonstrates its excellent capability on data handling, analysis, and graphical reports. Modifying this tool is also significantly more convenient than making changes on the Web-based Kanban System. As a result, the Excel-based program becomes the official DEA-Leanness Solver of this research. It solves the SBM model and provides numerical outputs as well as graphical outputs which can be revised conveniently.

Using the Excel-based DEA-Solver, the model solving process is automated by a *Visual Basic Applets* (VBA) program. A SBM LP model is constructed and solved for each DMU to obtain the leanness score. The *Cost, Time*, and *Value* data can be input manually or imported from a data table. Lacking data collection capability is the weakness of this software program. The framework, functionality and the inputs/outputs of this tool are illustrated in detail as follows.

6.2.1 Framework and Functionality of Excel-based DEA-Leanness Solver

The Excel-based DEA-Leanness Solver is constructed on the platform of *Microsoft Excel* together with *Visual Basic Applets* (VBA). *Microsoft Excel* provides the spreadsheet function to store, handle, and analyze the *Cost, Time,* and *Value* data. A VBA program controls and automates the model solving process. Based on this platform, components of the DEA-Leanness Solver are developed.

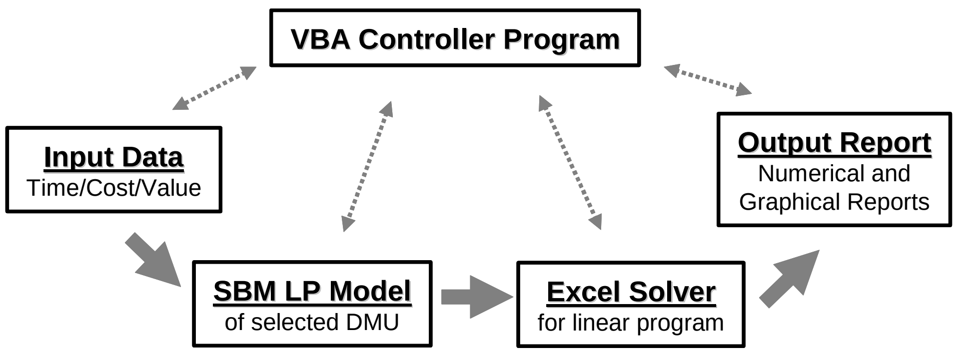


Figure 6.9 Excel-based DEA-Leanness Solver: SBM Model

As shown in Figure 6.9, the framework of the DEA-Leanness Solver contains following components:

1) **Input Data**: A spreadsheet is constructed to prepare the data for DEA-Leanness measurement. The input data includes time stamps of the observed activities, cost breakdown, and product values. Using the spreadsheet, the three types of data are synthesized into the input/output variables of the ADMU and IDMU for DEA-Leanness Measure.
2) **SBM Model**: The linear optimization program of the SBM model is constructed in the second spreadsheet together with the synthesized Cost/Time/Value data. As shown in Figure 6.10, equations of the SBM linear program are established for a selected DMU (DMU #1 at the upper left corner in the figure). The leanness score is derived by using the *Excel Solver*. After solving the model of this DMU, the results will be sent to the output report. Then, the next DMU will be selected and the model will be restructured accordingly. This model solving process is repeated until all

DMUs in the data set have been solved. The repetitive process can be carried out manually but takes time and extra care. A VBA program is developed to execute the process.

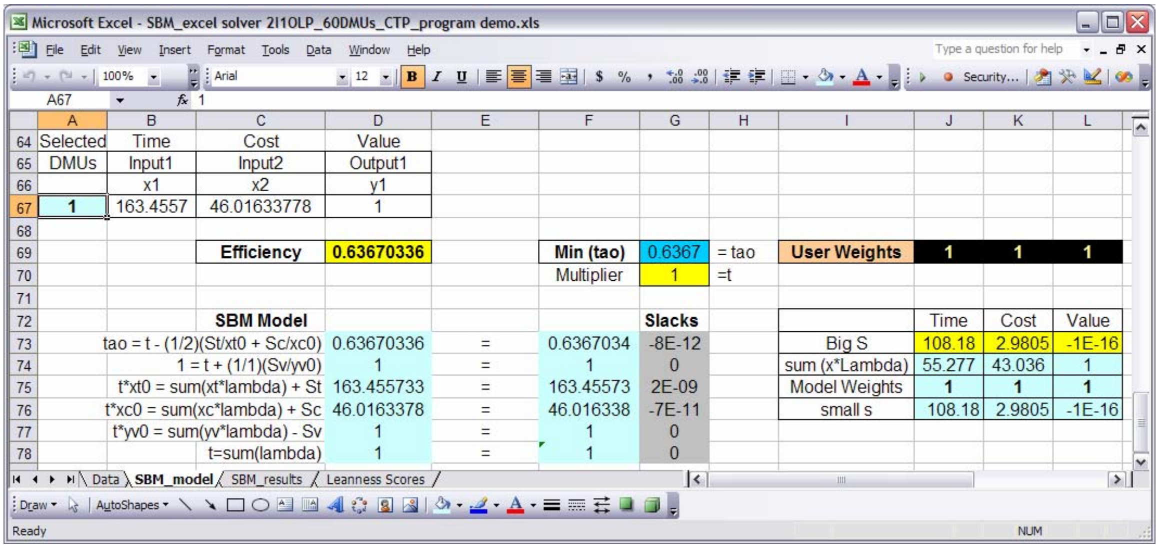


Figure 6.10 Excel-based DEA-Leanness Solver: SBM Model

3) **Excel Solver**: The *Excel Solver* is an "Add-in" function in the "Analysis Tool Pack" of the software package. It is a built-in tool of the Excel package but not activated in the default setting. The solver is used to solve the SBM linear program constructed in the second spreadsheet. The objective function and the constraints must be structured in the solver, and the data cells of decision variables need to be specified for the solver to change the values. As mentioned earlier, the *Excel Solver* can only solve one model at a time. Therefore, switching the selected DMU is done by a VBA program.
4) **VBA Controller Program**: VBA is commonly used by *Excel* users to setup a sequence of tasks that can be carried out automatically. A *VBA Controller Program* is developed for the DEA-Leanness Solver to switch the selected DMU and construct the corresponding linear program (Appendix B). The *Excel Solver* is then activated to perform the optimization and obtain the results. Finally, the VBA program records the results of each individual linear model in a separate spreadsheet designated to the numerical outputs. The procedure repeats until all DMUs are processed.

5) **Output Reports**: When a linear model is solved, the numerical outputs are recorded in a separate spreadsheet, including a leanness score, slacks of input/output variables, and weights of the reference set. After all DMUs are processed, the numerical outputs are summarized in another spreadsheet for the final report. The average leanness score, best DMU, and worst DMU are identified in the report together with graphical analyses. Details of the output report are introduced in the next subsection.

6.2.2 Input and Output of Excel-based DEA-Leanness Solver

The data to be analyzed by the *DEA-Leanness Solver* includes time stamps, cost breakdown, and product output values. The data can be obtained by observers and input manually, or imported from data tables generated by other software programs. In the spreadsheet of input data, the times tamps of production activities are translated into VA and NVA intervals. Using the cost breakdown, the VA and NVA costs associated with the intervals are calculated as (see Figure 6.11).

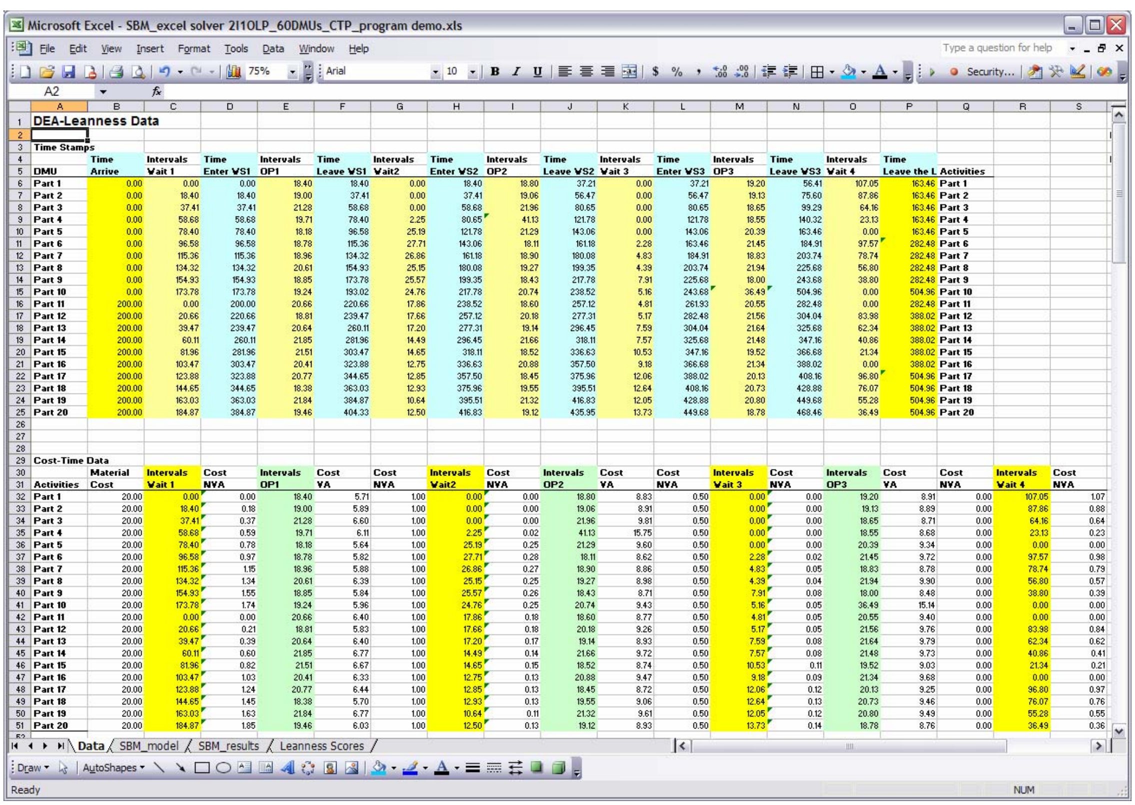


Figure 6.11 Excel-based DEA-Leanness Solver: Input Data

The intervals and costs are aggregated into *Total Time, Total Cost, VA Time,* and *VA Cost* of each ADMU and IDMU. Together with the data of product *Value*, the input data of the DEA-Leanness Solver is readily prepared as shown in Figure 6.12.

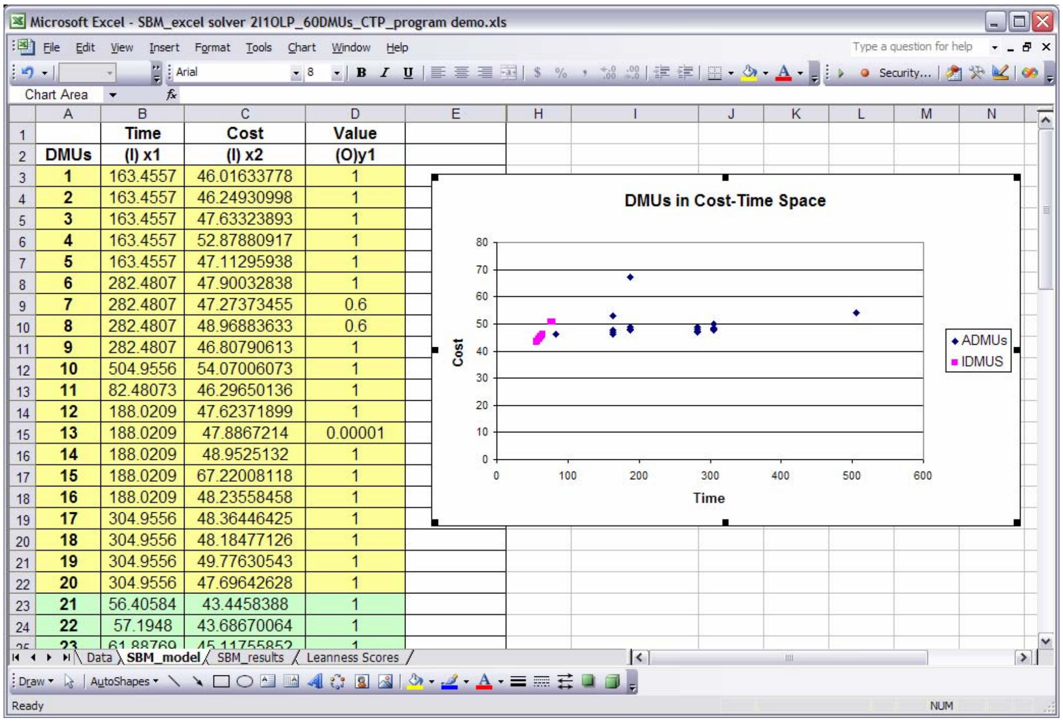
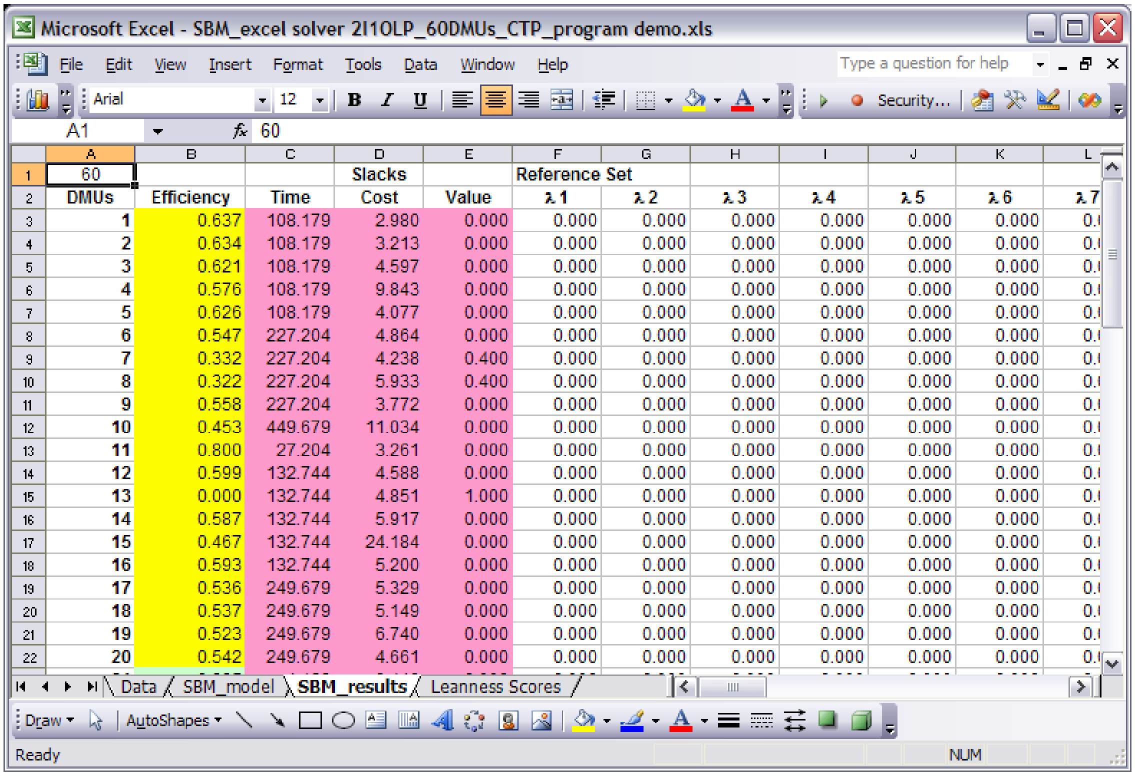


Figure 6.12 Excel-based DEA-Leanness Solver: ADMUs and IDMUs

After the SBM models are constructed and solved for all DMUs, the results are summarized into numerical and graphical output reports. In the numerical output spreadsheet (Figure 6.13), a leanness core is determined for every DMU with associated slacks (input excesses and output shortfalls) and weights of reference set (λ). As discussed in Chapter 3, convex combination of the DMUs in a reference set forms the benchmark for the selected DMU. Therefore, most of the weights (λ's) are zero, and only the λ's for DMUs forming the benchmark have positive value. Therefore, the table of λ's is used to identify the reference set for each DMU.

The leanness scores are duplicated in the final report spreadsheet (see Figure 6.14), where *Average Leanness Score* is calculated for the batch of ADMU. The DMUs with highest and lowest leanness scores are also identified as the *Best* and *Worst* DMUs.



60			Slacks		Reference Set						
DMUs	Efficiency	Time	Cost	Value	λ 1	λ 2	λ 3	λ 4	λ 5	λ 6	λ 7
1	0.637	108.179	2.980	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
2	0.634	108.179	3.213	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
3	0.621	108.179	4.597	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
4	0.576	108.179	9.843	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
5	0.626	108.179	4.077	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
6	0.547	227.204	4.864	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
7	0.332	227.204	4.238	0.400	0.000	0.000	0.000	0.000	0.000	0.000	0.
8	0.322	227.204	5.933	0.400	0.000	0.000	0.000	0.000	0.000	0.000	0.
9	0.558	227.204	3.772	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
10	0.453	449.679	11.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
11	0.800	27.204	3.261	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
12	0.599	132.744	4.588	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
13	0.000	132.744	4.851	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
14	0.587	132.744	5.917	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
15	0.467	132.744	24.184	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
16	0.593	132.744	5.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
17	0.536	249.679	5.329	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
18	0.537	249.679	5.149	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
19	0.523	249.679	6.740	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.
20	0.542	249.679	4.661	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.

Figure 6.13 Excel-based DEA-Leanness Solver: Numerical Outputs

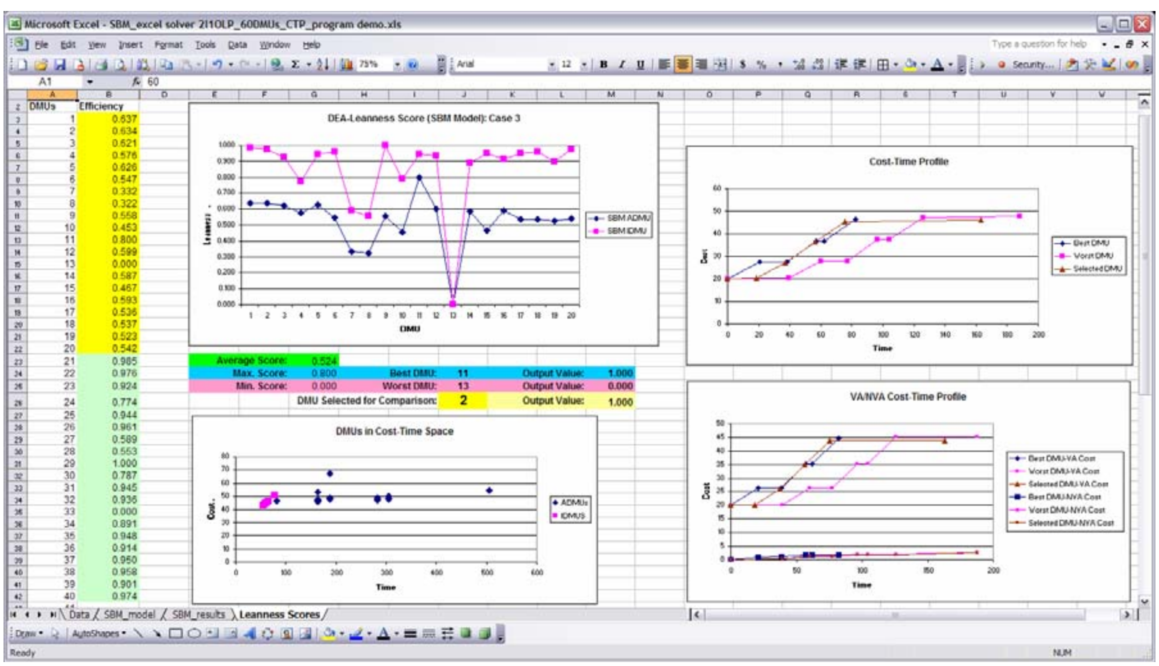


Figure 6.14 Excel-based DEA-Leanness Solver: Graphical Outputs

In the reporting spreadsheet (Figure 6.14), a line chart shows the leanness scores graphically. The ADMUs and IDMUs are plotted in a scatter diagram in the Cost-Time space for comparison. In addition, a Cost-Time-Profile (CTP) with *Total Cost* (Figure 6.15) and a CTV Chart with *VA and NVA Costs* (Figure 6.16) are plotted with the Best ADMU, Worst ADMU, and a selected DMU. Using the CTP and CTV charts, the profiles of production processes are compared to identify potential improvements as discussed in Section 4.3.

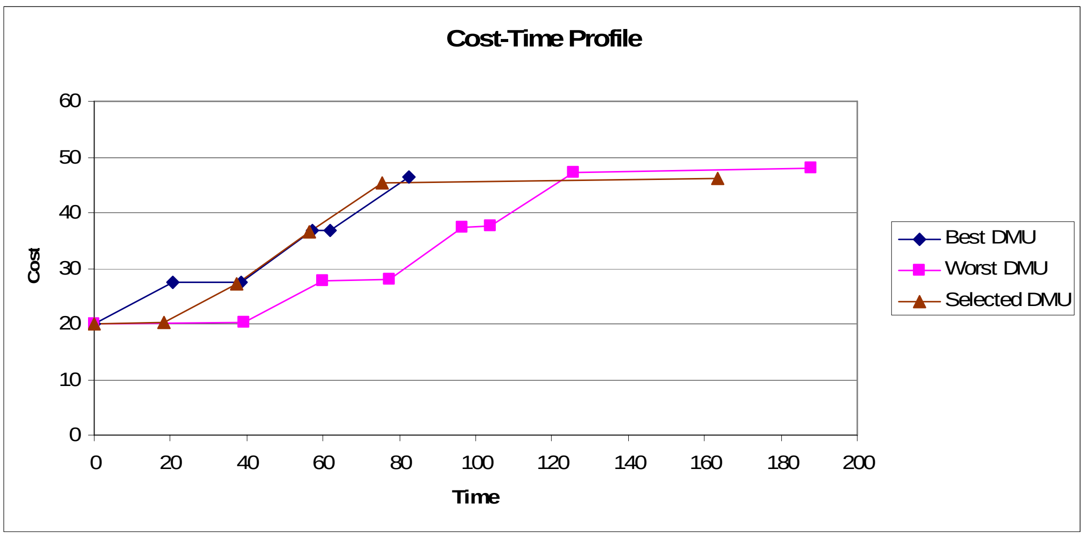


Figure 6.15 Excel-based DEA-Leanness Solver: Cost-Time Profile

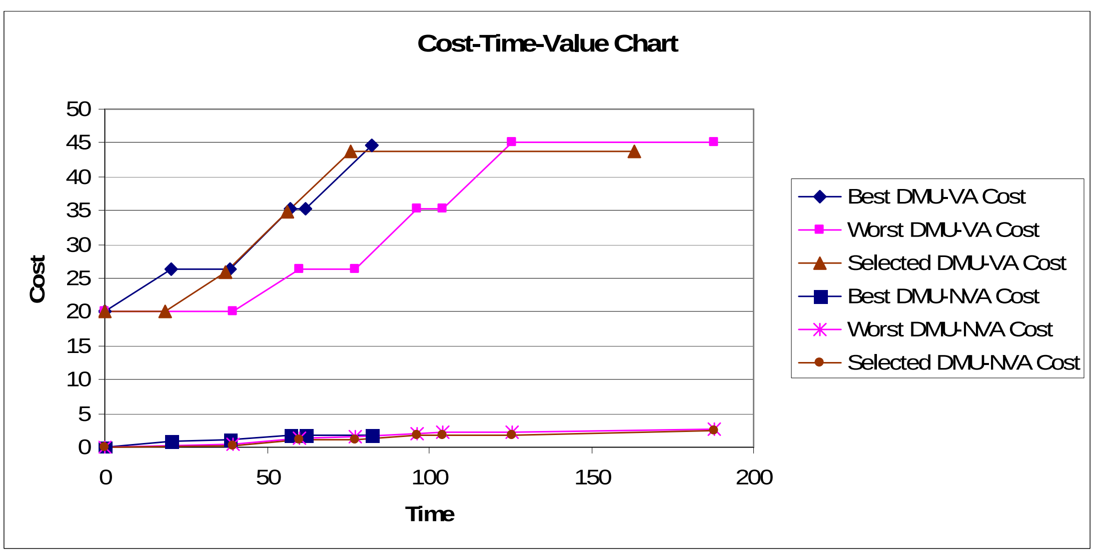


Figure 6.16 Excel-based DEA-Leanness Solver: VA vs. NVA Costs

6.2.3 Discussions on Excel-based DEA-Leanness Solver

The Excel-based DEA-Leanness Solver has been used to solve the cases and examples in this research. The capability of handling numerical data and generating graphical outputs carries out the DEA-Leanness Measure. The software program is built on the platform of Microsoft Excel with VBA. Since the *Microsoft Office Package* has become one of the most popular software packages, the DEA-Leanness Solver can run on different computers conveniently without extra installation efforts. Beside of the handy functions of graphical outputs, modification is also easier compared to the Web-based Kanban System using PHP+MySQL. Therefore, the Excel-based DEA-Leanness Solver is used to solve the SBM models throughout this research.

Numerical data for the DEA-Leanness Solver can be input manually or imported from data table from other software programs. The data can be collected manually from manufacturing systems or provided by computer systems for shop floor control. The Excel-based DEA-Leanness Solver itself lacks the capability of data collection. Therefore, the Web-Kanban System or an ERP system is needed to provide the data when manual data collection is not feasible.

Interfacing the Excel-based DEA-Leanness Solver with the Web-Kanban System or other software programs can connect the processes of data collection and leanness analysis. VBA is a programming language that is potentially capable of building the interfaces among the software programs. Therefore, establishing the interface to integrate the programs is a direction for further development of the Excel-based DEA-Leanness Solver.

Chapter 7 Conclusions

7.1 Summary and Conclusions

The objective of this research is to develop a leanness measure for manufacturing systems that tells lean practitioners "how lean their system is" and "how lean it should be." Since the late 1990's, lean manufacturing has become one of the most popular improvement strategies for manufacturing systems. The "waste elimination" concept is simple yet effective for manufacturing systems and various other settings. Earlier tools and techniques developed for implementing lean concepts focus mostly on "how to make the system leaner." Specific problems are tackled by these tools and techniques, and the visible improvements of performance can be achieved. Using performance metrics, the improvements can be quantified to justify the implementation of lean manufacturing. However, the conventional lean metrics cannot tell the lean practitioners how lean their system is, how much leaner it can be, or how lean it should be.

In this research, a DEA-Leanness Measure has been developed to quantify the leanness level of manufacturing systems. The DEA technique evaluates performance of DMUs by comparing the outputs/inputs ratio of each DMU. Most efficient DMUs form the efficiency frontier, which provides a benchmark for every DMU to quantify its performance. Using virtually generated IDMUs, the leanness frontier is pushed towards an ideally lean stage. Thus, leanness scores of the DMUs can be calculated by comparing the DMUs against the frontier. A CCR model is originally used to perform the DEA-Leanness measurement. However, the scores of CCR model overestimate the leanness level whenever slacks (i.e., input excesses or output shortfalls) exist in a benchmark. From the hypothetical cases, it is found that the slacks exist frequently while measuring leanness of manufacturing systems. A SBM model is then adapted to replace the CCR model. The DEA-Leanness Measure using SBM model effectively identifies the leanness benchmark and calculates the leanness scores accordingly. Through hypothetical cases, the results obtained from the SBM model are proven to be more accurate than the CCR model. Therefore, the DEA-Leanness Measure is developed based on SBM model.

Using the DEA-Leanness Measure, leanness level of manufacturing systems can be quantified and compared. It is an indication of "how lean the system is." On the other hand, it tells practitioners "how much leaner" the system can be, because the leanness score is obtained by comparing against a perfectly lean state.

Performing the DEA-Leanness measurement requires detailed *Cost, Time*, and *Value* data of every DMU. Collecting, handling and analyzing the large amount of data may require extra time and effort. Two software programs are then developed to perform these tasks. A Web-Kanban System is developed to facilitate the data collection. It is a computerized Kanban system enabled by web-based technology. Using the system, the time stamps of every activity can be recorded and then translated into VA and NVA time spans for forming the ADMUs and IDMUs. After the required data is collected, the leanness scores can be derived by an Excel-based DEA-Leanness Solver. The solver is developed to solve the SBM models of the DMUs and generate the leanness scores. CTP of the DMUs with VA, NVA and total costs are generated automatically for the users to identify potential improvements.

The abovementioned two software programs are developed to handle large amount of DMUs. However, there are situations that only very little data can be obtained. The application of DEA-Leanness Measure using VSM data is explored. It has been demonstrated that as long as corresponding *Costs* and product *Value* can be identified, the leanness level of a value stream can be measured based on the averages of time-based performance found in a VSM. The SBM model is capable of generating a reasonable leanness score using one pair of ADMU and IDMU. This application is useful for the scenarios where detailed data is hard to obtained, such as manufacturing systems with extremely short cycle time or complicated supply chains.

The DEA-Leanness Measure can also be an index for decision makers to compare the effectiveness of different improvement initiatives. Tradeoffs between the initiatives can be quantified using the leanness scores. Furthermore, weights can be applied to the input/output variables (i.e., *Cost, Time,* and *Value*) of the leanness measure so that the Weighted DEA-Leanness Measure can reflect the performance changes with consideration of the company's focus. Consequently, companies adapting different competitive strategies can establish leanness measures that match their needs.

With the ability of measuring leanness, the next question to be answered is “how lean the system should be.” A methodology is developed in this research to identify the leanness target considering unavoidable delays in and out of the manufacturing system. Internally, the imbalance between production processes delays the flow of products inevitably. For this situation, an Online-delay target is identified based on the concept of “supermarket pulling system” developed by Toyota. On the other hand, the fluctuation of demand cannot always be addressed by adjusting the pace of production. Inventory or working overtime is necessary to satisfy the customers with an acceptable agility level. An Offline-delay target is developed to represent the necessary inventory level to address the demand fluctuation. Combining the two targets, a leanness target can be identified for certain level of agility. Based on the leanness target, the Lean-Agile Performance Index shows whether the system is lean enough for the desired level of agility.

In conclusion, a DEA-Leanness Measure is developed to quantify leanness level of manufacturing systems, which reflects the current state of a system against perfection, and a leanness target can be identified for desired agility level. The effectiveness of the leanness measure has been verified by hypothetical cases. Certain limitations associated with the methodologies developed in this research are listed as follows.

1) **Scope of the Measure**: The DEA-Leanness Measure can be applied to different levels of a manufacturing system. However, the scope of application and granulation of details included in the input/output variables affect the result of leanness measurement. In a single workstation or a small production cell, transportation, buffering and other NVA activities are expected to be less than those in a complicated production line or a whole factory. As a result, the leanness scores associated with smaller scopes are expected to be higher than the overall score of a large scope. Therefore, when two systems are compared using the leanness score, the scope of the applications should be kept in mind while interpreting the difference of the scores.
2) **Granulation of the Input Data**: The granulation of details of the input data also affects the accuracy of the measure. While analyzing the VA and NVA components of the production processes, including finer details tends to identify

more NVA cost and time from an activity since wastes can be hidden in the VA activities. For example, if the time and cost spent in a workstation are considered as fully value-adding, then the time wasted on load/unload and the cost of scrapped material are mislabeled, and the leanness score would be overestimated. Similarly for the leanness measure of a supply chain, the cost and time spent in one plant should not be considered all VA. Keeping a finer granulation of the input data can deliver a more accurate leanness score and more importantly, helps the lean practitioners identify more opportunities of improvement.

3) **Evaluation of Product Value**: The output variable, *Value*, of DMU is designed to reflect the customers' perception of the product. Unlike the cost and time data, some components of customer satisfaction can only be evaluated qualitatively. Subjective judgments can sometimes affect the results of the leanness measure. For example, if one of ten customers is unsatisfied with a product and the one is included in a sample of two customers, the result will be quite different from the fact. Nevertheless, following up the satisfaction rate of every customer is not always possible. An appropriate sample size should be obtained to deliver more reasonable evaluation of customer satisfaction.
4) **Identification of Improvements**: The CTP with VA and NVA costs provide a way to identify wastes in the production processes. However, some wastes may not be trivially visible in the chart. The CTV analysis may shed a light on potential improvements by comparing costs and time spans, but more improvement opportunities may be hidden in the charts. Detailed investigation on the value stream is still the most effective way to identify wastes and further improve the system.

The contributions of this research and potential directions of future research are discussed in the following two sections.

7.2 Contributions of this Research

The major accomplishment of this research is the development of a quantitative leanness measure for manufacturing systems based on DEA technique. Unlike the conventional lean manufacturing tools and techniques, the DEA-Leanness Measure helps lean practitioners understand "how lean the system is" as well as "how lean it should be." The contributions of this research to the development and implementation of lean manufacturing are listed below.

1) **An Integrated Index of Leanness of Manufacturing Systems**: The DEA-Leanness Measure provides an integrated index of leanness level, which eliminates the need to interpret several lean metrics at the same time. The *Cost, Time*, and *Value* variables are considered simultaneously in the measure, and a unit-invariant score between 0 and 1 is provided. It provides the information on how much waste can possibly be removed from the current system in order to get to the ideal leanness. The measure can be applied to different scopes of systems, and the self-contained leanness benchmark eliminates the need to outsource the performance standard repeatedly
2) **A Weighted Leanness Measure Considering Competitive Strategies**: The DEA-Leanness Measure can take different weights assigned to the input/output variables (i.e., *Cost, Time* and *Value*). The resulting leanness score can reflect the performance of the system or the impact of improvement initiatives considering the competitive focus of the company.
3) **Leanness Target Identification Considering Agility Level**: An appropriate leanness level considering desirable agility level can be identified based on the DEA-Leanness Measure. Acceptable delays in a manufacturing system or in inventory are identified to form the leanness target that tells lean practitioners "*how lean the system should be*."
4) **Potential Improvements Identification**: The Cost-Time-Value analysis developed in this research provides a way to identify potential improvements by comparing the Cost-Time Profiles of different DMUs.

5) **A Web-based Kanban System**: A computerized Kanban system is developed using web-based technology. Comparing to existing proprietary ERP or MES systems, the Web-Kanban System demonstrates a possibility to computerize the shop floor control simply using web services and standard web browsers. On the other hand, the web-based system enhanced the functionality of Kanban system by adding the capability of Kanban tracking and monitoring. The time-based data can be recorded in detail and analyzed by the web server. Performance of the system can then be monitored by authorized users in real time.

7.3 Future Research Areas

The goal of this research is to develop a methodology to help lean manufacturing practitioners implement lean concepts in a more efficient and more effective way. The solution provided by this research is a leanness measure that tells the lean practitioners "*how lean the system is*," "*how lean it should be*," and eventually "*how to achieve the desired leanness level*." In the future, the methodology can be further enhanced in the following areas.

1) **Empirical Study on Real-World Systems**: The approaches developed in this research are verified using hypothetical cases. Case studies based on real manufacturing system should be carried out to verify and improve the methodology. The case studies should include leanness measure and target identification for manufacturing systems, leanness measure using VSM, weighted leanness measure for different strategies, and improvement direction identification using CTP. Carrying out the case studies can help lean practitioners gain more insight into the performance of their systems and the impacts of the lean initiatives. Meanwhile, potential enhancements of the leanness measure can be explored.
2) **Including Cost-Time Investment (CTI) in the Leanness Measure**: In the CTP approach, the CTI (area under the curve) represents the time-value of monetary investments. The objective to minimize CTI supports the Just-in-Time strategy

and the postponement of product differentiation in agile manufacturing. However, the current DEA-Leanness Measure can hardly capture this characteristic since the cost and time variables are separated. Revising the leanness measure to include CTI as part of the input data may deliver a performance index that identifies competitive advantages more effectively.

3) **Applying DEA-Leanness Measure on Other Environments**: The proposed leanness measure is developed mainly for manufacturing systems. The same methodology can possibly be applied to other circumstance, such as service sectors, administrative works, research and development, etc. The way to identify input/output variables and collecting appropriate data needs to be further investigated.
4) **Developing Leanness Target for Various Scenarios**: Currently, the lean-agile target is represented by a leanness score considering the imbalance within a manufacturing system and the fluctuation of demand. The quantity and variability of customer's demand is taken as the requirement of agility, and inventory is assumed to be the solution to address the agility. Besides, the imbalances between workstations are assumed to be unchangeable. In reality, fluctuation in demand can also be addressed by other actions, such as working overtime or outsourcing. On the other hand, imbalances in the production line can be improved by reengineering. The target of lean-agile performance should be further investigated in order to develop a better methodology to help lean practitioners understand "*how lean the system should be*" and "*how to achieve the leanness*."
5) **Constructing Web-based Manufacturing System**: A Web-Kanban system has been developed in this research to explore the possibility of computerizing the Kanban system with web services and standard web browser. Although the software program does not possess many functions, the simplicity and effectiveness of web-based infrastructure demonstrates potential impacts on the information system for manufacturing. Actually, web-based technology has been improved dramatically in the past decade and will be further reinforced continuously. The capability of real-time data collection and analysis and the accessibility of online information have made web-based programming a trend for

the next generation of information system for manufacturing. The Web-Kanban System can be further enhanced by adding the interfaces with data collection devices and other computer programs for manufacturing systems. Also, leanness measurement and other performance metrics can be built into the Web-Kanban System. In the near future, developing "Performance-based Manufacturing Systems" with web-based technology should be a promising area for research.

The *Lean Manufacturing* concepts continue to be the most popular improvement strategy for manufacturing systems in 21^{st} century. Furthermore, the *Lean Thinking* has been expanded to cover various settings beyond manufacturing. The service sectors, administrative works, health care systems and many other systems have all been explored by supporters of lean thinking, and the results are impressive reportedly. This research provides a novel approach to measure leanness level of manufacturing systems. The effort is expected to bring impacts and contributions to the research and applications of lean concepts. Hopefully, the ideas and methodologies will inspire more research in this area to reinforce the impact of lean concepts continuously.

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Appendix A. Numerical Data of Hypothetical Cases

Table A.1 Time Stamps and Intervals of Case 1

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 1	0.00	0.00	0.00	18.40	18.40	0.00	18.40	18.80	37.21	0.00	37.21	19.20	56.41	87.05	143.46
Part 2	0.00	18.40	18.40	19.00	37.41	0.00	37.41	19.06	56.47	0.00	56.47	19.13	75.60	67.86	143.46
Part 3	0.00	37.41	37.41	21.28	58.68	0.00	58.68	21.96	80.65	0.00	80.65	18.65	99.29	44.16	143.46
Part 4	0.00	58.68	58.68	19.71	78.40	2.25	80.65	21.13	101.78	0.00	101.78	18.55	120.32	23.13	143.46
Part 5	0.00	78.40	78.40	18.18	96.58	5.19	101.78	21.29	123.06	0.00	123.06	20.39	143.46	0.00	143.46
Part 6	0.00	96.58	96.58	18.78	115.36	7.71	123.06	18.11	141.18	2.28	143.46	21.45	164.91	77.02	241.93
Part 7	0.00	115.36	115.36	18.96	134.32	6.86	141.18	18.90	160.08	4.83	164.91	18.83	183.74	58.19	241.93
Part 8	0.00	134.32	134.32	20.61	154.93	5.15	160.08	19.27	179.35	4.39	183.74	21.94	205.68	36.25	241.93
Part 9	0.00	154.93	154.93	18.85	173.78	5.57	179.35	18.43	197.78	7.91	205.68	18.00	223.68	18.25	241.93
Part 10	0.00	173.78	173.78	19.24	193.02	4.76	197.78	20.74	218.52	5.16	223.68	18.25	241.93	0.00	241.93
Part 11	200.00	0.00	200.00	20.66	220.66	0.00	220.66	18.60	239.26	2.67	241.93	20.55	262.48	84.20	346.68
Part 12	200.00	20.66	220.66	18.81	239.47	0.00	239.47	20.18	259.65	2.83	262.48	21.56	284.04	62.64	346.68
Part 13	200.00	39.47	239.47	20.64	260.11	0.00	260.11	19.14	279.24	4.80	284.04	21.64	305.68	41.00	346.68
Part 14	200.00	60.11	260.11	21.85	281.96	0.00	281.96	21.66	303.62	2.06	305.68	21.48	327.16	19.52	346.68
Part 15	200.00	81.96	281.96	21.51	303.47	0.15	303.62	18.52	322.14	5.02	327.16	19.52	346.68	0.00	346.68
Part 16	200.00	103.47	303.47	20.41	323.88	0.00	323.88	20.88	344.75	1.93	346.68	21.34	368.02	80.44	448.46
Part 17	200.00	123.88	323.88	20.77	344.65	0.10	344.75	18.45	363.21	4.82	368.02	20.13	388.16	60.31	448.46
Part 18	200.00	144.65	344.65	18.38	363.03	0.18	363.21	19.55	382.76	5.40	388.16	20.73	408.88	39.58	448.46
Part 19	200.00	163.03	363.03	21.84	384.87	0.00	384.87	21.32	406.19	2.69	408.88	20.80	429.68	18.78	448.46
Part 20	200.00	184.87	384.87	19.46	404.33	1.86	406.19	19.12	425.31	4.37	429.68	18.78	448.46	0.00	448.46

Unit: Minute

Table A.2 Costs of Value-Added Intervals of Case 1

DMU	Material Cost	Interval OP1	Cost VA	Cost NVA	Interval OP2	Cost VA	Cost NVA	Interval OP3	Cost VA	Cost NVA
Part 1	20.00	18.40	5.71	1.00	18.80	8.83	0.50	19.20	8.91	0.00
Part 2	20.00	19.00	5.89	1.00	19.06	8.91	0.50	19.13	8.89	0.00
Part 3	20.00	21.28	6.60	1.00	21.96	9.81	0.50	18.65	8.71	0.00
Part 4	20.00	19.71	6.11	1.00	21.13	9.55	0.50	18.55	8.68	0.00
Part 5	20.00	18.18	5.64	1.00	21.29	9.60	0.50	20.39	9.34	0.00
Part 6	20.00	18.78	5.82	1.00	18.11	8.62	0.50	21.45	9.72	0.00
Part 7	20.00	18.96	5.88	1.00	18.90	8.86	0.50	18.83	8.78	0.00
Part 8	20.00	20.61	6.39	1.00	19.27	8.98	0.50	21.94	9.90	0.00
Part 9	20.00	18.85	5.84	1.00	18.43	8.71	0.50	18.00	8.48	0.00
Part 10	20.00	19.24	5.96	1.00	20.74	9.43	0.50	18.25	8.57	0.00
Part 11	20.00	20.66	6.40	1.00	18.60	8.77	0.50	20.55	9.40	0.00
Part 12	20.00	18.81	5.83	1.00	20.18	9.26	0.50	21.56	9.76	0.00
Part 13	20.00	20.64	6.40	1.00	19.14	8.93	0.50	21.64	9.79	0.00
Part 14	20.00	21.85	6.77	1.00	21.66	9.72	0.50	21.48	9.73	0.00
Part 15	20.00	21.51	6.67	1.00	18.52	8.74	0.50	19.52	9.03	0.00
Part 16	20.00	20.41	6.33	1.00	20.88	9.47	0.50	21.34	9.68	0.00
Part 17	20.00	20.77	6.44	1.00	18.45	8.72	0.50	20.13	9.25	0.00
Part 18	20.00	18.38	5.70	1.00	19.55	9.06	0.50	20.73	9.46	0.00
Part 19	20.00	21.84	6.77	1.00	21.32	9.61	0.50	20.80	9.49	0.00
Part 20	20.00	19.46	6.03	1.00	19.12	8.93	0.50	18.78	8.76	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.3 Costs of Non-Value-Added Intervals of Case 1

DMU	Interval	Cost	Interval	Cost	Interval	Cost	Interval	Cost
	Wait 1	**NVA**	**Wait2**	**NVA**	**Wait 3**	**NVA**	**Wait 4**	**NVA**
Part 1	0.00	0.00	0.00	0.00	0.00	0.00	87.05	0.87
Part 2	18.40	0.18	0.00	0.00	0.00	0.00	67.86	0.68
Part 3	37.41	0.37	0.00	0.00	0.00	0.00	44.16	0.44
Part 4	58.68	0.59	2.25	0.02	0.00	0.00	23.13	0.23
Part 5	78.40	0.78	5.19	0.05	0.00	0.00	0.00	0.00
Part 6	96.58	0.97	7.71	0.08	2.28	0.02	77.02	0.77
Part 7	115.36	1.15	6.86	0.07	4.83	0.05	58.19	0.58
Part 8	134.32	1.34	5.15	0.05	4.39	0.04	36.25	0.36
Part 9	154.93	1.55	5.57	0.06	7.91	0.08	18.25	0.18
Part 10	173.78	1.74	4.76	0.05	5.16	0.05	0.00	0.00
Part 11	0.00	0.00	0.00	0.00	2.67	0.03	84.20	0.84
Part 12	20.66	0.21	0.00	0.00	2.83	0.03	62.64	0.63
Part 13	39.47	0.39	0.00	0.00	4.80	0.05	41.00	0.41
Part 14	60.11	0.60	0.00	0.00	2.06	0.02	19.52	0.20
Part 15	81.96	0.82	0.15	0.00	5.02	0.05	0.00	0.00
Part 16	103.47	1.03	0.00	0.00	1.93	0.02	80.44	0.80
Part 17	123.88	1.24	0.10	0.00	4.82	0.05	60.31	0.60
Part 18	144.65	1.45	0.18	0.00	5.40	0.05	39.58	0.40
Part 19	163.03	1.63	0.00	0.00	2.69	0.03	18.78	0.19
Part 20	184.87	1.85	1.86	0.02	4.37	0.04	0.00	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.4 Time Stamps and Intervals of Case 2

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 1	0.00	0.00	0.00	18.40	18.40	0.00	18.40	18.80	37.21	0.00	37.21	19.20	56.41	0.00	56.41
Part 2	18.40	0.00	18.40	19.00	37.41	0.00	37.41	19.06	56.47	0.00	56.47	19.13	75.60	0.00	75.60
Part 3	37.41	0.00	37.41	21.28	58.68	0.00	58.68	21.96	80.65	0.00	80.65	18.65	99.29	0.00	99.29
Part 4	58.68	0.00	58.68	19.71	78.40	2.25	80.65	21.13	101.78	0.00	101.78	18.55	120.32	0.00	120.32
Part 5	78.40	0.00	78.40	18.18	96.58	5.19	101.78	21.29	123.06	0.00	123.06	20.39	143.46	0.00	143.46
Part 6	96.58	0.00	96.58	18.78	115.36	7.71	123.06	18.11	141.18	2.28	143.46	21.45	164.91	0.00	164.91
Part 7	115.36	0.00	115.36	18.96	134.32	6.86	141.18	18.90	160.08	4.83	164.91	18.83	183.74	0.00	183.74
Part 8	134.32	0.00	134.32	20.61	154.93	5.15	160.08	19.27	179.35	4.39	183.74	21.94	205.68	0.00	205.68
Part 9	154.93	0.00	154.93	18.85	173.78	5.57	179.35	18.43	197.78	7.91	205.68	18.00	223.68	0.00	223.68
Part 10	173.78	0.00	173.78	19.24	193.02	4.76	197.78	20.74	218.52	5.16	223.68	18.25	241.93	0.00	241.93
Part 11	193.02	0.00	193.02	20.66	213.68	4.84	218.52	18.60	237.12	4.81	241.93	20.55	262.48	0.00	262.48
Part 12	213.68	0.00	213.68	18.81	232.48	4.64	237.12	20.18	257.31	5.17	262.48	21.56	284.04	0.00	284.04
Part 13	232.48	0.00	232.48	20.64	253.12	4.19	257.31	19.14	276.45	7.59	284.04	21.64	305.68	0.00	305.68
Part 14	253.12	0.00	253.12	21.85	274.97	1.47	276.45	21.66	298.11	7.57	305.68	21.48	327.16	0.00	327.16
Part 15	274.97	0.00	274.97	21.51	296.48	1.63	298.11	18.52	316.63	10.53	327.16	19.52	346.68	0.00	346.68
Part 16	296.48	0.00	296.48	20.41	316.89	0.00	316.89	20.88	337.77	8.91	346.68	21.34	368.02	0.00	368.02
Part 17	316.89	0.00	316.89	20.77	337.67	0.10	337.77	18.45	356.22	11.80	368.02	20.13	388.16	0.00	388.16
Part 18	337.67	0.00	337.67	18.38	356.05	0.18	356.22	19.55	375.78	12.38	388.16	20.73	408.88	0.00	408.88
Part 19	356.05	0.00	356.05	21.84	377.89	0.00	377.89	21.32	399.21	9.67	408.88	20.80	429.68	0.00	429.68
Part 20	377.89	0.00	377.89	19.46	397.35	1.86	399.21	19.12	418.33	11.35	429.68	18.78	448.46	0.00	448.46

Unit: Minute

Table A.5 Costs of Value-Added Intervals of Case 2

DMU	Material Cost	Interval OP1	Cost VA	Cost NVA	Interval OP2	Cost VA	Cost NVA	Interval OP3	Cost VA	Cost NVA
Part 1	20.00	18.40	5.71	1.00	18.80	8.83	0.50	19.20	8.91	0.00
Part 2	20.00	19.00	5.89	1.00	19.06	8.91	0.50	19.13	8.89	0.00
Part 3	20.00	21.28	6.60	1.00	21.96	9.81	0.50	18.65	8.71	0.00
Part 4	20.00	19.71	6.11	1.00	21.13	9.55	0.50	18.55	8.68	0.00
Part 5	20.00	18.18	5.64	1.00	21.29	9.60	0.50	20.39	9.34	0.00
Part 6	20.00	18.78	5.82	1.00	18.11	8.62	0.50	21.45	9.72	0.00
Part 7	20.00	18.96	5.88	1.00	18.90	8.86	0.50	18.83	8.78	0.00
Part 8	20.00	20.61	6.39	1.00	19.27	8.98	0.50	21.94	9.90	0.00
Part 9	20.00	18.85	5.84	1.00	18.43	8.71	0.50	18.00	8.48	0.00
Part 10	20.00	19.24	5.96	1.00	20.74	9.43	0.50	18.25	8.57	0.00
Part 11	20.00	20.66	6.40	1.00	18.60	8.77	0.50	20.55	9.40	0.00
Part 12	20.00	18.81	5.83	1.00	20.18	9.26	0.50	21.56	9.76	0.00
Part 13	20.00	20.64	6.40	1.00	19.14	8.93	0.50	21.64	9.79	0.00
Part 14	20.00	21.85	6.77	1.00	21.66	9.72	0.50	21.48	9.73	0.00
Part 15	20.00	21.51	6.67	1.00	18.52	8.74	0.50	19.52	9.03	0.00
Part 16	20.00	20.41	6.33	1.00	20.88	9.47	0.50	21.34	9.68	0.00
Part 17	20.00	20.77	6.44	1.00	18.45	8.72	0.50	20.13	9.25	0.00
Part 18	20.00	18.38	5.70	1.00	19.55	9.06	0.50	20.73	9.46	0.00
Part 19	20.00	21.84	6.77	1.00	21.32	9.61	0.50	20.80	9.49	0.00
Part 20	20.00	19.46	6.03	1.00	19.12	8.93	0.50	18.78	8.76	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.6 Costs of Non-Value-Added Intervals of Case 2

DMU	Interval	Cost	Interval	Cost	Interval	Cost	Interval	Cost
	Wait 1	**NVA**	**Wait2**	**NVA**	**Wait 3**	**NVA**	**Wait 4**	**NVA**
Part 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Part 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Part 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Part 4	0.00	0.00	2.25	0.02	0.00	0.00	0.00	0.00
Part 5	0.00	0.00	5.19	0.05	0.00	0.00	0.00	0.00
Part 6	0.00	0.00	7.71	0.08	2.28	0.02	0.00	0.00
Part 7	0.00	0.00	6.86	0.07	4.83	0.05	0.00	0.00
Part 8	0.00	0.00	5.15	0.05	4.39	0.04	0.00	0.00
Part 9	0.00	0.00	5.57	0.06	7.91	0.08	0.00	0.00
Part 10	0.00	0.00	4.76	0.05	5.16	0.05	0.00	0.00
Part 11	0.00	0.00	4.84	0.05	4.81	0.05	0.00	0.00
Part 12	0.00	0.00	4.64	0.05	5.17	0.05	0.00	0.00
Part 13	0.00	0.00	4.19	0.04	7.59	0.08	0.00	0.00
Part 14	0.00	0.00	1.47	0.01	7.57	0.08	0.00	0.00
Part 15	0.00	0.00	1.63	0.02	10.53	0.11	0.00	0.00
Part 16	0.00	0.00	0.00	0.00	8.91	0.09	0.00	0.00
Part 17	0.00	0.00	0.10	0.00	11.80	0.12	0.00	0.00
Part 18	0.00	0.00	0.18	0.00	12.38	0.12	0.00	0.00
Part 19	0.00	0.00	0.00	0.00	9.67	0.10	0.00	0.00
Part 20	0.00	0.00	1.86	0.02	11.35	0.11	0.00	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.7 Time Stamps and Intervals of Case 3

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 1	0.00	0.00	0.00	18.40	18.40	0.00	18.40	18.80	37.21	0.00	37.21	19.20	56.41	107.05	163.46
Part 2	0.00	18.40	18.40	19.00	37.41	0.00	37.41	19.06	56.47	0.00	56.47	19.13	75.60	87.86	163.46
Part 3	0.00	37.41	37.41	21.28	58.68	0.00	58.68	21.96	80.65	0.00	80.65	18.65	99.29	64.16	163.46
Part 4	0.00	58.68	58.68	19.71	78.40	2.25	80.65	41.13	121.78	0.00	121.78	18.55	140.32	23.13	163.46
Part 5	0.00	78.40	78.40	18.18	96.58	25.19	121.78	21.29	143.06	0.00	143.06	20.39	163.46	0.00	163.46
Part 6	0.00	96.58	96.58	18.78	115.36	27.71	143.06	18.11	161.18	2.28	163.46	21.45	184.91	97.57	282.48
Part 7	0.00	115.36	115.36	18.96	134.32	26.86	161.18	18.90	180.08	4.83	184.91	18.83	203.74	78.74	282.48
Part 8	0.00	134.32	134.32	20.61	154.93	25.15	180.08	19.27	199.35	4.39	203.74	21.94	225.68	56.80	282.48
Part 9	0.00	154.93	154.93	18.85	173.78	25.57	199.35	18.43	217.78	7.91	225.68	18.00	243.68	38.80	282.48
Part 10	0.00	173.78	173.78	19.24	193.02	24.76	217.78	20.74	238.52	5.16	243.68	36.49	504.96	0.00	504.96
Part 11	200.00	0.00	200.00	20.66	220.66	17.86	238.52	18.60	257.12	4.81	261.93	20.55	282.48	0.00	282.48
Part 12	200.00	20.66	220.66	18.81	239.47	17.66	257.12	20.18	277.31	5.17	282.48	21.56	304.04	83.98	388.02
Part 13	200.00	39.47	239.47	20.64	260.11	17.20	277.31	19.14	296.45	7.59	304.04	21.64	325.68	62.34	388.02
Part 14	200.00	60.11	260.11	21.85	281.96	14.49	296.45	21.66	318.11	7.57	325.68	21.48	347.16	40.86	388.02
Part 15	200.00	81.96	281.96	21.51	303.47	14.65	318.11	18.52	336.63	10.53	347.16	19.52	366.68	21.34	388.02
Part 16	200.00	103.47	303.47	20.41	323.88	12.75	336.63	20.88	357.50	9.18	366.68	21.34	388.02	0.00	388.02
Part 17	200.00	123.88	323.88	20.77	344.65	12.85	357.50	18.45	375.96	12.06	388.02	20.13	408.16	96.80	504.96
Part 18	200.00	144.65	344.65	18.38	363.03	12.93	375.96	19.55	395.51	12.64	408.16	20.73	428.88	76.07	504.96
Part 19	200.00	163.03	363.03	21.84	384.87	10.64	395.51	21.32	416.83	12.05	428.88	20.80	449.68	55.28	504.96
Part 20	200.00	184.87	384.87	19.46	404.33	12.50	416.83	19.12	435.95	13.73	449.68	18.78	468.46	36.49	504.96

Unit: Minute

Table A.8 Costs of Value-Added Intervals of Case 3

DMU	Material Cost	Interval OP1	Cost VA	Cost NVA	Interval OP2	Cost VA	Cost NVA	Interval OP3	Cost VA	Cost NVA
Part 1	20.00	18.40	5.71	1.00	18.80	8.83	0.50	19.20	8.91	0.00
Part 2	20.00	19.00	5.89	1.00	19.06	8.91	0.50	19.13	8.89	0.00
Part 3	20.00	21.28	6.60	1.00	21.96	9.81	0.50	18.65	8.71	0.00
Part 4	20.00	19.71	6.11	1.00	41.13	15.75	0.50	18.55	8.68	0.00
Part 5	20.00	18.18	5.64	1.00	21.29	9.60	0.50	20.39	9.34	0.00
Part 6	20.00	18.78	5.82	1.00	18.11	8.62	0.50	21.45	9.72	0.00
Part 7	20.00	18.96	5.88	1.00	18.90	8.86	0.50	18.83	8.78	0.00
Part 8	20.00	20.61	6.39	1.00	19.27	8.98	0.50	21.94	9.90	0.00
Part 9	20.00	18.85	5.84	1.00	18.43	8.71	0.50	18.00	8.48	0.00
Part 10	20.00	19.24	5.96	1.00	20.74	9.43	0.50	36.49	15.14	0.00
Part 11	20.00	20.66	6.40	1.00	18.60	8.77	0.50	20.55	9.40	0.00
Part 12	20.00	18.81	5.83	1.00	20.18	9.26	0.50	21.56	9.76	0.00
Part 13	20.00	20.64	6.40	1.00	19.14	8.93	0.50	21.64	9.79	0.00
Part 14	20.00	21.85	6.77	1.00	21.66	9.72	0.50	21.48	9.73	0.00
Part 15	20.00	21.51	6.67	1.00	18.52	8.74	0.50	19.52	9.03	0.00
Part 16	20.00	20.41	6.33	1.00	20.88	9.47	0.50	21.34	9.68	0.00
Part 17	20.00	20.77	6.44	1.00	18.45	8.72	0.50	20.13	9.25	0.00
Part 18	20.00	18.38	5.70	1.00	19.55	9.06	0.50	20.73	9.46	0.00
Part 19	20.00	21.84	6.77	1.00	21.32	9.61	0.50	20.80	9.49	0.00
Part 20	20.00	19.46	6.03	1.00	19.12	8.93	0.50	18.78	8.76	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.9 Costs of Non-Value-Added Intervals of Case 3

DMU	Interval Wait 1	Cost NVA	Interval Wait2	Cost NVA	Interval Wait 3	Cost NVA	Interval Wait 4	Cost NVA
Part 1	0.00	0.00	0.00	0.00	0.00	0.00	107.05	1.07
Part 2	18.40	0.18	0.00	0.00	0.00	0.00	87.86	0.88
Part 3	37.41	0.37	0.00	0.00	0.00	0.00	64.16	0.64
Part 4	58.68	0.59	2.25	0.02	0.00	0.00	23.13	0.23
Part 5	78.40	0.78	25.19	0.25	0.00	0.00	0.00	0.00
Part 6	96.58	0.97	27.71	0.28	2.28	0.02	97.57	0.98
Part 7	115.36	1.15	26.86	0.27	4.83	0.05	78.74	0.79
Part 8	134.32	1.34	25.15	0.25	4.39	0.04	56.80	0.57
Part 9	154.93	1.55	25.57	0.26	7.91	0.08	38.80	0.39
Part 10	173.78	1.74	24.76	0.25	5.16	0.05	0.00	0.00
Part 11	0.00	0.00	17.86	0.18	4.81	0.05	0.00	0.00
Part 12	20.66	0.21	17.66	0.18	5.17	0.05	83.98	0.84
Part 13	39.47	0.39	17.20	0.17	7.59	0.08	62.34	0.62
Part 14	60.11	0.60	14.49	0.14	7.57	0.08	40.86	0.41
Part 15	81.96	0.82	14.65	0.15	10.53	0.11	21.34	0.21
Part 16	103.47	1.03	12.75	0.13	9.18	0.09	0.00	0.00
Part 17	123.88	1.24	12.85	0.13	12.06	0.12	96.80	0.97
Part 18	144.65	1.45	12.93	0.13	12.64	0.13	76.07	0.76
Part 19	163.03	1.63	10.64	0.11	12.05	0.12	55.28	0.55
Part 20	184.87	1.85	12.50	0.13	13.73	0.14	36.49	0.36

Time Unit: Minute
Cost Unit: Dollar

Table A.10 Time Stamps and Intervals of Case 4

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 1	0.00	0.00	0.00	4.60	4.60	0.00	4.60	18.80	23.40	0.00	23.40	9.60	33.00	0.00	33.00
Part 2	4.60	0.00	4.60	4.75	9.35	14.05	23.40	19.06	42.47	0.00	42.47	9.56	52.03	0.00	52.03
Part 3	23.40	0.00	23.40	5.32	28.72	13.75	42.47	21.96	64.43	0.00	64.43	9.32	73.75	0.00	73.75
Part 4	42.47	0.00	42.47	4.93	47.40	17.03	64.43	21.13	85.56	0.00	85.56	9.27	94.83	0.00	94.83
Part 5	64.43	0.00	64.43	4.55	68.98	16.58	85.56	21.29	106.85	0.00	106.85	10.20	117.04	0.00	117.04
Part 6	85.56	0.00	85.56	4.69	90.25	16.59	106.85	18.11	124.96	0.00	124.96	10.73	135.69	0.00	135.69
Part 7	106.85	0.00	106.85	4.74	111.59	13.37	124.96	18.90	143.86	0.00	143.86	9.42	153.28	0.00	153.28
Part 8	124.96	0.00	124.96	5.15	130.11	13.74	143.86	19.27	163.13	0.00	163.13	10.97	174.10	0.00	174.10
Part 9	143.86	0.00	143.86	4.71	148.57	14.56	163.13	18.43	181.56	0.00	181.56	9.00	190.56	0.00	190.56
Part 10	163.13	0.00	163.13	4.81	167.94	13.62	181.56	20.74	202.30	0.00	202.30	9.12	211.43	0.00	211.43
Part 11	181.56	0.00	181.56	5.16	186.72	15.58	202.30	18.60	220.91	0.00	220.91	10.27	231.18	0.00	231.18
Part 12	202.30	0.00	202.30	4.70	207.00	13.90	220.91	20.18	241.09	0.00	241.09	10.78	251.87	0.00	251.87
Part 13	220.91	0.00	220.91	5.16	226.07	15.02	241.09	19.14	260.23	0.00	260.23	10.82	271.05	0.00	271.05
Part 14	241.09	0.00	241.09	5.46	246.55	13.68	260.23	21.66	281.89	0.00	281.89	10.74	292.63	0.00	292.63
Part 15	260.23	0.00	260.23	5.38	265.61	16.29	281.89	18.52	300.41	0.00	300.41	9.76	310.17	0.00	310.17
Part 16	281.89	0.00	281.89	5.10	287.00	13.41	300.41	20.88	321.29	0.00	321.29	10.67	331.96	0.00	331.96
Part 17	300.41	0.00	300.41	5.19	305.60	15.68	321.29	18.45	339.74	0.00	339.74	10.07	349.81	0.00	349.81
Part 18	321.29	0.00	321.29	4.60	325.88	13.86	339.74	19.55	359.29	0.00	359.29	10.36	369.66	0.00	369.66
Part 19	339.74	0.00	339.74	5.46	345.20	14.09	359.29	21.32	380.61	0.00	380.61	10.40	391.01	0.00	391.01
Part 20	359.29	0.00	359.29	4.86	364.16	16.45	380.61	19.12	399.73	0.00	399.73	9.39	409.12	0.00	409.12

Unit: Minute

Table A.11 Costs of Value-Added Intervals of Case 4

DMU	Material Cost	Interval OP1	Cost VA	Cost NVA	Interval OP2	Cost VA	Cost NVA	Interval OP3	Cost VA	Cost NVA
Part 1	20.00	4.60	1.43	1.00	18.80	8.83	0.50	9.60	5.46	0.00
Part 2	20.00	4.75	1.47	1.00	19.06	8.91	0.50	9.56	5.44	0.00
Part 3	20.00	5.32	1.65	1.00	21.96	9.81	0.50	9.32	5.36	0.00
Part 4	20.00	4.93	1.53	1.00	21.13	9.55	0.50	9.27	5.34	0.00
Part 5	20.00	4.55	1.41	1.00	21.29	9.60	0.50	10.20	5.67	0.00
Part 6	20.00	4.69	1.46	1.00	18.11	8.62	0.50	10.73	5.86	0.00
Part 7	20.00	4.74	1.47	1.00	18.90	8.86	0.50	9.42	5.39	0.00
Part 8	20.00	5.15	1.60	1.00	19.27	8.98	0.50	10.97	5.95	0.00
Part 9	20.00	4.71	1.46	1.00	18.43	8.71	0.50	9.00	5.24	0.00
Part 10	20.00	4.81	1.49	1.00	20.74	9.43	0.50	9.12	5.28	0.00
Part 11	20.00	5.16	1.60	1.00	18.60	8.77	0.50	10.27	5.70	0.00
Part 12	20.00	4.70	1.46	1.00	20.18	9.26	0.50	10.78	5.88	0.00
Part 13	20.00	5.16	1.60	1.00	19.14	8.93	0.50	10.82	5.89	0.00
Part 14	20.00	5.46	1.69	1.00	21.66	9.72	0.50	10.74	5.87	0.00
Part 15	20.00	5.38	1.67	1.00	18.52	8.74	0.50	9.76	5.51	0.00
Part 16	20.00	5.10	1.58	1.00	20.88	9.47	0.50	10.67	5.84	0.00
Part 17	20.00	5.19	1.61	1.00	18.45	8.72	0.50	10.07	5.62	0.00
Part 18	20.00	4.60	1.42	1.00	19.55	9.06	0.50	10.36	5.73	0.00
Part 19	20.00	5.46	1.69	1.00	21.32	9.61	0.50	10.40	5.74	0.00
Part 20	20.00	4.86	1.51	1.00	19.12	8.93	0.50	9.39	5.38	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.12 Costs of Non-Value-Added Intervals of Case 4

DMU	Interval	Cost	Interval	Cost	Interval	Cost	Interval	Cost
	Wait 1	NVA	Wait2	NVA	Wait 3	NVA	Wait 4	NVA
Part 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Part 2	0.00	0.00	14.05	0.14	0.00	0.00	0.00	0.00
Part 3	0.00	0.00	13.75	0.14	0.00	0.00	0.00	0.00
Part 4	0.00	0.00	17.03	0.17	0.00	0.00	0.00	0.00
Part 5	0.00	0.00	16.58	0.17	0.00	0.00	0.00	0.00
Part 6	0.00	0.00	16.59	0.17	0.00	0.00	0.00	0.00
Part 7	0.00	0.00	13.37	0.13	0.00	0.00	0.00	0.00
Part 8	0.00	0.00	13.74	0.14	0.00	0.00	0.00	0.00
Part 9	0.00	0.00	14.56	0.15	0.00	0.00	0.00	0.00
Part 10	0.00	0.00	13.62	0.14	0.00	0.00	0.00	0.00
Part 11	0.00	0.00	15.58	0.16	0.00	0.00	0.00	0.00
Part 12	0.00	0.00	13.90	0.14	0.00	0.00	0.00	0.00
Part 13	0.00	0.00	15.02	0.15	0.00	0.00	0.00	0.00
Part 14	0.00	0.00	13.68	0.14	0.00	0.00	0.00	0.00
Part 15	0.00	0.00	16.29	0.16	0.00	0.00	0.00	0.00
Part 16	0.00	0.00	13.41	0.13	0.00	0.00	0.00	0.00
Part 17	0.00	0.00	15.68	0.16	0.00	0.00	0.00	0.00
Part 18	0.00	0.00	13.86	0.14	0.00	0.00	0.00	0.00
Part 19	0.00	0.00	14.09	0.14	0.00	0.00	0.00	0.00
Part 20	0.00	0.00	16.45	0.16	0.00	0.00	0.00	0.00

Time Unit: Minute
Cost Unit: Dollar

Table A.13 Time Stamps and Intervals of Case 5: Day 1

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 1	0.00	0.00	0.00	18.05	18.05	0.00	18.05	18.09	36.14	0.00	36.14	18.14	54.28	383.45	437.73
Part 2	18.05	0.00	18.05	20.58	38.63	0.00	38.63	18.22	56.85	0.00	56.85	19.86	76.71	361.03	437.73
Part 3	38.63	0.00	38.63	18.65	57.28	0.00	57.28	20.70	77.98	0.00	77.98	18.76	96.74	340.99	437.73
Part 4	57.28	0.00	57.28	20.35	77.63	0.35	77.98	18.40	96.39	0.36	96.74	20.46	117.20	320.53	437.73
Part 5	77.63	0.00	77.63	18.84	96.47	0.00	96.47	18.60	115.07	2.13	117.20	18.36	135.56	302.17	437.73
Part 6	96.47	0.00	96.47	20.65	117.12	0.00	117.12	21.85	138.97	0.00	138.97	19.06	158.03	279.70	437.73
Part 7	117.12	0.00	117.12	21.19	138.31	0.66	138.97	19.37	158.34	0.00	158.34	21.54	179.88	257.86	437.73
Part 8	138.31	0.00	138.31	18.28	156.59	1.75	158.34	18.61	176.95	2.93	179.88	18.95	198.83	238.91	437.73
Part 9	156.59	0.00	156.59	19.00	175.59	1.36	176.95	18.73	195.68	3.14	198.83	18.46	217.29	220.44	437.73
Part 10	175.59	0.00	175.59	18.43	194.02	1.66	195.68	19.13	214.81	2.48	217.29	19.82	237.11	200.62	437.73
Part 11	194.02	0.00	194.02	20.71	214.74	0.08	214.81	18.71	233.52	3.59	237.11	20.70	257.81	179.92	437.73
Part 12	214.74	0.00	214.74	18.03	232.76	0.75	233.52	18.62	252.14	5.67	257.81	19.22	277.03	160.70	437.73
Part 13	232.76	0.00	232.76	18.12	250.88	1.26	252.14	18.09	270.24	6.80	277.03	18.07	295.11	142.63	437.73
Part 14	250.88	0.00	250.88	18.23	269.11	1.12	270.24	18.43	288.67	6.44	295.11	18.63	313.74	124.00	437.73
Part 15	269.11	0.00	269.11	21.21	290.32	0.00	290.32	21.91	312.23	1.51	313.74	18.61	332.34	105.39	437.73
Part 16	290.32	0.00	290.32	18.87	309.19	3.03	312.23	21.80	334.02	0.00	334.02	20.73	354.75	82.98	437.73
Part 17	309.19	0.00	309.19	18.47	327.66	6.36	334.02	21.85	355.87	0.00	355.87	21.23	377.10	60.63	437.73
Part 18	327.66	0.00	327.66	18.87	346.53	9.35	355.87	20.53	376.40	0.70	377.10	18.18	395.28	42.45	437.73
Part 19	346.53	0.00	346.53	19.17	365.70	10.70	376.40	19.98	396.38	0.00	396.38	20.78	417.16	20.57	437.73
Part 20	365.70	0.00	365.70	18.55	384.25	12.13	396.38	21.30	417.68	0.00	417.68	20.06	437.73	0.00	437.73

Unit: Minute

Table A.14 Time Stamps and Intervals of Case 5: Day 2

DMU	Time Arrive	Interval Wait 1	Time Enter WS1	Interval OP1	Time Leave WS1	Interval Wait2	Time Enter WS2	Interval OP2	Time Leave WS2	Interval Wait 3	Time Enter WS3	Interval OP3	Time Leave WS3	Interval Wait 4	Time Leave System
Part 21	0.00	0.00	0.00	19.24	19.24	0.00	19.24	21.92	41.15	0.00	41.15	20.59	61.75	287.63	349.38
Part 22	19.24	0.00	19.24	19.66	38.90	2.26	41.15	21.42	62.58	0.00	62.58	19.18	81.76	267.62	349.38
Part 23	38.90	0.00	38.90	20.09	58.99	3.59	62.58	19.54	82.11	0.00	82.11	18.99	101.10	248.27	349.38
Part 24	58.99	0.00	58.99	20.21	79.20	2.92	82.11	19.26	101.37	0.00	101.37	18.30	119.67	229.70	349.38
Part 25	79.20	0.00	79.20	18.12	97.32	4.05	101.37	19.99	121.36	0.00	121.36	21.86	143.21	206.16	349.38
Part 26	97.32	0.00	97.32	20.01	117.32	4.04	121.36	21.85	143.21	0.01	143.21	19.69	162.91	186.47	349.38
Part 27	117.32	0.00	117.32	18.25	135.57	7.63	143.21	18.98	162.19	0.72	162.91	19.71	182.61	166.76	349.38
Part 28	135.57	0.00	135.57	21.52	157.09	5.10	162.19	20.76	182.95	0.00	182.95	20.00	202.95	146.43	349.38
Part 29	157.09	0.00	157.09	18.59	175.68	7.27	182.95	21.99	204.94	0.00	204.94	21.40	226.33	123.04	349.38
Part 30	175.68	0.00	175.68	18.15	193.83	11.10	204.94	18.37	223.31	3.03	226.33	18.58	244.91	104.46	349.38
Part 31	193.83	0.00	193.83	18.96	212.79	10.51	223.31	19.62	242.93	1.99	244.91	20.29	265.20	84.18	349.38
Part 32	212.79	0.00	212.79	20.47	233.27	9.66	242.93	18.87	261.80	3.40	265.20	21.27	286.47	62.91	349.38
Part 33	233.27	0.00	233.27	18.87	252.13	9.67	261.80	19.63	281.43	5.04	286.47	20.39	306.86	42.52	349.38
Part 34	252.13	0.00	252.13	20.76	272.89	8.54	281.43	21.25	302.67	4.19	306.86	21.74	328.59	20.78	349.38
Part 35	272.89	0.00	272.89	20.30	293.19	9.48	302.67	20.54	323.22	5.38	328.59	20.78	349.38	0.00	349.38
Part 36	293.19	0.00	293.19	18.65	311.84	11.38	323.22	20.70	343.92	5.46	349.38	18.76	368.13	663.11	1031.24
Part 37	311.84	0.00	311.84	20.74	332.58	11.34	343.92	20.59	364.51	3.62	368.13	20.45	388.58	642.66	1031.24
Part 38	332.58	0.00	332.58	20.92	353.49	11.02	364.51	18.30	382.80	5.77	388.58	19.67	408.25	622.99	1031.24
Part 39	353.49	0.00	353.49	21.57	375.06	7.75	382.80	19.61	402.41	5.84	408.25	21.65	429.91	601.33	1031.24
Part 40	375.06	0.00	375.06	20.42	395.48	6.93	402.41	18.73	421.15	8.76	429.91	21.05	450.96	580.28	1031.24

Unit: Minute

Table A.15 Time Stamps and Intervals of Case 5: Day 3

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	**Wait 1**	**Enter WS1**	**OP1**	**Leave WS1**	**Wait2**	**Enter WS2**	**OP2**	**Leave WS2**	**Wait 3**	**Enter WS3**	**OP3**	**Leave WS3**	**Wait 4**	**Leave System**
Part 41	0.00	0.00	0.00	18.37	18.37	0.00	18.37	19.13	37.50	0.00	37.50	19.89	57.39	493.85	551.24
Part 42	18.37	0.00	18.37	20.27	38.64	0.00	38.64	21.71	60.35	0.00	60.35	19.14	79.49	471.74	551.24
Part 43	38.64	0.00	38.64	19.45	58.09	2.26	60.35	21.45	81.80	0.00	81.80	19.45	101.25	449.99	551.24
Part 44	58.09	0.00	58.09	20.84	78.93	2.87	81.80	21.49	103.29	0.00	103.29	18.14	121.43	429.81	551.24
Part 45	78.93	0.00	78.93	21.19	100.12	3.17	103.29	20.53	123.82	0.00	123.82	19.87	143.69	407.55	551.24
Part 46	100.12	0.00	100.12	20.80	120.92	2.90	123.82	21.08	144.90	0.00	144.90	21.37	166.27	384.96	551.24
Part 47	120.92	0.00	120.92	19.19	140.10	4.80	144.90	18.88	163.79	2.49	166.27	18.57	184.85	366.39	551.24
Part 48	140.10	0.00	140.10	20.73	160.84	2.95	163.79	19.67	183.45	1.40	184.85	18.60	203.45	347.79	551.24
Part 49	160.84	0.00	160.84	19.06	179.89	3.56	183.45	19.19	202.64	0.80	203.45	19.33	222.78	328.46	551.24
Part 50	179.89	0.00	179.89	21.90	201.80	0.85	202.64	19.72	222.37	0.41	222.78	21.54	244.32	306.92	551.24
Part 51	201.80	0.00	201.80	21.72	223.52	0.00	223.52	20.51	244.03	0.29	244.32	19.30	263.62	287.62	551.24
Part 52	223.52	0.00	223.52	21.74	245.26	0.00	245.26	21.90	267.16	0.00	267.16	18.05	285.21	266.03	551.24
Part 53	245.26	0.00	245.26	19.69	264.95	2.21	267.16	19.88	287.04	0.00	287.04	20.07	307.10	244.13	551.24
Part 54	264.95	0.00	264.95	20.50	285.45	1.58	287.04	21.36	308.39	0.00	308.39	18.21	326.61	224.63	551.24
Part 55	285.45	0.00	285.45	18.02	303.47	4.92	308.39	19.07	327.46	0.00	327.46	20.11	347.57	203.67	551.24
Part 56	303.47	0.00	303.47	19.82	323.29	4.17	327.46	20.21	347.67	0.00	347.67	20.61	368.28	182.95	551.24
Part 57	323.29	0.00	323.29	18.65	341.95	5.73	347.67	21.80	369.48	0.00	369.48	20.95	390.43	160.81	551.24
Part 58	341.95	0.00	341.95	21.64	363.59	5.89	369.48	20.40	389.88	0.55	390.43	19.17	409.60	141.64	551.24
Part 59	363.59	0.00	363.59	19.71	383.30	6.58	389.88	21.14	411.02	0.00	411.02	18.56	429.58	121.65	551.24
Part 60	383.30	0.00	383.30	21.87	405.16	5.86	411.02	19.38	430.40	0.00	430.40	20.89	451.29	99.95	551.24
Part 61	405.16	0.00	405.16	19.93	425.09	5.31	430.40	19.15	449.55	1.74	451.29	18.38	469.67	81.57	551.24
Part 62	425.09	0.00	425.09	21.31	446.39	3.16	449.55	18.89	468.44	1.23	469.67	20.47	490.13	61.10	551.24
Part 63	446.39	0.00	446.39	21.09	467.48	0.95	468.44	20.89	489.32	0.81	490.13	20.69	510.82	40.42	551.24
Part 64	467.48	0.00	467.48	20.16	487.64	1.68	489.32	18.18	507.50	3.32	510.82	20.20	531.03	20.21	551.24
Part 65	487.64	0.00	487.64	19.17	506.81	0.70	507.50	21.69	529.19	1.83	531.03	20.21	551.24	0.00	551.24

Unit: Minute

Table A.16 Time Stamps and Intervals of Case 5: Day 4

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	**Wait 1**	**Enter WS1**	**OP1**	**Leave WS1**	**Wait2**	**Enter WS2**	**OP2**	**Leave WS2**	**Wait 3**	**Enter WS3**	**OP3**	**Leave WS3**	**Wait 4**	**Leave System**
Part 66	0.00	0.00	0.00	19.93	19.93	0.00	19.93	19.15	39.08	0.00	39.08	18.38	57.46	188.11	245.57
Part 67	19.93	0.00	19.93	21.31	41.23	0.00	41.23	18.89	60.12	0.00	60.12	20.47	80.58	164.99	245.57
Part 68	41.23	0.00	41.23	21.09	62.32	0.00	62.32	20.89	83.21	0.00	83.21	20.69	103.90	141.67	245.57
Part 69	62.32	0.00	62.32	20.16	82.48	0.73	83.21	18.18	101.39	2.51	103.90	20.20	124.10	121.47	245.57
Part 70	82.48	0.00	82.48	19.17	101.64	0.00	101.64	21.69	123.33	0.77	124.10	20.21	144.31	101.26	245.57
Part 71	101.64	0.00	101.64	21.08	122.73	0.60	123.33	19.14	142.47	1.84	144.31	21.20	165.51	80.06	245.57
Part 72	122.73	0.00	122.73	21.70	144.43	0.00	144.43	18.43	162.86	2.65	165.51	19.17	184.68	60.89	245.57
Part 73	144.43	0.00	144.43	21.12	165.55	0.00	165.55	20.84	186.39	0.00	186.39	20.56	206.95	38.61	245.57
Part 74	165.55	0.00	165.55	19.86	185.41	0.98	186.39	21.03	207.42	0.00	207.42	18.21	225.63	19.94	245.57
Part 75	185.41	0.00	185.41	20.24	205.65	1.77	207.42	19.46	226.89	0.00	226.89	18.68	245.57	0.00	245.57
Part 76	205.65	0.00	205.65	20.59	226.25	0.64	226.89	21.47	248.36	0.00	248.36	18.34	266.70	564.92	831.62
Part 77	226.25	0.00	226.25	19.13	245.37	2.98	248.36	18.64	267.00	0.00	267.00	18.15	285.15	546.47	831.62
Part 78	245.37	0.00	245.37	18.42	263.80	3.20	267.00	18.28	285.27	0.00	285.27	18.13	303.40	528.22	831.62
Part 79	263.80	0.00	263.80	20.89	284.69	0.59	285.27	21.74	307.01	0.00	307.01	18.59	325.60	506.02	831.62
Part 80	284.69	0.00	284.69	19.31	304.00	3.01	307.01	18.76	325.77	0.00	325.77	18.21	343.99	487.64	831.62

Unit: Minute

Table A.17 Time Stamps and Intervals of Case 5: Day 5

DMU	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time	Interval	Time
	Arrive	Wait 1	Enter WS1	OP1	Leave WS1	Wait2	Enter WS2	OP2	Leave WS2	Wait 3	Enter WS3	OP3	Leave WS3	Wait 4	Leave System
Part 86	0.00	0.00	0.00	20.09	20.09	0.00	20.09	20.14	40.23	0.00	40.23	20.20	60.43	291.19	351.62
Part 87	20.09	0.00	20.09	18.72	38.81	1.43	40.23	19.05	59.28	1.15	60.43	19.38	79.81	271.81	351.62
Part 88	38.81	0.00	38.81	21.63	60.44	0.00	60.44	19.82	80.26	0.00	80.26	18.01	98.27	253.36	351.62
Part 89	60.44	0.00	60.44	20.76	81.20	0.00	81.20	20.66	101.86	0.00	101.86	20.55	122.41	229.21	351.62
Part 90	81.20	0.00	81.20	20.92	102.12	0.00	102.12	19.82	121.94	0.47	122.41	18.71	141.12	210.50	351.62
Part 91	102.12	0.00	102.12	18.23	120.35	1.59	121.94	21.94	143.88	0.00	143.88	21.66	165.54	186.08	351.62
Part 92	120.35	0.00	120.35	19.64	139.99	3.89	143.88	20.94	164.82	0.71	165.54	18.24	183.78	167.84	351.62
Part 93	139.99	0.00	139.99	21.39	161.39	3.44	164.82	21.26	186.08	0.00	186.08	21.12	207.20	144.42	351.62
Part 94	161.39	0.00	161.39	18.17	179.55	6.53	186.08	21.96	208.04	0.00	208.04	21.76	229.80	121.82	351.62
Part 95	179.55	0.00	179.55	19.69	199.24	8.80	208.04	20.12	228.16	1.64	229.80	20.55	250.35	101.27	351.62
Part 96	199.24	0.00	199.24	19.87	219.11	9.05	228.16	19.23	247.39	2.95	250.35	18.59	268.94	82.68	351.62
Part 97	219.11	0.00	219.11	18.28	237.39	10.00	247.39	19.95	267.34	1.60	268.94	21.62	290.56	61.06	351.62
Part 98	237.39	0.00	237.39	20.57	257.96	9.38	267.34	21.19	288.53	2.03	290.56	21.80	312.36	39.26	351.62
Part 99	257.96	0.00	257.96	20.01	277.97	10.56	288.53	20.60	309.13	3.23	312.36	21.20	333.56	18.06	351.62
Part 100	277.97	0.00	277.97	20.14	298.11	11.03	309.13	19.10	328.23	5.33	333.56	18.06	351.62	0.00	351.62
Part 101	298.11	0.00	298.11	18.37	316.48	11.75	328.23	21.04	349.27	2.35	351.62	19.70	371.33	588.67	960.00
Part 102	316.48	0.00	316.48	20.02	336.50	12.77	349.27	21.97	371.23	0.09	371.33	19.91	391.24	568.76	960.00
Part 103	336.50	0.00	336.50	19.35	355.85	15.39	371.23	19.83	391.07	0.17	391.24	20.32	411.55	548.45	960.00
Part 104	355.85	0.00	355.85	18.49	374.33	16.73	391.07	19.61	410.68	0.87	411.55	20.74	432.29	527.71	960.00
Part 105	374.33	0.00	374.33	21.85	396.18	14.50	410.68	20.13	430.81	1.48	432.29	18.41	450.70	509.30	960.00

Unit: Minute

Table A.18 ADMU and IDMU of Case 5: Day 1 to Day 2

		ADMU		IDMU					ADMU		IDMU	
		Total Time	**Total Cost**	**VA Time**	**VA Cost**				**Total Time**	**Total Cost**	**VA Time**	**VA Cost**
Day 1	**Part 1**	437.73	48.07	54.28	42.73		**Day 2**	**Part 21**	349.38	49.55	61.75	45.17
	Part 2	419.69	49.29	58.66	44.18			**Part 22**	330.14	48.84	60.26	44.64
	Part 3	399.10	48.86	58.11	43.95			**Part 23**	310.48	48.14	58.62	44.12
	Part 4	380.46	49.09	59.21	44.38			**Part 24**	290.39	47.65	57.77	43.82
	Part 5	360.10	47.76	55.81	43.22			**Part 25**	270.18	48.28	59.96	44.68
	Part 6	341.26	49.33	61.56	45.04			**Part 26**	252.06	48.47	61.55	45.07
	Part 7	320.62	49.41	62.10	45.33			**Part 27**	232.05	46.89	56.94	43.64
	Part 8	299.42	47.19	55.84	43.26			**Part 28**	213.80	48.32	62.27	45.31
	Part 9	281.15	47.09	56.20	43.35			**Part 29**	192.29	48.09	61.98	45.28
	Part 10	262.14	47.33	57.38	43.78			**Part 30**	173.70	45.70	55.10	43.01
	Part 11	243.71	48.01	60.12	44.67			**Part 31**	155.54	46.73	58.87	44.26
	Part 12	223.00	46.45	55.87	43.28			**Part 32**	136.58	47.11	60.61	44.85
	Part 13	204.97	45.74	54.28	42.73			**Part 33**	116.11	46.35	58.88	44.27
	Part 14	186.85	45.89	55.30	43.07			**Part 34**	97.25	47.68	63.74	45.85
	Part 15	168.62	47.63	61.72	45.06			**Part 35**	76.49	46.79	61.63	45.14
	Part 16	147.41	47.43	61.40	45.07			**Part 36**	738.05	52.25	58.10	43.95
	Part 17	128.54	47.31	61.55	45.14			**Part 37**	719.40	53.25	61.78	45.17
	Part 18	110.07	45.78	57.58	43.76			**Part 38**	698.66	52.14	58.89	44.24
	Part 19	91.21	46.43	59.93	44.62			**Part 39**	677.74	53.21	62.83	45.56
	Part 20	72.03	46.19	59.90	44.57			**Part 40**	656.18	52.18	60.20	44.72

Table A.19 ADMU and IDMU of Case 5: Day 3 to Day 4

		ADMU		IDMU	
		Total Time	Total Cost	VA Time	VA Cost
Day 3	**Part 41**	551.24	50.22	57.39	43.79
	Part 42	532.87	51.12	61.13	44.91
	Part 43	512.60	50.70	60.35	44.68
	Part 44	493.15	50.48	60.47	44.65
	Part 45	472.31	50.70	61.60	45.09
	Part 46	451.12	51.05	63.25	45.68
	Part 47	430.32	48.72	56.64	43.49
	Part 48	411.13	49.24	59.00	44.22
	Part 49	390.40	48.64	57.58	43.82
	Part 50	371.34	50.24	63.17	45.66
	Part 51	349.44	49.42	61.53	45.04
	Part 52	327.72	49.19	61.69	45.03
	Part 53	305.98	48.45	59.64	44.49
	Part 54	286.29	48.30	60.07	44.53
	Part 55	265.79	47.32	57.20	43.74
	Part 56	247.76	48.20	60.64	44.83
	Part 57	227.95	48.25	61.41	45.08
	Part 58	209.29	47.92	61.21	44.93
	Part 59	187.65	47.13	59.41	44.35
	Part 60	167.94	47.86	62.14	45.31
	Part 61	146.08	46.12	57.46	43.73
	Part 62	126.15	55.96	60.66	52.19
	Part 63	104.84	63.72	62.66	59.38
	Part 64	83.76	68.32	58.54	63.32
	Part 65	63.60	70.43	61.07	64.88

		ADMU		IDMU	
		Total Time	Total Cost	VA Time	VA Cost
Day 4	**Part 66**	245.57	47.11	57.46	43.73
	Part 67	225.64	47.98	60.66	44.83
	Part 68	204.34	48.38	62.66	45.46
	Part 69	183.25	46.91	58.54	44.16
	Part 70	163.09	47.46	61.07	44.94
	Part 71	143.93	47.43	61.43	45.10
	Part 72	122.84	46.48	59.30	44.34
	Part 73	101.14	47.30	62.52	45.41
	Part 74	80.02	45.94	59.09	44.23
	Part 75	60.16	45.55	58.39	44.03
	Part 76	625.97	51.80	60.41	44.64
	Part 77	605.38	50.24	55.92	43.24
	Part 78	586.25	49.72	54.83	42.90
	Part 79	567.82	51.47	61.22	44.91
	Part 80	546.93	49.77	56.28	43.36
	Part 81	527.62	50.68	59.71	44.50
	Part 82	507.70	50.51	59.66	44.53
	Part 83	487.25	50.09	58.92	44.30
	Part 84	467.43	50.31	60.53	44.74
	Part 85	446.58	50.40	61.34	45.05

Note: Part 61 to Part 65 are produced during overtime.

Table A.20 ADMU and IDMU of Case 5: Day 5

		ADMU		IDMU	
		Total Time	Total Cost	VA Time	VA Cost
Day 5	Part 86	351.62	49.15	60.43	44.74
	Part 87	331.53	47.93	57.15	43.68
	Part 88	312.82	48.37	59.46	44.33
	Part 89	291.18	49.03	61.97	45.24
	Part 90	270.42	47.97	59.45	44.36
	Part 91	249.50	48.63	61.83	45.25
	Part 92	231.27	47.37	58.83	44.15
	Part 93	211.63	48.80	63.77	45.82
	Part 94	190.23	48.06	61.89	45.27
	Part 95	172.07	47.35	60.36	44.74
	Part 96	152.38	46.26	57.70	43.82
	Part 97	132.51	46.86	59.85	44.63
	Part 98	114.23	47.80	63.56	45.79
	Part 99	93.66	47.04	61.80	45.22
	Part 100	73.65	45.33	57.30	43.66
	Part 101	661.89	51.84	59.11	44.31
	Part 102	643.52	52.50	61.90	45.18
	Part 103	623.50	51.60	59.50	44.46
	Part 104	604.15	51.23	58.84	44.28
	Part 105	585.67	51.39	60.39	44.64

Appendix B. VBA Controller Program for Excel-based DEA-Leanness Solver

```
Sub SBM_LP()
'
' DEA-SBM-LP Model for Leanness Measure of 60 DMUs
' Modified from Course Material
' ISE 5144 Performance  and Productivity Measurement and Evaluation
' Dr. K. Triantis (Virginia Tech)
'
' Edited by Hung-da Wan
'

Application.ScreenUpdating = False

Dim n As Integer

Sheets("SBM_results").Select
Sheets("SBM_results").Range("B3").Select
For n = 1 To 60

   Sheets("SBM_model").Select
   Sheets("SBM_model").Range("A67").Value = n

      SolverOk SetCell:="$G$69", MaxMinVal:=2, ValueOf:=0, ByChange:= _
      "$D$69,$G$70,$J$73:$L$73,$F$3:$F$62"
      SolverSolve (True)

   Sheets("SBM_model").Select
   Range("D69").Copy
   Sheets("SBM_results").Select
   ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
         False, Transpose:=False

ActiveCell.Offset(0, 1).Select
   Range("J76:L76").Copy
   Sheets("SBM_results").Select
   ActiveCell.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
         False, Transpose:=False

ActiveCell.Offset(0, 3).Select
   Range("G3:G62").Copy
   Sheets("SBM_results").Select
   ActiveCell.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
         False, Transpose:=True
```

```
ActiveCell.Offset(1, -4).Select

Next n

End Sub
```

---

*Note: The cells of the spreadsheet are constructed to represent the data, objective function, and constraints of the SBM model as introduced in Section 6.2.1.

Vita

Hung-da Wan was born in Taipei, Taiwan, in 1971. He received his B.S. degree in Mechanical Engineering from National Taiwan University (NTU) in 1994. With his strong interests in mechanical design, he won two titles in technology contests and received one patent of new design during his undergraduate years. He continued his studies in NTU and received his M.S. degree in Industrial Engineering in 1996. His thesis, "*Computer Integrated Rapid Prototyping and Reverse Engineering*" supervised by Dr. Ming-tzong Wang, was a pioneering work among researchers in Taiwan in the mid 1990's. After serving two years in the army, he joined Mady Enterprise, one of the major trading companies in bicycle and sporting goods in Taiwan. He started as a project leader of product development and then became the manager of second division conducting product developments and marketing of bicycles, exercisers, and automobile parts until June 2002. His team brought out several new models of electric light vehicles and received the "Best Design Award" of Year 2001 from the China External Trade Development Council in Taiwan. During the four years of tenure in industry, he visited various types of manufacturing facilities in several countries, which inspired him to pursue further knowledge in the field of industrial engineering.

He entered the Ph.D. program in the Grado Department of Industrial and Systems Engineering at Virginia Tech, Manufacturing Systems Engineering Option, in August 2002. At the same time, he joined the Center for High Performance Manufacturing (CHPM) as a graduate research assistant under the direction of Dr. F. Frank Chen. Wan's major research interests include *Lean Manufacturing*, *Web-based Manufacturing Systems*, *Performance Measurement*, and *Lean Supply Chain*. One of his works, "*Decision Support and Analysis Tool for Lean Manufacturing Assessment and Implementation*," delivered a software program copyrighted in 2005. He also contributed to the research project "*Enhanced Lean Manufacturing and Six-sigma Integration*" and led the major R&D activities in the project "*Flexible Web-based Kanban System.*" He is a recipient of 2003-2004 *Dover Endowed ISE Fellowship Award*.