A Systematic Approach for the Best Use of Skilled Labor in Manufacturing

by

Youmin Ding

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

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Department of Mechanical and Manufacturing Engineering

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ABSTRACT

How to use skilled labor effectively and efficiently in manufacturing is the main topic of this thesis. Skilled labor, an expensive resource, is used when machinery and unskilled labor are unable to perform the required manufacturing operations properly. Generally speaking, the aim of skilled labor-intensive manufacturing is to produce the required quantity of defect free product within a defined time at a reasonable cost.

For a company that has an extensive skilled labor process such as Boeing that builds aircraft, how to use skilled labor most effectively and efficiently becomes a more and more critical issue. Unfortunately no comprehensive guidelines are available to tell the company how to effectively use skilled labor, and each company chooses its own way, using both good and bad techniques.

This thesis creates a generic, fundamental and systematic approach for effective and efficient use of skilled labor in manufacturing. The approach answers the three questions: 1) Should skilled labor be used in production? 2) What are the most suitable specifications for using skilled labor? 3) How is the defined productivity attained and maintained over time?

This approach includes a "Procedure" and the corresponding "Tools, Methods and Knowledge", which is supported by a series of models. Of particular importance are: a **procedure** related to the assessment of the productivity level in the skilled labor manufacturing environment, which provides a qualitative guideline for the field users; **Tools** related to operational measurements and cost analysis, which provide quantitative methods for the users; **Techniques** to track waste to cause, and to solution; and **Consideration of production problems** as a necessary integral part of skilled labor production.

ACKNOWLEDGMENT

I would like to take this opportunity to thank my advisor, Professor Doug Strong for his tremendous effort, support and guidance during my entire course of seeking a Ph.D. degree. Beyond that, he changed my entire life in Canada by supporting me financially, helping me get a job and providing me such valuable opinions to do my job successfully. All he has done for me are really beyond the responsibility as a thesis advisor. Truly appreciated!

I would also like to express my sincere gratitude to my two committee members, Professor Charles Mossman and Professor Gary Wang, for providing their expert opinions and consistent support to help complete this thesis.

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I would like to thank the Head, professors and staff in the Department of Mechanical & Manufacturing Engineering of the University of Manitoba for their general support.

Last, but certainly not least, I would like to thank my family for their support and encouragement.

LIST OF FIGURE

CONTENTS

1 Chapter I: Introduction

The purpose of this chapter is to provide readers a general overview on the thesis, which is addressed by the topics: "Background of the Thesis", "Objective of the Thesis", "Areas Not Covered in This Thesis", "Main Achievements of the Thesis" and "General Structure of the Thesis".

1.1 Background of the Thesis

Canadian manufacturing companies are experiencing extreme challenges in retaining their production in Canada, since more and more manufacturing jobs, especially those low skilled labor intensive jobs, have been moved to developing countries such as China and India, where the lower cost of labor significantly reduces the production cost. The jobs that still remain in Canada or other developed nations are mainly skilled labor or machine intensive jobs. Even these jobs will also tend to move to developing countries as their infrastructure, efficiency and worker skill levels are improved.

Keeping as many jobs as possible in Canada is now a major concern for many Canadian companies. One way to do this is to reduce production cost while maintaining quality level, required quantity and delivery time. At this moment, each company has its own methods to reduce the production cost by using different managerial concepts or tools, such as "Lean Manufacturing", "JIT (Just in Time)" and "TQC (Total Quality Control)". But none of these provides a systematic guideline to help improve productivity step by step, since they are designed in a way only to recognize the specific manufacturing problems. Therefore, the managerial guidance used in one company may or may not be suitable for another company. This un-sharable issue causes each company to incur a significant cost in seeking a solution, since each company may duplicate work that has already been done. The reasons for not having a systematic approach to seek a solution are: "Hard to Recognize the Manufacturing Problem", "Hard to Locate the Root Cause", "Hard to Find the Solution" and "No Standard Procedure Available".

- **Hard to recognize the manufacturing problem** addresses the problems which occur randomly with multiple symptoms.

- "Randomly occurring" addresses the problems that occur at anytime and at any location in the course of production.
- "Multiple symptoms" addresses a problem presented in multiple ways that easily blocks the human being's recognition process.

- **Hard to locate the root cause** addresses the linkages between the problems and causes, which may be extremely complicated or there is no information available.
  - "Complicated linkages" address whether the links between problem and causes are "One to one, One to many, Many to one and Many to many".
  - "No information available" addresses the situation where the required information, such as an electronic version of BOM, is missing because it is not collected at source.
- **Hard to find the solution** addresses the situation where the root causes and corresponding solution are very difficult to find. Thus the attempted solution may only solve some problems.
- **No standard procedure available** addresses the situation where the different companies may emphasize different production issues than others and find different solutions for the same or similar problems. This makes choosing subjective and the solutions less effective than they could be.

In order to relieve this situation, it is necessary to develop a systematic approach to help companies selectively improve their productivity, and this systematic approach theme is the central topic of this thesis.

1.2 Objective of the Thesis

The focus of this Industrial Engineering study is the retention of skilled labor manufacturing in the industrialized world. The objective of the thesis is "To Develop a Generic, Fundamental and Systematic Approach for Using Skilled Labor Effectively and Efficiently in Manufacturing".

"Generic" means the approach can be applied to most situations; "Fundamental" means the approach considers the basic aspects of skilled labor manufacturing; "Systematic" means the approach is a step-by-step one; "Effective" means the job is done as expected; "Efficient" means the job is done with the least cost.

"Skilled labor" and "Manufacturing" will be discussed in details in Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure.

1.3 Areas Not Covered in This Thesis

In order to focus on the objective of this thesis, some areas are not covered. They include: "Non-Shop Floor Issue; Production Relocation; Contracting Out; Training Method; Motivation Method; Obtaining Orders; Handling of Defect Returns and Time Scheduling".

- **Non-shop floor issue,** such as transportation, purchasing and inventory are not covered.
- **Production relocation,** such as moving a production line to another country or another plant is not covered.
- **Contracting out, Training method** and **Motivation method** are not the focus in this thesis since any of them is not directly a production process.
- **Obtaining orders** is not covered since it is a marketing issue.
- **Handling of defect returns** is not covered since it is not a part of the primary production process.
- **Time scheduling** is not of concern since skilled labor-intensive manufacturing is usually given enough time to perform the job.

Although the above issues are not of concern, they may still be considered if a complete discussion is required.

1.4 Main Achievements of the Thesis

There are two main achievements in the thesis, which are the creation of "Procedure for the Best Use of Skilled Labor" and "Task and Knowledge to Support the Procedure" as shown in Figure 1.1.

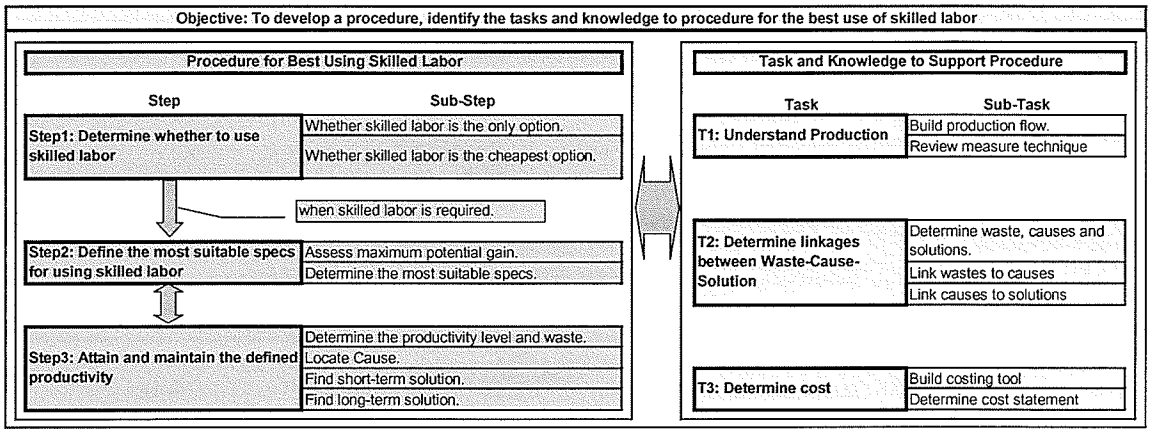


Figure 1.1 Procedure Supported by Tasks and Knowledge

1.4.1 Procedure for the Best Use of Skilled Labor

A systematic procedure, known as the "Three-Step Procedure (3SP)", was developed to determine the best use of skilled labor, which has **Step 1:** Determine whether to use skilled labor; **Step 2:** Define the most suitable specifications for using skilled labor; **Step 3:** Attain and maintain the defined productivity. The following are brief discussions and the details are found in Chapter V: Three-Step Procedure (3SP).

- **Step 1: Determine whether to use skilled labor.** Many production options exist in manufacturing, such as skilled labor, unskilled labor and NC machine. In reality, a company usually needs to know which option is the best fit for fulfilling the customer order in terms of cost effectiveness, which is identified as the task of Step 1 and supported by two sub-steps: 1) Check whether skilled labor is the only option and 2) Check whether skilled labor is the cheapest option.

- **Step 2: Define The Most Suitable Specifications for Using Skilled Labor.** Once skilled labor is chosen to do the job in Step1, the next question is how to use this labor most effectively and efficiently (Least loss). Therefore "Define the Most

Suitable Specifications for Using Skilled Labor" is identified as the task of Step 2 and supported by two sub-steps: 1) Assess maximum potential gain and 2) Determine the most suitable specifications.

- **Step 3: Attain and Maintain The Defined Productivity.** Once the skilled labor option is chosen and the most suitable specifications are defined, the next question is to attain and maintain the defined productivity, which is identified as the task of Step 3 and supported by four sub-steps: 1) Determine the productivity level and waste; 2) Locate the cause of waste; 3) Find a short-term solution and 4) Find a long-term solution.

1.4.2 Task and Knowledge to Support the Procedure

To support the above procedure, a set of tasks and knowledge is identified as follows: **T1:** Understand production of concern; **T2:** Determine linkages between Waste-Cause-Solution; and **T3:** Determine cost. Some of these tasks are well known in manufacturing, others had been independently discovered and used by some manufacturers, and others have never been created to our knowledge. The new tasks and the organization of the tasks are contributions of this thesis.

- **T1: Understand Production of Concern.** This means to understand how the production is done in terms of material and information flow; and how well the production is done. They are supported by two sub-tasks: 1) Build production flow and 2) Review measurement technique. The details are discussed in Chapter VI: Production Flow and Measurement.

- **T2: Determine Linkages between Loss-Cause-Solution.** To reduce the loss in production, the loss must be identified, then the causes must be located and solutions must be found, which is supported by three sub-tasks: 1) Determine loss, cause and solution; 2) Link loss to causes and 3) Link causes to solutions. The details are found in Chapter VII: Matrix of Loss-Cause-Solution.

- **T3: Determine Cost.** Every issue in the effort towards the best use of skilled labor needs to be converted to a "Dollar" value if a comparison is required. This is

supported by two sub-tasks: 1) Build costing tool and 2) Determine cost statement. The details are given in Chapter IX: Costing of Loss and Solution (CLS).

1.4.3 Models to Help Achieve Main Aims

A comprehensive model, "Skilled Labor Based Productivity Improvement Model (SLBPIM)", was developed to guide the use of the procedure, tasks and knowledge, which is addressed by two topics: "SLBPIM" and "Analysis Flow inside SLBPIM".

- **SLBPIM** provides a quantitative and qualitative model to observe the production, identify waste, reveal the cause of loss and find the solution to improve and maintain the productivity level. SLBPIM is built on two models: 1) The Three Step Procedure (3SP) and 2) Costing of Loss and Solution (CLS), as shown in Figure 1.2.

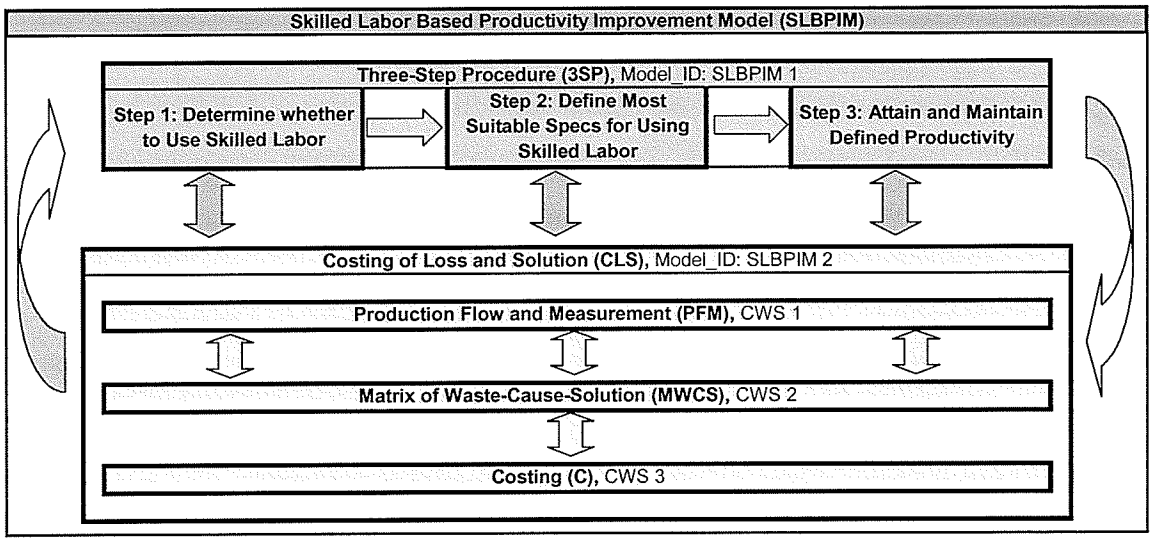


Figure 1.2 SLBPIM

  - "Three-Step Procedure (3SP)" provides three main decision points in the course of best use of skilled labor, which are: 1) Determine whether to use skilled labor; 2) Define the most suitable specifications for using skilled labor; 3) Attain and maintain the defined productivity. The details are provided in Chapter V: Three-Step Procedure (3SP).

  - "Costing of Loss and Solution (CLS)" is a model to estimate the cost of loss and solution, which has three tasks: 1) Build production flow and measurement" to

describe how the production is performed, what to measure, and how to measure through a production flow; 2) Determine linkages between loss-cause-solution" to provide a list of losses, causes, solutions and the linkages between them; 3) Determine costs including loss through a cost statement. The details refer to Chapter IX: Costing of Loss and Solution (CLS).

The details of SLBPIM are found in Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

- **Analysis Flow inside SLBPIM** provides an exact idea how this model works at each decision point, which is: 1) Determine whether to use skilled labor; 2) Define the most suitable specifications for using skilled labor; 3) Attain and maintain productivity defined in Step 2 or benchmark, as shown in Figure 1.3 (Simplified).

When handling "New Production", the first thing to do is to "Analyze the Process" to understand the process such as the planned throughput. The second thing to do is to "Determine whether to Use Skilled Labor" or alternatives such as unskilled labor and machine. If skilled labor is not chosen, no further discussion will be undertaken in this thesis, otherwise the next thing to do is to "Define the Most Suitable Specifications for Using Skilled Labor" that includes the definition of the process requirements, which can be used as the benchmarks of productivity. Once the benchmarks are defined, the next stage is to "Attain and Maintain Productivity Defined in Step 2 or Benchmark", which includes: 1) Determine the current productivity level and waste; 2) Locate the cause of waste and 3) Find the solution (Short-term and long-term solution).

If the solution cannot be found, the analysis flows back to Step 2 for re-defining the most suitable specifications or back to Step 1 for re-determining whether skilled labor should be used. Otherwise, the solution found is checked for whether it is under the control of Industrial Engineering (IE). If so, the cost of the solution is evaluated and the solution may not be implemented if it is not cost effective since "Leave Case as Is" may be the best solution in some situations; otherwise the case will be handed over to the relevant group for further action since there is no way for IE to solve the

waste problem. For example, when the problem is that costs have increased because wages have been increased, and wages cannot be decreased without union agreement, the IE has no control. The issue will be handed over to a management team for further action.

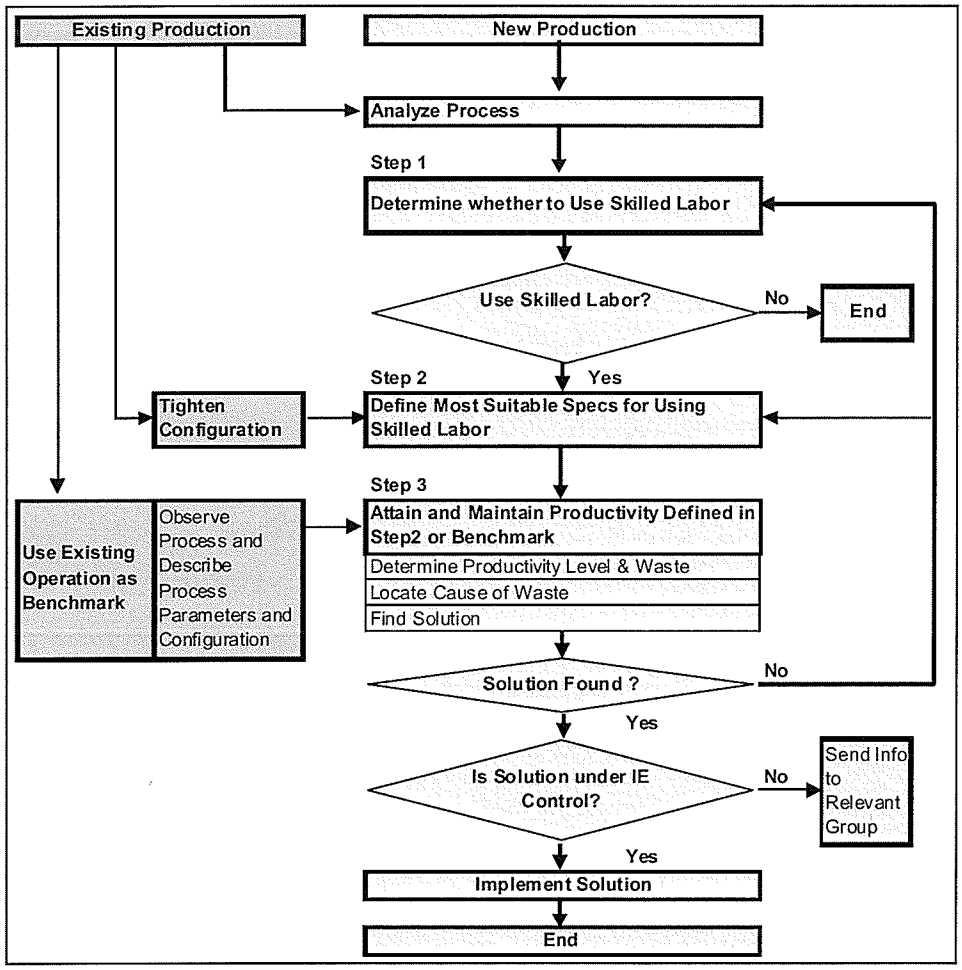


Figure 1.3 Analysis Flow inside SLBPIM (Simplified)

When handling "Existing Production", the analysis will join the main flow at some points, which are: 1) Join to "Analyze Process" for understanding the process; 2) Join to "Define the Most Suitable Specifications for Using Skilled Labor" when requiring "Tighten Configuration"; and 3) Join to "Attain and Maintain the Defined productivity" when requiring "Use Existing Operation as a Benchmark".

1.5 General Structure of Thesis

The general structure of this thesis is described in this section and shown in Figure 1.4 in order to provide an overview of how the thesis is organized and what the main content is in each chapter.

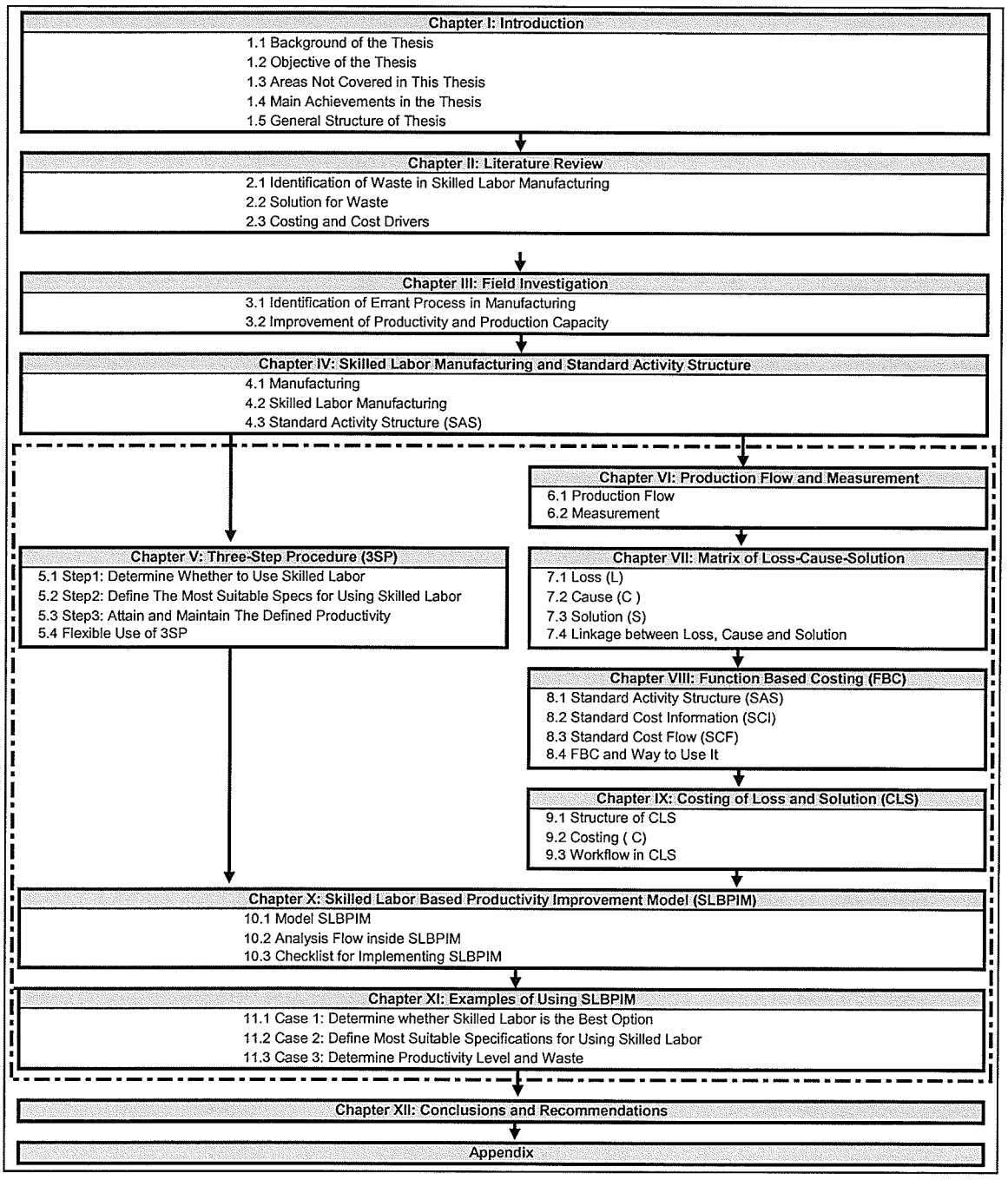


Figure 1.4 General Structure of Thesis

Chapter I: Introduction provides a general idea about the thesis, which is covered by the topics "Background of the Thesis", "Objective of the Thesis", "Areas not Covered in This Thesis", "Main Achievements in the Thesis" and "General Structure of Thesis". The reasons to focus on the thesis topic and take these research directions are:

The research on the thesis was started in 2000 without having an idea of the exact topic to focus on. At that time, there were some possible topics, such as "Forecasting and Optimum Decision Making Strategy for an Organization" and "Optimization and Simulation of Material Requirement Planning Systems in the Manufacturing Area". In order to determine the thesis topic and understand what high tech manufacturing companies really needed, two investigation projects were performed. One was in Bristol Aerospace Limited in 2001 and the other one was in Aero-Recip (Canada) Ltd in 2002. Both companies are typical of skilled labor intensive, high Tech manufacturing companies, and produce or overhaul aircraft and aircraft components. The project done in Bristol was related to the "Identification of Errant Process in Manufacturing", which is to find unusual processes in production in terms of reduced quality or increased time spent. The process studied in this project is the production of some parts for the time-consuming assembly of the "Tailcone" that houses an auxiliary power unit in the airplane DHC8-400. The project done in Aero-Recip was related to the "Improvement of Productivity and Capacity of Production" through analyzing the entire production including the processes in inventory, shop floor and delivery. The details of the two projects are presented in Chapter III: Field Investigation.

After these two projects were completed, it was realized that the common ground in both companies is the concern of "How to use the skilled labor effectively and efficiently". It was also believed that not only these two companies have this concern, but most other companies that use skilled labor have this concern as well. Therefore the thesis topic chosen was "A Systematic Approach for the Best Use of Skilled Labor in Manufacturing".

Chapter II: Literature Review presents a general literature review, which is covered by the topics "Identification of Waste in Manufacturing", "Solution for Waste" and "Costing and Cost Drivers". The reasons why these issues are covered in this chapter are:

Once the thesis topic was determined, an extensive literature search was performed, but no literature was found to address the above thesis topic. As research directions in the thesis where taken toward finding a solution, a literature search on each direction was made at the time and checked later. The topics where literature was found included "Costing" (including cost driver, costing tool and costing process), "Loss" (including waste) and "Solution" (including short-term and long-term solution).

Chapter III: Field Investigation provides two field investigations that were completed in two skilled labor intensive manufacturing companies. One study is "Identification of Errant Process in Manufacturing" at the assembly level and another one is "Improvement of Productivity and Production Capacity" at both assembly and company levels.

Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure provides some general concepts of manufacturing and a new model to represent any type of manufacturing activity, which is covered by the topics "Manufacturing", "Skilled Labor Manufacturing" and "Standard Activity Structure (SAS)". The reasons to have this chapter are:

The thesis topic focus, skilled labor manufacturing, has been a frequently discussed subject, and is understood differently by different people. Because of this, it was felt necessary to define some of the concepts of skilled labor manufacturing so the reader understands exactly what the author means. For example, regarding "Waste", Hesham K et al. (2005) stated that waste is deteriorating items and deterioration of process since both of them cost money; while Kenne J. P. et al. (2000) thought that the inventory cost and back order penalties are waste since they affect the performance of production. So the meaning of waste needed to be defined.

Another issue that came up was how to describe an activity in a consistent way instead of the various ways normally used in manufacturing, which is that different people

described an activity in different ways, leading to different understandings. Then the question raised was "Can we develop a structure to describe any type of activity in a consistent way?" If this structure can be created, all activities can be presented the same way at a generic level. Therefore a Standard Activity Structure (SAS) was created in this thesis which includes four activity elements "Input, Control, Doing and Output".

Chapter V: Three-Step Procedure (3SP) provides a systematic procedure of using skilled labor in manufacturing, which is covered by the topics "Step1: Determine whether to Use Skilled Labor", "Step2: Define the Most Suitable Specifications for Using Skilled Labor", "Step3: Attain and Maintain the Defined Productivity" and "Flexible Use of 3SP". The reasons to develop this 3SP are:

When the field managers or industrial engineers were deciding how they would improve manufacturing productivity, the first thought in their mind was, "How do I proceed this task in terms of 1st step, 2nd step and so on?". Was there any procedure in reality or the literature that can be followed by field personnel? The answer was negative after an extensive literature search, since procedures that were found were created for specific problems or were too general for detailed analysis. For example, J. Park et al. (2005) stated the procedure in the design phase could be: 1) Identify and classify the production activities and resources needed to produce the entire product line in a family with an activity table, a resource table, and a production flow statement; 2) Estimate the production costs; and 3) Investigate the components/design variables possible for the product family with the resource sharing methods through activity analysis.

Therefore it was necessary to develop a new procedure to provide field personnel with a new standard qualitative procedure for the best use of skilled labor. At the beginning, there was no idea what steps should be included in this procedure. Since the main topic of the thesis is a systematic approach of the best use of skilled labor, the questions finally chosen, in order were: "Whether skilled labor should be used in the first place?" "What was the maximum potential achievement to be set as a benchmark if skilled labor was selected?" and "In normal operation, how could the defined productivity be attained and maintained". Based on these three questions, a "Three Step Procedure (3SP)" was

developed in the thesis, which includes: "Step 1: Determine whether to use skilled labor"; "Step 2: Define the most suitable specifications for using skilled labor" and "Step 3: Attain and maintain the defined productivity". Although many manufacturers do variations of this informally or set up rigorous structures for parts of this for themselves, the whole statement was not found anywhere.

Chapter VI: Production Flow and Measurement provides a review of the production flow and the creation of the measurement used to assess the productivity level, which is covered by the topics "Production Flow" and "Measurement". The reasons to have this chapter are:

Since the thesis topic was related to the best use of skilled labor, it naturally raised a question of evaluating performance, which requires an understanding of the production situation, and the determination of what to measure and how to measure.

In order to understand the production situation, many ways could be taken, for example, doing the job by yourself, watching the job when performed and creating the production flowchart. In this thesis, we choose to create a production flowchart since you are not able to create the flowchart unless you understand the concerned production. In addition, this flowchart is a necessary part of the information required for determining what to measure.

Cost is identified as the most important final statement in manufacturing because profitability depends on the cost and is required for the manufacturer's survival. Therefore, performance evaluation in this thesis means productivity measurement, where productivity is considered to be the "Inverse of cost". The question here is what should be measured for costing. In order to estimate the cost, one of the issues that must be addressed was "Cost driver" that needs to be defined for this thesis since many versions were in the literature. For example, Daniel W. Miles (2001) indicated that "Performance, People, Part, Paper and Place" were the cost drivers. But those cost drivers found in the literature did not satisfy the criteria of cost driver identified in this thesis, which are "Cost contributor" and "Independent each other". Initially, three cost drivers were defined from the operation perspective, which were "Quantity, Quality and Time". But after a further

investigation, we found those three cost drivers did not reflect the unit cost from the Input (e.g. a high gas price), which determines the output cost at the first place. So another cost driver "Input Price" was added and the final cost drivers defined in the thesis were "Input Price, Quantity, Quality and Time".

Chapter VII: Matrix of Loss-Cause-Solution (MLCS) provides a compact and systematic module to present waste, cause, solution and their linkage, which is covered by the topics "Loss (L)", "Cause (C)", "Solution (S)" and "Linkage between Loss, Cause and Solution". The reasons to create this chapter are:

According to the thesis topic, it was required to assess and improve the productivity of the production of concern. That means the cost of production must be reduced since productivity is defined as the "Inverse of cost", as stated earlier. One significant way to reduce the cost, was to reduce any type of loss or increased cost during normal production compared with the costs of the benchmark operation. In order to do so, we need to know where the loss is, what cause is associated with that loss and what method is available to eliminate the cause and thereafter to reduce the loss. Thus it was an important part in improving productivity, and is formally defined in the thesis as "Identifying the loss, locating the cause of the loss and finding the solution to reduce the loss". The results of the above tasks were individually shown in the Loss table, Cause table and Solution table. The relationship between them was presented by a matrix, which is called as "Matrix of Loss-Cause-Solution (MLCS)".

Chapter VIII: Function Based Costing (FBC) provides a standard costing module that can be used in any manufacturing structure, which is discussed under the topics "Standard Activity Structure (SAS)", "Standard Cost Information (SCI)", "Standard Cost Flow (SCF)", "FBC" and "Way to Use It". The reasons to develop this tool are:

In assessing the productivity level, cost was the only indicator to be assessed and required a costing tool. Although OBC (Operation based costing) improved ABC (Activity based costing) by using 8 cost elements to confine the cost content, both ABC and OBC do not provide a systematic costing approach that was required by this thesis. Different people used the ABC and OBC in different ways and could come up with different results for the

same costing issue. So the question here is "Is there a costing tool that can be used by different people for any manufacturing case, in a systematic and consistent way, to come up with the same or similar result?"

In order to obtain such a tool, we developed a new costing tool "Function based costing (FBC)" in this thesis by standardizing the activity structure, cost information and costing flow. The reasons for standardizing those three items were: 1) The activity structure was the foundation of FBC, similar to a building frame; 2) Cost information was the attachment of FBC, similar to a door attached to the frame; 3) Costing flow was the linkage between the cost information in FBC, similar to a stair linking the first floor with the second floor.

Chapter IX: Costing of Loss and Solution (CLS) provides a way to estimate the cost of loss and solution based on FBC, which is covered by the topics "Structure of CLS", "Costing (C)" and "Workflow in CLS". The reasons to cover this issue are:

Once a new costing tool was developed and the losses and solutions were identified, the question would be how significant these losses and solutions were to determine the productivity level. So a "Cost statement" was created in this thesis by including an original value, value added, cost of loss and total cost. This cost statement provides the information in the change of cost or effectiveness of the production, and shows where the change of cost is located. The magnitude of each cost increase would indicate the severity level of the problem. In some cases, the cost statement leads to the fundamental cause of the change, otherwise further sleuthing is required.

Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM) provides a comprehensive model to systematically analyze the issue related to the best use of skilled labor in manufacturing, which is covered by the topics "Model SLBPIM", "Analysis Flow inside SLBPIM" and "Checklist for Implementing SLBPIM". The reasons to create this model are:

Once all issues required for the best use of skilled labor, such as 3SP, FBC and the Matrix of Losses-Causes- Solutions (MLCS), were addressed in the previous chapters,

how to use all of them for the best use of skilled labor became the next task. It was integrated into a comprehensive production analysis model in the thesis and named as "Skilled Labor Based Productivity Improvement Model (SLBPIM)".

Chapter XI: Examples of Using SLBPIM presents three examples to illustrate how SLBPIM can be used to estimate the cost of real manufacturing production, which is covered by "Case 1: Determine whether Skilled Labor is the Best Option", "Case 2: Define the Most Suitable Specifications for Using Skilled Labor" and "Case 3: Determine Productivity Level and Waste", which corresponds with each step in 3SP.

Chapter XII: Conclusions and Recommendations of the thesis are stated and discussed.

Appendix: References and Glossary.

2 Chapter II: Literature Review

In order to understand what has been done so far by other researchers related to this thesis topic, an extensive literature review has been undertaken and no literature was found to address the thesis topic. As research directions in the thesis where taken toward finding a solution, a literature search on each direction was made at the time and checked later. The topics where literature was found included "Identification of Waste in Manufacturing", "Solution for Waste" and "Costing and Cost Drivers".

2.1 Identification of Waste in Manufacturing

In order to improve the productivity, the first thing to determine in manufacturing is the waste. Therefore, the identification of waste is one of concerns in the literature survey. The first attempt in searching was focused on the identification of waste in skilled labor manufacturing, but no paper could be found. Then the searching was expanded to manufacturing instead of skilled labor manufacturing, which is reviewed as follows.

Many types of waste exist, for example, Hesham K. Alfares et al. (2005) stated "The deteriorating items and deterioration of process are considered to be a kind of waste since both deteriorating items and deterioration of process cost money"; Kenne J. P. et al. (2000) [27] said "Inventory cost and back order penalties will affect the performance of production, and is considered to be a waste".

In terms of identification of waste, only few papers could be found may be because not many researchers focused on this topic, as indicated by Britney, Brand and Lubicz, as "A relatively little work has been done to explore the process improvement on the cost saving by comparing to the research on the number and placement of inspection stations for the production costs like the costs associated with maintaining inspection stations, performing inspection tasks". The followings are some papers found.

Smith Marc (2008) [43] stated that the identification and elimination of waste is the core of any supplier development activity. He defined waste, and looked at possible causes and symptoms in a supply chain system.

Naruo et al. (1990) stated that expert system could be developed for diagnostic decision support, which transforms the cause-effect relationships into production rules and uses forward or backward chaining to infer fault causes from fault symptoms. However, the expert systems' ability to solve a problem is restrained to what is in the knowledge database due to the inability to learn and generalize knowledge.

Ye and Zhao B. (1996) [47] integrated the neural networks with a procedural decision making algorithm to come up a hybrid intelligent system for the identification of waste.

Peng and Reggia (1990) stated that from an Operations Research point of view a diagnostic problem can be considered as an optimization problem that represents a solution in terms of optimization indicators that are subject to constraints such as the cause-effect structure of a target system.

2.2 Solution for Waste

Once the waste is identified, the next consideration in the literature survey is the solution.

Many solutions can be found to reduce waste in manufacturing, for example, D. Challis et al. (2005) stated "TQM, JIT and Advanced manufacturing technology are important, however, the 'soft' human resource management practices such as leadership, teams, and employee performance is also significant in improving the manufacturing performance".

Hallihan A et al. (1997) stated "Some types of waste could be eliminated by using JIT. This would be done with management support and by setting the JIT in a specific manufacturing context which is the combination of people, machines, materials, processes, products, and managerial policies".

Inderfurth K. et al. (2005) [24] noted that it is necessary to coordinate the production and rework activities with respect to the timing of operations, since the state of defective items may change in the course of time while they wait to be reworked. Such a deterioration of rework-able goods can result in increasing rework time and rework cost per unit, which increases cost.

E. Houghton et al. (2005) stated "A cross-training of workers to perform multi-skilled jobs is one of the modern trends in job design for cost savings".

Lin Z-C et al. (2002) [32] stated "A tolerance design, based on neural networks, in product components could produce a product with the least manufacturing cost possible, while meeting all functional requirements of the product".

Lee B. (1999) [31] stated "Under the assumptions of profit maximization and cost minimization and ignoring the potential inefficiency in IT investment and management, the increase in the IT intensity will significantly reduce the technical, allocation and scale inefficiencies".

But in terms of a relative complete list of solutions for skilled labor manufacturing, it could not be found. That was why one of chapters in the thesis is to create a relative complete list of solutions.

2.3 Costing and Cost Drivers

Once waste is identified and the solution is obtained, the cost of the waste and solution is the next consideration in the literature survey, which is covered under the topics: "Costing Tool", "Cost Drivers" and "Costing Process".

2.3.1 Costing Tool

In a broad sense, the current costing tools used in manufacturing could be grouped into "Conventional Costing (CC)" and "Activity Based Costing (ABC)". Another newer tool "Operation Based Costing (OBC)" was also found in the literature survey.

2.3.1.1 Conventional Costing (CC)

Conventional Costing (CC) is the most established accounting system to capture and distribute resource costs in terms of direct and indirect cost, and is based on the organizational element account or the budgetary account (Department of Defense, USA, 1995) [14].

- **Organizational element account** is the accounting for each organizational element in the traditional bureaucratic structure. This accounting method provides management with information on the costs of the organizational elements, and contains direct and indirect cost. The direct cost in this tool means the salary. The indirect cost means the overhead cost as captured in a central repository, without clearly allocating the cost to specific production functions.

- **Budgetary account** is the accounting to track the budget execution to ensure that the total expenditures do not exceed the budgetary resources and that the resources assigned are fully used. This does not reduce expenses or enhance productivity, since any attempt to conserve resources will lead to a reduction in the future budget. Also this accounting method has no intention to cost output or even to define the output.

Johnson and Kaplan noted Conventional Costing was originally used for reporting purpose, but these reports are of little help to reduce the costs and improve productivity since they do not properly allocate the cost to the product and significantly distort the price of the product. So conventional costing will significantly distort the ultimate price of the final product and may lead to poor management decisions (Tage et al., 2007) [45].

Howell and Soucy (1989) stated Conventional Costing only considers the direct and indirect cost, and significantly distorts the ultimate price of the final product since it does not consider all aspects related to producing a product, such as manufacturing, engineering, marketing and administration activities.

2.3.1.2 Activity Based Costing (ABC)

To improve Conventional Costing, "Activity Based Costing (ABC)" was created, which is a new tool to quantitatively measure the activity in terms of cost including overheads whenever appropriate (Department of Defense, USA, 1995) [14].

In summery, ABC captures the organizational costs (production and administrative expenses) that are allocated to the defined activities required for producing the product. This tool provides more accurate cost estimation than CC by considering the costs of all activities involved in producing a product, as stated by Rahul "While doing ABC the only

thing to be kept in mind is the activity and the cost associated with it. It is a very helpful tool if you clearly understand ABC and the process under observation" (ABC Forum, 2008) [1].

Therefore, ABC is widely used in manufacturing when using "Material Requirement Planning (MRP)" or "Just in Time (JIT)" systems since it overcomes many limitations of CC systems, as stated by Ozbayrak M. (2004) [37]. For example, as presented by Ong N.S. (1995) [36], ABC is used to estimate the manufacturing cost of a "Printed Circuit Board (PCB)" assembly at its early design phase, to identify a possible problematic activity that has a substantial cost, and this considerably improves the productivity and manufacturing costs.

Amir observed in a review of articles related to Customer Relationship management (CRM) literature that many scholars believe that ABC is the best way to discover the profitable customer and this technique is more applicable as compared to conventional accounting or costing. However, he also observed that this technique would be better if modified keeping in view some notes to customer relationship management and customer profitability analysis (ABC Forum, 2008).

On the other hand, Deo et al (2003) [12] stated that ABC does not provide a work content and does not convey an analysis of how the activity relates to the production of the part or product. This undefined work content opens a door to subjectivity in using the concept for processes that do not directly relate to the production effort. For example, an activity may mean a process, a system, a sub-system or a small work component.

Innes J. et al. (1991) [25] also indicated that "The definition of activities involves subjectivity in the grouping of expenses for calculating costs, which means that different people will get different results on the same issue".

2.3.1.3 Operation Based Costing (OBC)

To improve Activity Based Costing, Deo & Strong (2002) [13] proposed "Operation Based Costing (OBC)", by adding a work and resource content to the activity (i.e. operation), through the use of eight cost elements, as shown in Figure 2.1.

The eight cost elements in OBC are defined as: 1) Machinery for the Operation; 2) Fixture to hold material or help shape the material undergoing an Operation; 3) Operator to operate the machine or work with other tools, on materials undergoing an Operation; 4) Work Space for a workstation to conduct an Operation, and a small buffer Space for inputs and outputs of the Operation; 5) Contract with outside parties for some operations or for support functions and services required in production; 6) Incentive quality and timely delivery of materials; 7) Materials to make the products required by customers and 8) The resources "Tied Up" in inventories in and around each operation.

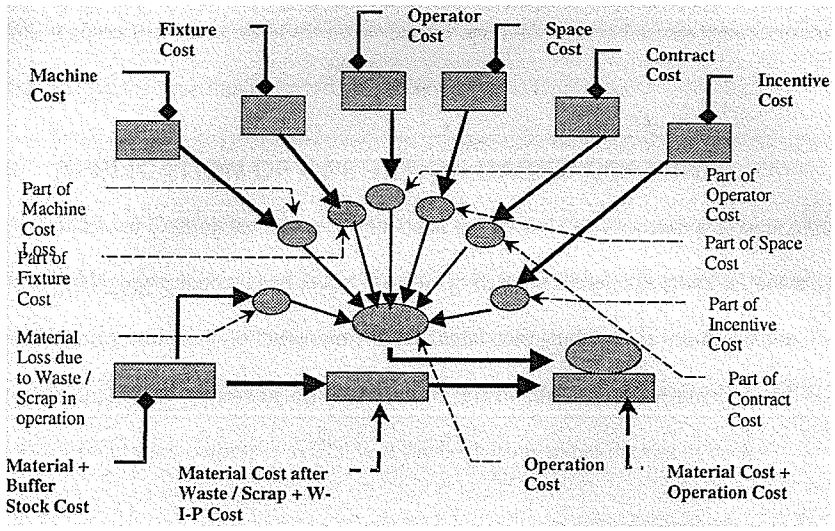


Figure 2.1 Operation Based Costing (OBC, Deo Balbinder S. 2001)

Generally speaking OBC reduces the subjectivity level in ABC by defining the cost elements. However, both ABC and OBC still blend the process analysis and costing process, which causes confusion between the two analyses. They also do not provide a generic structure to describe how the activity is performed in terms of information flow and material flow; and they do not provide a step by step approach to estimate the cost.

2.3.2 Costing Process

The "costing process" is the second issue of concern in the literature survey. The costing process refers to what and how to measure the cost, which is subjective and complicated, as stated by Jha N.K. (1996) [26], "Costing in manufacturing is a complicated process. The normal approach to costing is to estimate the cost based on time required for the

production processes, and the costs for materials, and then add some profit margin on top that is pre-determined by the managerial judgment and experience".

There are many costing processes in the literature, but most of them are case based. For example, Newnes L. B. et al. (2007) mentioned an on-screen real-time cost estimation used in the early phase of design of injection moldings to identify the avoidable cost; Shehab E M et al. (2002) [42] used an object-oriented and rule-based system to estimate the product cost at an early design stage. The main function of the system, besides estimating the product cost, is to generate initial process planning, including the generation and selection of machining processes, their sequence and their machining parameters, to recommend the most economical assembly technique for a product and provide design improvement suggestions based on a design feasibility technique.

Some processes do provide a general approach, but no detailed step by step approach is available. For example, Michelle stated "There are basically four steps in assigning production resources to the end product in the costing process: 1) Define activity groups that have a direct relation with the end product; 2) Determine resource drivers that show the relation between production resources and activity groups and cost drivers that show the causal relation between an activity group and a type of end product; 3) Assign the costs and resources to activities based on the resource drivers; 4) Assign the costs of activity groups to the end product based on the Cost" (ABC Forum, 2008) [1].

Simon observed that it is essential to first make the decision about the level of detail that needs to be captured in the costing process. At the strategic level, about 100-150 activities are most commonly used to determine the profitability of a customer or a product. At an operational level the number goes up to 500+ activities to improve the costing process (ABC Forum, 2008).

Park J. et al. (2005) [39] also stated that estimation of the production cost of a family of products involves both estimation of the production cost of each product in the family and the costs incurred by common and variant components/design variables in the family. The way to determine cost includes: 1) **Allocation**, in which the production activities and resources needed to produce the entire product lines in a family are identified and

classified with an activity table, a resource table, and a production flow statement; 2) **Estimation**, in which the production costs are estimated by cost estimation methods; and 3) **Analysis**, in which the components/design variables possible for the product family are investigated with resource sharing methods through activity analysis.

P. R. Roy et al. (2008) [38] developed a process "Function-based cost estimating" that links the commercial and engineering communities through a structured approach at the conceptual design stage. This process is to translate the un-quantified terminology and the requests associated with the product specifications by using a standardized approach. It starts with functional decomposition, and then identifies product parameters that are related to a top level function, and finally associate product costs to the function using past knowledge and data. It is validated in two case studies from the automotive and aerospace industries.

Sharma Rajiv Kumar et al. (2007) presented a quality costing in process industries through QCAS: a practical case, which is to implement, sustain and manage a quality-costing program in a process industry by attaching fuzziness to the notion of "quality".

Chen K. S. et al. (2006) [10] proposed a performance measurement for a manufacturing system based on quality, cost and time that are three of the major concerns in a manufacturing system. This study proposes a product capability index to evaluate the quality of a multi-process product and addresses the relationship between process yield and product capability index.

Some other costing processes found are mainly associated with the phase of "Design" or "Run".

- **Costing in the "Design" phase.** H'Mida F. and Vernadat, F. (2009) [20] developed a constraint approach for alternative cost estimation of a mechanical product, which is used in the design phase based on a flexible constraints satisfaction problem (flexible CSP). For a given mechanical part or product, this model makes it possible to determine a set of process plan solutions with a cost for each one; Heilala J. et al. (2006) [22] created a novel analysis methodology that integrates component-based

simulation, overall equipment efficiency with cost of ownership, and other analysis methods to improve the design of flexible, modular reconfigurable assembly systems; Y.F.Z. et al. (1996) [46] stated that cost estimation plays an important role in the product development cycle. The proper cost estimation can help designers make good trade-off decisions regarding product structures, material, and manufacturing processes; Schreve K. et al. (1999) [41] developed a cost model based on the data collected through time studies and analyzed it using robust regression statistical methods to get the production cost in the design phase.

- **Costing in the "Run" phase.** Brinke Erik Ten et al. (2004) [8] presented "Cost Estimation Architecture for Integrated Cost Control Based on Information Management"; Smunt T.L. (1999) stated that a learning curve model could be used in production research and cost estimation such as a cumulative average cost or unit costs; Kiritsis D. et al. (1999) [29] stated a Petri Net-based cost model, which considers the machine, setup and tool changing cost, could be used to estimate the production cost; Kingsman B.G. (1997) [28] stated that a major problem in "Make-to-customer" is the determination of the cost of producing the order and the price to be quoted during the design stage. The standard approach here is to first to make a cost estimate based on the time spent and the cost of materials, by ABC for example, and then add the pre-determined profit margin. This method not only requires the manipulation of known information, but also requires extensive use of managerial experience and judgment, which have been identified as including almost 200 heuristic "Expert" rules.

In terms of cost modeling, Simon stated "When planning to build a costing model it is essential to first make the decision of what level of detail is to be captured. For the strategic phase, about 100-150 activities are most commonly used to determine the profitability of customer or product"; for the operational phase, 500+ activities are commonly used to improve the process" (ABC Forum, 2008) [1].

2.3.3 Cost Drivers

The third issue in the literature survey is "Cost Drivers" since it is another key concept widely used in this thesis.

A cost driver is defined as "Any situation or event that causes a change in the consumption of a resource, or influences quality or cycle time" (www.gpworldwide.com, 2000) [48]. Many cost drivers can be found in the literature for manufacturing. One example is presented by Miles Daniel W. (2001) [33] and named as "5P Cost Drivers", which refer to Performance, People, Part, Paper and Place, as shown in Figure 2.2.

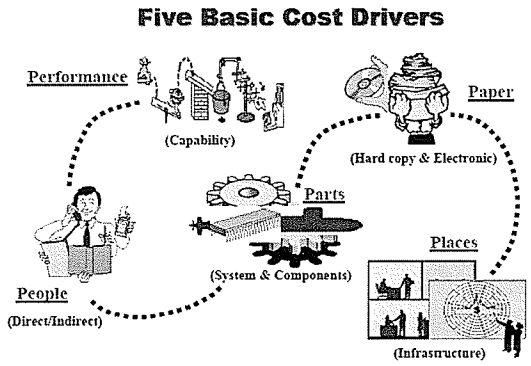


Figure 2.2 5P Cost Drivers (Daniel W. Miles, 2001)

Performance means the "Capability" of activity. **People** means the person involved in performing the activity "Directly or indirectly". **Part** means the "System and component" used in performing the activity. **Paper** means the "Hard copy and electronics" used in performing the activity. **Place** means the "Infrastructure" used in performing the activity.

3 Chapter III: Field Investigation

In order to determine the aim, scope and topic of the thesis, two field investigations were done in two aerospace manufacturing companies in Winnipeg, which are mainly skilled labor-intensive manufacturing. One investigation was for "Identification of Errant Process in Manufacturing", and other one was for "Improvement of Productivity and Capacity of Production".

3.1 Identification of Errant Process in Manufacturing

This project was proposed by the University of Manitoba and funded by Bristol Aerospace Limited, and was worked on for over one year. Bristol Aerospace is a typical skilled labor-intensive manufacturing company that produces aircraft components or overhauls aircraft and aircraft components.

The company experienced difficulty identifying problems that occurred in some of their processes including information systems. The processes with problems were called "Errant Processes" and the management team requested a method to identify them. To do this investigation, the assembly, "Tailcone" as shown in Figure 3.1, was used since it is a very skilled manpower intensive process and the management team needs to know this part is assembled correctly.

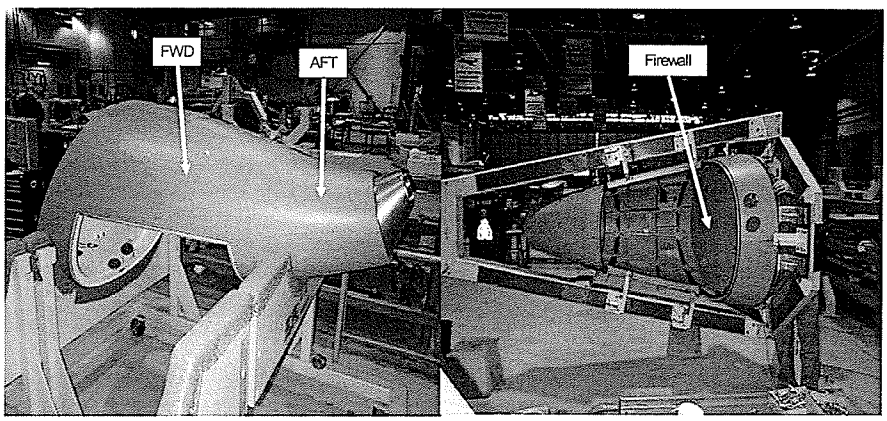


Figure 3.1 Tailcone

The Tailcone houses an auxiliary power unit that is used when the aircraft is on the ground, and is installed at the AFT end of the airplane (DHC 8 - 400). It has three sub-

assemblies (i.e. the FWD (forward) Tailcone, AFT (after) Tailcone and Firewall), which are composed of 1,105 components and sub-assemblies.

3.1.1 Production Flow

The production flow to produce this Tailcone assembly starts from the store depot where the parts to be ready for assembly are issued and runs to the end of assembling, as shown in Figure 3.2.

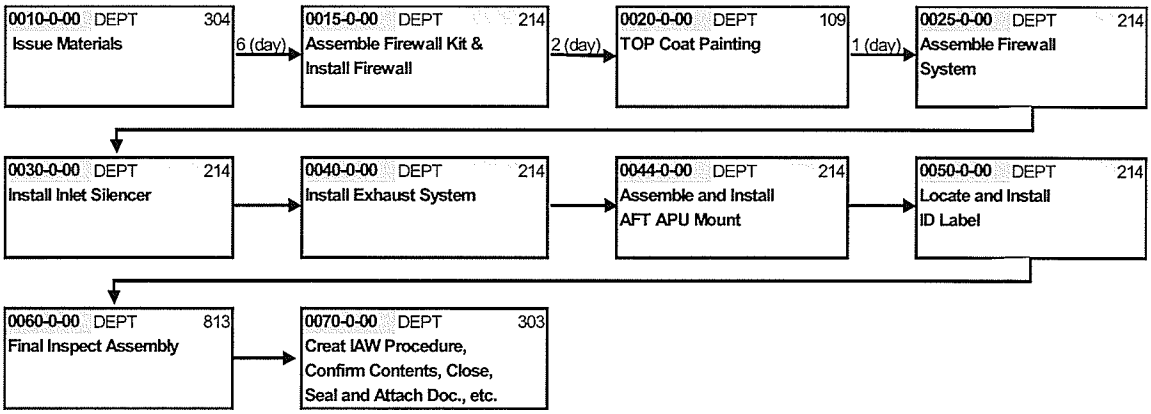


Figure 3.2 Production Flow of Tailcone (Extracted from A Shop Order, Bristol)

In Figure 3.2, the firewall kit is issued from Dept 304 and received by Dept 214 for assembling. The assembled firewall is then sent to Dept 109 for top coat painting. The painted firewall is sent back to Dept 214 for installing the inlet silencer and exhaust system. Dept 214 also assembles and installs AFT APU mount (After Auxiliary Power Unit), locates and installs the ID label to the Tailcone. The Tailcone is then sent to Dept 813 for the final inspection. Dept 303 creates the IAW procedure, confirms the contents, seals the package and attaches the documents, and then send the Tailcone to the next assembling workstation.

Based on the time spent in each process, about 80% of the time is used for processes, 0015 (Assemble firewall kit / Install firewall) and 0025 (Assemble firewall system), which have careful, difficult and frustrating work, such as making sure all surfaces are blended smoothly, the holes are drilled accurately, and parts are riveted together with extreme accuracy and smoothness. A part of the process flow for process 0015 is shown in Figure 3.3.

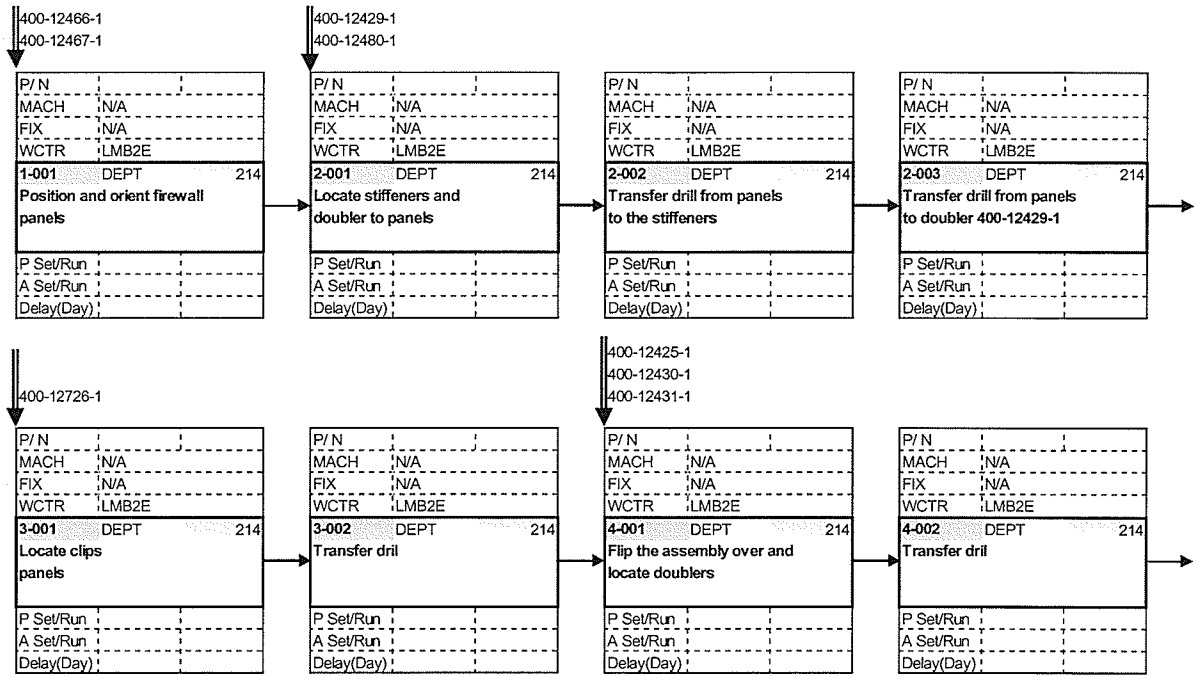


Figure 3.3 A Part of Process Flow for Process 0015 (Extracted from A SO, Bristol)

3.1.2 Production Problems Found

During the one year investigation, many production problems were discovered through discussions with supervisors, workers and inspectors, and also from the collected data. The problems found are mainly related to three groups: 1) Quantity related, 2) Quality related and 3) Time related.

- **Quantity related.** Any problem related to "Quantity" is in this group, for example,
  - **Part is missing** when required because of many reasons, for example, low levels of stock, late ordering, wrong recording, used for another assembly. This situation was a significant problem stated by the operator, and often caused the next process to wait for a few days.
  - **Too many repeated operations** exist in the process such as matching the centerline, edge and curve, and inspecting. Matching the centerline (or edge) is to align the centerline (or edge) between two metal sheets that are then riveted together. The operator adjusted the sheets to fit together with their centerlines (or

edge) by visual observation and causes significant time to be spent aligning and realigning while joining. The operators estimate that assembly time would be reduced by 50% if the quality of the parts received from upstream were shaped exactly to the specification and no repeated operations such as reshaping are required.

- **Missing operation** such as not removing the tooling lugs.

- **Quality related.** Any problem related to "Quality" is in this group, for example,
  - **Defective parts or assemblies** such as
    - **Wrong dimension.** For example the hole of the cast is sometime drilled smaller or larger than the specifications, or at a wrong location.
    - **Mismatched centerline, edge and curve.** For example the central lines on the adjacent sheets are mismatched; the interference with rivet head is wrongly positioned; the curvature of one sheet metal part from upstream is out of specification, and needs reshaping to specification.
    - **A sheet metal part with a long crack.** It could be caused by a bending operation.
  - **Wrong doing** such as attaching a wrong tag, drilling a hole at the wrong location of the wrong size, bending a sheet in a way that it cracks, missing inspection steps.

- **Time related.** Any problem related to "Time" is in this group, which includes early, late and long operations. The variation of operations is also included in this group.
  - **Early operation,** such as producing the parts early, which imbalances the workflow and requires more WIP storage.
  - **Late operation,** such as producing the required part late, which creates a waiting time, sometimes a few days in the downstream operation.

- **Long operation,** for example, the average time spent for issuing the requested item from inventory is 13 days or more, and causes a long waiting time in the next operation.

- **Variation of operation,** for example, time spent in the alignment operation varies from assembly to assembly, and causes a significant time to balance the entire production schedule.

The problems found in this investigation are "Product defects mixed with production delays". However, in this company, final inspection is very good, and the extra cost is related to rework and lateness rather than bad final product.

Although a list of production problems is shown above, some of them are not considered as problems by the company and are ignored. These problems tend to waste time and can cause other problems. Examples of ignored problems are: the long time required for matching the centerline or edge, longer than acceptable levels of assembly time, and slightly out specification parts.

When defining the scope of this research, the method of solving the problems was not included. But for the completeness of the discussion, some parts of the solutions are mentioned as follows. One step related to improve the productivity is to collect extensive information. For example, the problems that are noted by and of interest to the workers, inspectors and supervisors, should be easily recorded and transmitted; the problems noted by customers, such as a late delivery should be available, along with an analysis of the cause of the problems; the information that can be automatically obtained, such as start and stop time of an operation, should be recorded. The planned information, such as the typical range of time to perform an operation, date for delivery, date for batch run, should be available for comparison with actual information.

3.1.3 Criteria to Identify Errant Process

As noted above, the problems found in this investigation are mainly related to aspects of "Time" and "Quality", which were used to create a set of criteria to identify the "Errant process", as shown in Figure 3.4.

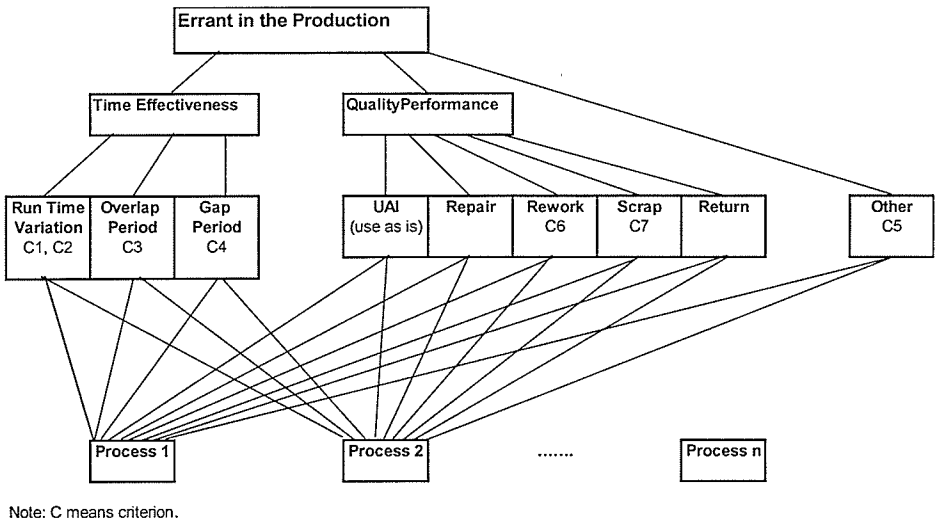


Figure 3.4 Criteria to Identify Problems

Seven important criteria are developed in the investigation based on the average of 19 actual work orders. These criteria could be integrated into the production data system to indicate when significant production problems occurred.

- **Criterion 1: Total operation gap / Time of "work in process" >= 80%.** "Total Operation Gap" is the total gaps between operations, as shown in Figure 3.5. This criterion identifies the significance of the delay (or waiting) between operations vs. the total time spent for the job, which provides a sense of how much time is actually for doing the job. If this rate is greater than 80%, it means the 80% of total time is waiting, and considered as "Unacceptable" in this investigation because of the late customer delivery.

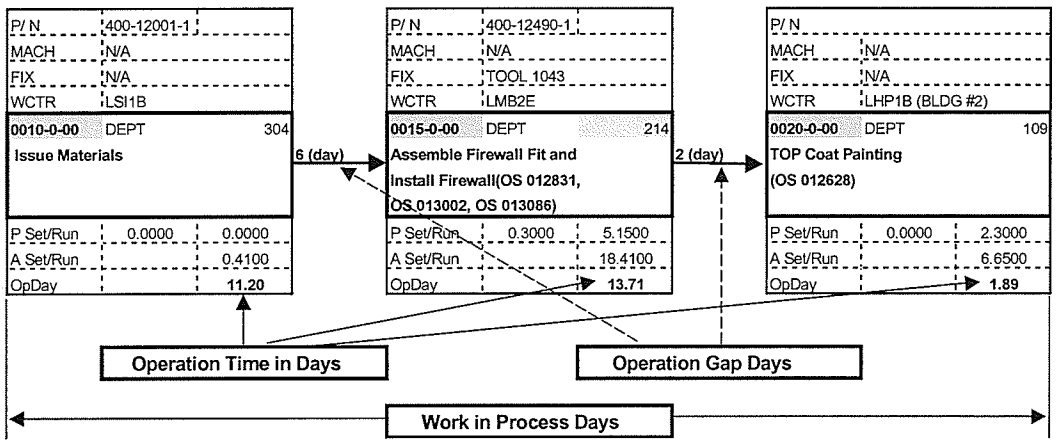


Figure 3.5 Operation Gap and Work in Process

The data in Figure 3.5 are the average number based on 19 shop orders and 7.5 hours per day, such as "Operation Time in Days" in the process "Issuing materials" is 11.2 days. One of reasons to need 11.2 days is 7 days are allowed for inventory to purchase the new parts. The discussion of the data is off the focus; therefore no further explanation is presented here.

- **Criterion 2: Actual run time / Estimated run time >= 300%.** "Actual Run Time" is shown in Figure 3.6. This criterion identifies the difference of actual run time vs. planned run time, which provides a sense of how much gap is between the actual time used and the planned time. If this rate is greater than 300%, the corresponding job is an errant job, and indicates either actual work needs to be improved or planned time needs to be redefined. For the Tailcone, the total actual run time is averagely 2.77 times the total estimated run time.

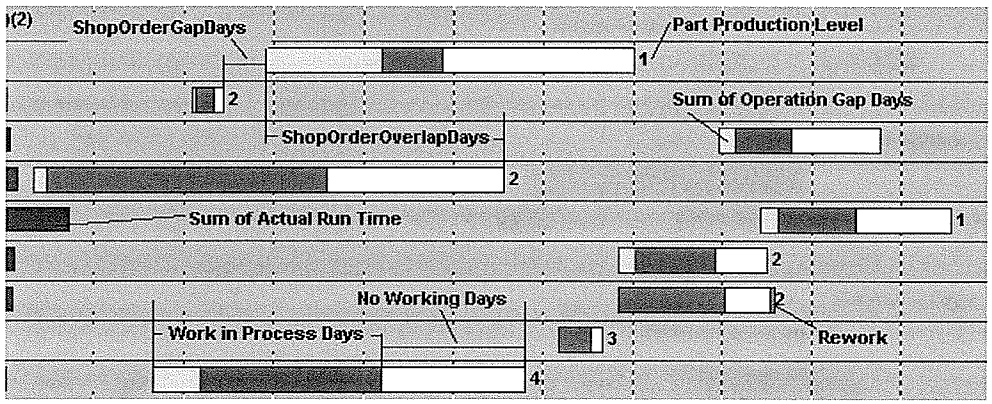


Figure 3.6 Actual Run Time, Gap and Overlap

- **Criterion 3: Shop order overlap time >= 10 working days.** "Shop Order Overlap Time" is the time that the downstream shop order starts running before the upstream shop order stops, as shown in Figure 3.6. This criterion identifies the level of jam in the production, which provides a sense of how much smoothness of the production when two processes depend on each other, and causes either a high WIP stock level or a long waiting in the following operation. It is thought to be an errant case in this investigation if this overlap is longer than 10 days.

- **Criterion 4: Shop order gap >= 10 working days.** "Shop Order Gap" is the delay between shop orders, as shown in Figure 3.6. This criterion identifies the significance

of the delay (or waiting) between shop orders, which provides a sense of how much idle time is in production when two processes depend on each other. It is a problematic shop order if the gap is longer than 10 working days.

- **Criterion 5: Missing Part.** "Missing part" means the part can't be found when required. It indicates buying the extra parts.

- **Criterion 6: Rework.** "Rework" means the part is out of specification and can be reworked, which is an unnecessary extra work.

- **Criterion 7: Scrap.** "Scrap" means the part is defective and needs to be replaced, which generates an extra effort.

The above indicators can be used individually or together by creating an **integrated criterion** as shown as below.

- **Integrated criterion (IC)** = $w_1*C_1 + w_2*C_2 + w_3*C_3 + w_4*C_4 + w_5*C_5 + w_6*C_6 + w_7*C_7$

  In which, $C_1, C_2, \ldots, C_7$ present whether the criterion is "True" or "False"; $w_1, w_2 \ldots w_7$ present seven contribution weights to the total IC from each criterion. For example, when $w_1 = 0.3$, $w_2 = 0.2$, $w_3 = 0.1$, $w_4 = 0.1$, $w_5 = 0.1$, $w_6 = 0.1$ and $w_7 = 0.1$, it the means C_1 has the most contribution; C_2 has the second contribution; and the rests of C have the same contribution level. The determination of weights is an experience based management decision.

The value of IC indicates a severity of errant process; the bigger the value is, the worse the process is. Based on this rule, 19 shop orders performed in 1999 were assessed, and the shop order J11559 is the worst one since it has the highest value of IC, as highlighted as Yellow in Figure 3.7.

This approach provides the company an integrated method to identify the errant process in production and assess the severity level of the errant process. The severity level can be grouped as "Critical", "Major" or "Minor", which will likely result in a hazardous (or

unsafe situation), or prevent a good production performance, or a failure to reduce the level of intended functioning.

OpID	StartDate	StopDate	Vaule of IC
534321	99/01/21	99/01/22	0.00
534322	99/02/03	99/02/04	0.04
534323	99/01/29	99/02/22	0.04
534324	99/02/11	99/03/08	0.05
534325	99/02/23	99/03/12	0.06
534326	99/03/30	99/04/14	0.09
534327	99/03/25	99/05/07	0.15
534328	99/04/20	99/05/20	0.12
534329	99/05/13	99/06/25	0.13
J00741	99/05/18	99/07/09	0.15
J05787	99/06/23	990827	0.14
J07283	99/06/29	99/09/03	0.13
J11559	99/08/17	99/09/17	0.17
J12541	99/08/25	99/09/25	0.16
J15834	99/09/20	99/10/08	0.10
J18550	99/10/04	99/10/29	0.14
J22715	99/10/29	99/11/19	0.14
J24786	99/11/15	99/12/03	0.14
J25303	99/11/16	99/12/17	0.14
J27758	99/12/03	99/12/16	0.16
J28816	99/12/14	99/12/17	0.15
J28817	99/12/14	99/12/24	0.13

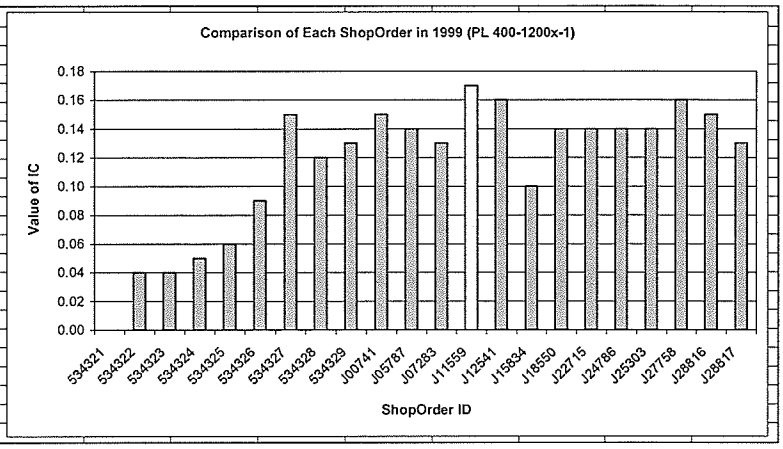


Figure 3.7 Evaluation of 19 Shop Orders Produced in 1999

The details of the investigation refer to the reference [19].

3.2 Improvement of Productivity and Production Capacity

This project was proposed by the University of Manitoba, and funded by NRC (National Research Counsel) and Aero-Recip (Canada) Ltd, which was carried out at Aero-Recip over one year. Aero-Recip is a typical skilled labor intensive manufacturing company that rebuilds about 300 aircraft piston engines per year. Some of the products, such as engines and cylinders, are shown in Figure 3.8.

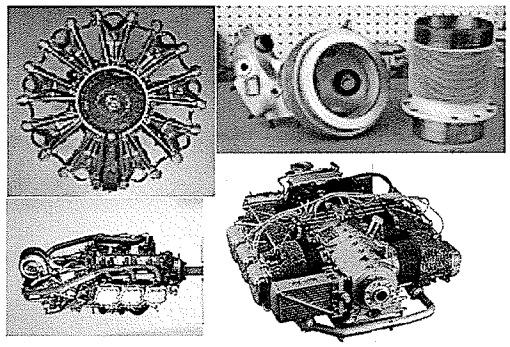


Figure 3.8 Some Products Produced in Aero-Recip

In 2001, the company spent about $6.8m to run the business, in which material costs $4.8m (70% of total), Labor costs $0.7m (10% of total) and Overhead costs $1.4m (20% of total), as shown in Figure 3.9.

Name		$ / year
Labor		686,729
Overhead		1,327,956
Materials		4,765,435
	/00	3,074,628
	/62	423,876
	/03 Ext	1,266,932
Total		6,780,120

Overhead Includes:
- General Management
- General Support
- Machine
- Fixture
- Space
- Supervision
- Incentive
- Mis Contract
- Inventory
  - Space and Equipment
  - Tied Cost
- etc.

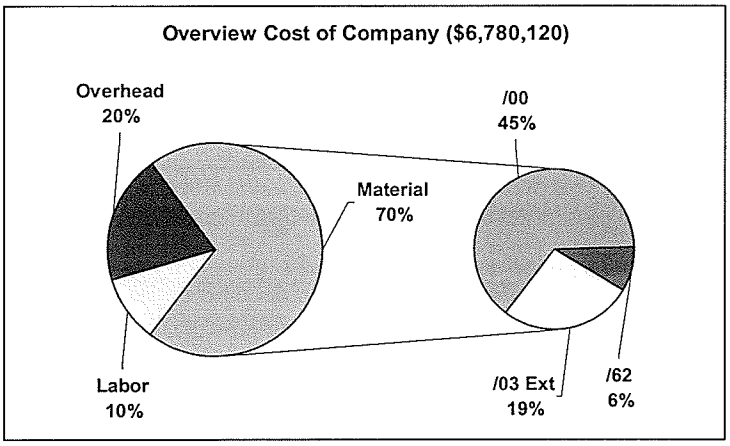


Figure 3.9 Cost Overview (at Company Level)

In Figure 3.9, material contributes the largest cost including the cost for the newly purchased parts, consigned new parts, reparable parts, contracted out rebuilt parts, and the cost of maintaining inventory; The overhead is the second largest cost including the general support, machine, space and overtime; The labor contributes the third largest cost including the direct and indirect cost.

The management team has no exact idea where the most money is spent in inventory and how the cost can be reduced. The team wants to know which process is the most expansive in the entire production, from receiving to shipping; where the related causes are and what the effective solutions are.

3.2.1 Production Flow

The entire production flow in the company is shown in Figure 3.10 and described as follows.

The customer sends the engine core to the company. Operators receive and roughly inspect the core and raise a chargeback if any missing or broken parts are found. Then the engine core is dismantled and cleaned. The detached parts are inspected to see whether they are acceptable for reuse by separating into "Use as is", "Discarded" and "Part core". The "Use as is" parts stay with the original engine core without record. The "Discarded" parts are replaced by purchasing the new parts. The "Part core" parts are

sent to either internal or external rebuilding processes through inventory. Once the part core parts are rebuilt, they are sent back to inventory for issuing. All required parts will be sent to the shop floor for assembling. When the assembly is completed, the engine is sent for testing, inspecting and rework if necessary until the specifications are satisfied. The rebuilt engine is then packed and shipped to the customer.

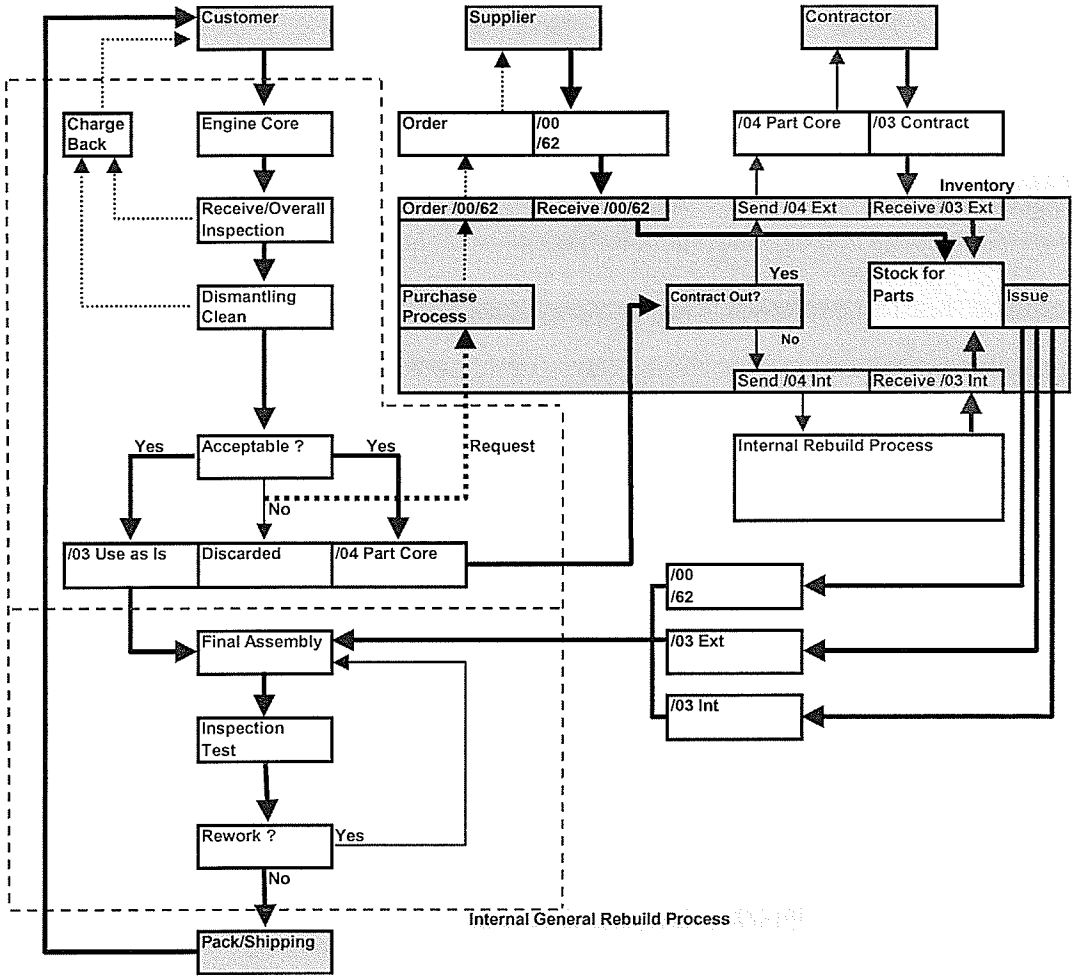


Figure 3.10 Production Flow in Aero-Recip

3.2.2 Production Problems Found

After one year's investigation, the following problems were found. For details refer to reference [15].

- **Inaccurate inventory records.** 20% of the parts in inventory were not correctly recorded and could not be located in the computer system, and a manual process was

required to find the parts. In many cases, the required parts could not be found and new parts had to be purchased.

- **Too tight specifications.** Sometimes new part specifications were used to determine the reusability of the used part. The new part specifications were tighter than the used part specifications and caused many used parts to be rejected that were still serviceable. Replacement parts had to be purchased.

- **Missing chargeback.** After the engine core is received, the inspection must be done before the chargeback deadline. However, this inspection is not done in time in many cases and chargeback for some missing or damaged parts cannot be made.

- **Part damaged in dismantling or cleaning.** The operator may damage the parts in dismantling or cleaning because of inexperience, and if the damage is significant, the parts must be repaired or replaced.

- **Unnecessary dismantling.** The operator may dismantle more of the engine core than required, and causes unnecessary time in dismantling, cleaning, inspection and engine reassembly.

- **A long storage time.** The average storage time in the company is 3 months and 40% of total parts are stored for more than 6 months; this situation causes a significant inventory cost.

- **Operation time for the same operation varies from worker to worker.** The time for performing the same operation, such as fitting, varies significantly from operator to operator, and causes the extra planning effort to smooth the entire process.

- **Inspection error.** A less skilled inspector may treat a good part as bad one or vise versa in some cases. This causes the purchasing of more new parts in the case of taking a good part as bad one or creates a lower quality or even malfunctioning engine that requires rework in the case of taking bad part as good one. The inspection error is usually identified by another inspection if it is not the last step in production.

Otherwise, the error is found by customer inspection or eventual through the customer use.

- **Information system is mainly for accounting purposes.** The information system in this company is not intended for the production. For example, some BOM's (Bill of Material's) of the old engine types are not available in the system. The BOM knowledge is mainly part of the knowledge of the experienced people in the company. In the short term, they may do the job or pass the related knowledge to others to do the job. However, in the long run, if these experienced people leave the company such as through retirement, the required knowledge of BOM is no longer available and the company faces the challenge of retention of intellectual property.

3.2.3 Solution and Possible Saving

In order to solve the problems mentioned above, the possible solutions are listed as follow with the possible savings.

- **Do more detailed engine core inspections before the chargeback deadline.** This action should allow the company to limit the extra costs that could be otherwise lost, which is about **$14,000/year** (1% of total engine core value). Some costs may be required for possible expedited inspections.

- **Purchase less new parts or contract less repairable parts out by**
    - **Training or using a more experienced worker**
        - To dismantle and clean the engine core for the **least damage**.
        - To dismantle the engine core to the right level to reduce **unnecessary dismantling** and **reassembling** later on.
        - For the least possible **inspection error**.
    - **Using serviceable level specifications to accept serviceable old parts.** The service level specifications (i.e. "Use as is") are the right specifications to use when determining the reusability of the old parts since many old parts may fail the

"as new" inspection and have to be replaced or rebuilt if the new specification is used.

- **Move external rebuilding of parts to an internal process.** After checking all rebuild processes, they should be done in house as much as possible if the company has the capability to do so with a lower cost than the cost of contracting out.

The projected saving by all the above solutions is about **$0.54 m/year** (11% of total material cost).

- **Improve the information system by**
  - **Creating an electronic BOM.** A complete electronic BOM (Bill of Material) for each type of engine is essential in production for the long run. This solution reduces the possibility of losing the knowledge.
  - **More inventory counting.** Count the inventory twice a year to increase the accuracy level of the information system.
  - **Using "Bar code system".** A bar code system is an efficient way to reduce the human errors in typing, and increase the ability to locate a part.
  - **Creating an automatic communication mechanism.** An automatic communication between shop floor and inventory will reduce the time lag and information errors between requesting and issuing.
- **Use machinery wherever possible.** This will increase the quality and consistency of the work for less rework later on.
- **Reduce inventory level.** This will increase the turnover rate and decrease the inventory cost. For example, if 50% of untraceable parts can be removed, about **$0.66m**, including labor and tied costs, can be saved as a one-time saving.

Conclusions of Chapter:

- The first investigation handles the issues at the Tailcone assembly level for exploring waste and cause. A set of criteria to identify errant processes was developed. The worst shop order is found from 19 shop orders in 1999.

- The second investigation handles the issues at the company level for exploring waste, cause and solution. The main problems are found related to inventory and work on the shop floor. The solutions with the possible savings are suggested.

- These two investigations provide strong clues on the thesis topics, such as how skilled labor can be best used, how to identify waste, locate the cause and find a solution, in the course of using skilled labor.

4 Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure

Since this thesis is basically about how to best use **skilled labor** in manufacturing, the breadth and depth of manufacturing and the dimensions of interest in skilled labor are discussed in this chapter to refresh the reader. A standard activity structure is also developed in this chapter. The topics covered here are "Manufacturing", "Skilled Labor Manufacturing", "Basic Requirements to Perform an Activity" and "Standard Activity Structure (SAS)".

4.1 Manufacturing

Manufacturing is one of the key terms used in this thesis, and has many definitions. For example, one definition is "Manufacturing is the creation of value or wealth by producing goods and services" (American Heritage Dictionary, 2000) [2]. In this thesis, **manufacturing** is defined as "A collection of activities which transform raw materials into semi-finished or final products". It is discussed as follows under the topics "Objective of Manufacturing" and "Activity and Its Classification in Manufacturing".

4.1.1 Objective of Manufacturing

Based on the above definition of manufacturing, the **objective of manufacturing** is defined, in this thesis, as "To produce the required amount of the defect-free product within the required customer lead-time at the right cost", and covers four aspects: 1) required amount; 2) defect free; 3) required customer lead-time; 4) right cost.

- "Required amount" means the quantity requested by the customers or inventory, which is related to the Quantity aspect.
- "Defect free" means "No defect" in the item produced, which is related to the Quality aspect.
- "Required customer lead-time" means the time from customer order to customer receipt, which includes the production time and delivery time, and is related to the Time aspect.

- "Right cost" means the cost accepted by the market, which is related to Cost aspect. The "right cost" is not necessary the "least cost" since seeking the least cost usually compromises the quality aspect.

Among the above four aspects, "Quantity, Quality and Time" are relatively independent of each other in measure, but highly correlated with "Cost", which means those three aspects can be measured by Cost.

4.1.2 Activity and Its Classification in Manufacturing

Activity is another term widely used in this thesis. An activity may mean the action in general or a task [2]. In manufacturing, it could be cutting, drilling, etc. Since so many activities exist in manufacturing, it is necessary to classify them for an easy understanding. There are many ways to classify the activity depending on the interest of concern. One of ways used in this thesis is based on the legitimate manufacturing hierarchical structure that includes the level at company, product, process, operation, step and micro step, as shown in Figure 4.1.

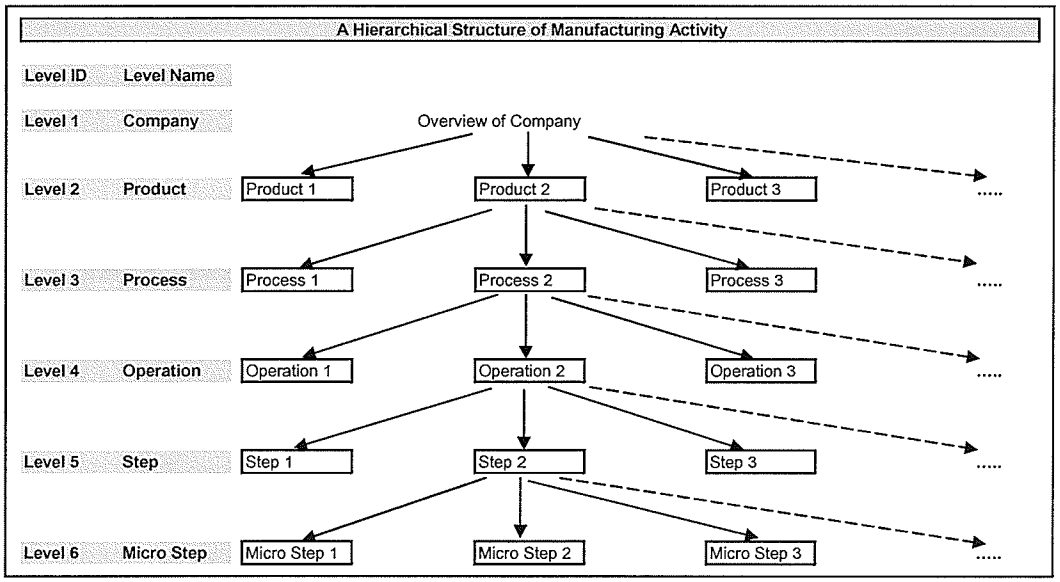


Figure 4.1 Activity Level in Manufacturing

- **Activity at the company level** is the activity that benefits the entire company such as determining which product should be produced or which company-wide used facility or machine should be maintained.

- **Activity at the product level** is the activity that benefits a product such as creating "Bill of Material" for a specific product.

- **Activity at the process level** is the activity that benefits a process, such as assembling a part, as shown in Figure 4.2.

- **Activity at the operation level** is the activity that benefits an operation, such as a lapping that is a part of surface correction process, as shown in Figure 4.2.

Process	Operation	Process	Operation	Process	Operation	Process	Operation
Collect	Collecting material Cleaning workplace	Form	Bending Coining Contouring Deep drawing Dimpling Embossing Hemming Ironing Necking Nosing Press brake forming Spinning Straightening Stretching Swaging	Shear	Blanking Cutting off Facing Lancing Notching Nibbling Parting Piercing Shaving Slitting Trimming	Assembly (place and join)	Placing Welding Gluing Bolting
Change Material Properties	Heating Physical changing Chemical changing					Disassembly	
Shape	Cutting Sawing Flame cutting Turning Boring Drilling Broaching Reaming Milling Chemical machining Electrical-discharge machining Electron-beam machining Laser machining Electrochemical machining Molding Pressing	Surface / Inner Addition	Coating Filling holes	Surface Correction	Nailing hole fill Polishing Electro polishing Lapping Super finishing Grinding Electrochemical grinding Roller burnishing Snagging Honing Planning Barrel finishing	Sort	
		Adjust	Fitting			Inspect	Observing Measuring Testing Experiment
						Wait	Watching

Figure 4.2 Activities at Process and Operation Level (Altiok Tayfur, 1996)

- **Activity at step level** is the activity that benefits a step such as a setup, loading, running, waiting, unloading and cleaning.

- **Activity at micro-step level** is the lowest level of activity in manufacturing as defined in this thesis, such as a reaching and grasping, as shown in Figure 4.3.

The classification of activities in manufacturing is knowledge and case based, which means that different people may classify the same activity into different levels. For example, an activity may grouped as a "process" by one person and an "operation" by another person. In order to reduce this arbitration, the group should not be changed once it is classified within one analysis cycle.

ID	Micro-Step	Activity	Definition	Start Time	Stop Time
1	Think	Brain	What to do next	Start thinking	Stop thinking
2	Search	Eye	Look for item	Start looking for	Found item
3	Select	Hand	Choose from similar items		
4	Reach	Hand	Approach item	Start approaching	Touch item
5	Grasp	Hand		Start grasping	Grasping completed
6	Move	Hand	Move item to another place	Start moving	Stop moving
7	Hold	Hand	Keep in static state		
8	Pre-Position	Hand	Move items to position in advance		
9	Position	Hand	Move items to correct position	Start positioning	Placing correct position
10	Assemble	Hand	Put items together	Start joining	Joining completely
11	Disassemble	Hand	Separate items	Start separating	Separating completely
12	Use	Hand	Use tool or machine for operation		
13	Inspect	Hand	Check		
14	Release	Hand	Free items	Start releasing	Completely releasing
15	**Delay**				
16	Rest				

Figure 4.3 Activities at Micro Step Level (Altiok Tayfur, 1996)

4.2 Skilled Labor Manufacturing

Skilled labor manufacturing is the main concern in this thesis and will be given a detailed discussion in this section by the topics: "Definition of Skilled Labor", "Normal Manufacturing Approaches" and "Capability of Skilled Labor Manufacturing".

4.2.1 Definition of Skilled Labor

Skill is a proficiency, facility, or dexterity that is acquired or developed through training or experience [2]. Many skill levels could be required for fulfilling an order. In this thesis, the main concern is skilled level and non-skilled level.

- **Skilled** refers to a unique-skill or the multiple-skills. A **unique-skill** worker possesses a complete knowledge and ability (obtained through intensive training) to perform a specific, complex job independently. The **multiple-skills** worker possesses the knowledge and abilities to perform many complex job types independently. The worker at this level is sufficiently independent, flexible and versatile (obtained through a wide range of training and practice) to accurately perform many tasks with enough creativity and intelligence to recognize the issues, enough knowledge to interpret the complex information, and enough conscientiousness to perform the job properly.

- **Non-skilled** refers to an un-skilled or semi-skilled individual. An **un-skilled** worker possesses an ability (obtained through a basic education or general training) to perform a basic routine job that does not require any advanced knowledge. A **semi-skilled** worker possesses a certain level of a specific ability (obtained through training) to perform a specific skilled job with some supervision.

4.2.2 Normal Manufacturing Approaches

Many manufacturing approaches exist, but only three approaches are considered in this thesis. They are: "Skilled labor manufacturing", "Non-skilled labor manufacturing" and "Machine manufacturing", which is classified by the "Cost significance".

- **Skilled labor manufacturing** is the approach, in which skilled labor contributes the major cost. For example, assembling an aircraft engine is a skilled labor manufacturing job since skilled labor contributes the major cost.

- **Non-skilled labor manufacturing** is the approach, in which non-skilled labor contributes the major cost. For example, cleaning a shop floor is a non-skilled (unskilled or semiskilled) labor manufacturing job since non-skilled labor contributes the major cost.

- **Machine manufacturing** is the approach in which the machine contributes the major cost. For example, a 3-D casting and modeling process is a machine manufacturing job since the machines contribute the major cost.

Among above three approaches, skilled labor manufacturing is of most interest in this thesis, and the other approaches will only be mentioned when required.

4.2.3 Capability of Skilled Labor Manufacturing

As mentioned above, as skilled labor is the main topic in this thesis, it is necessary to know the capability of skilled labor manufacturing since in some cases only skilled labor is able to perform the required job effectively and efficiently. Such cases include: "Small volume of orders; Non existent machine; Unavailable documents; Complex item with

small volume; Uncertainty in process; Extreme accuracy, Extensive measure and adjustment required; and Significant judgment required", which are discussed as follows.

- **Small volume of orders** addresses the case when the order is small. In such a case, expensive machines cannot be justified, since each operation would have to carry a large part of the capital cost. If the machine also requires a significant setup time, the setup cost per operation for a small volume run would be large. For example, when only milling 100 cases of the radial aircraft engines per year, it will be very expensive per case if a NC machine is used because of its high capital cost.

- **Non existent machine** addresses the case when no machine exists to do the required job, and the only way is to use skilled labor. For example, for aligning the metal sheet on the body of an old type of aircraft with an extreme surface smoothness, no machine currently exists to handle this job, and the only way is to use skilled labor.

- **Unavailable documents** address the case when the required documents are unavailable to do the required job, and skilled labor is the only option. For example, "Bill of Material (BOM)" of an old type of engine with many variations is not available, and causes significant difficulty to determine which parts fit where. The solution could be recreating a BOM or use skilled labor with the knowledge of BOM for this type of engine.

- **Complex item with small volume** addresses the case when the requested item is complicated and the order volume is small as well, and skilled labor is the only option to do the job in terms of cost effectiveness. For example, a customized motor cycle requires many unique assembling operations such as "Fitting and aligning", which requires a sophisticated process that could only be done by skilled labor.

- **Uncertainty in procedure** addresses the case when the next step is unknown until the current step is completed. For example, when cutting a diamond, the placement of the next cut can't be known before the current cut is completed because of the variations in physical properties throughout the natural diamond. In such a case, skilled labor is the only option.

- **Extreme accuracy, extensive measurement and adjustment required** addresses the case where intelligence is required. For example, two pieces of thin metal sheet are often aligned very accurately when assembling the aircraft. Because of the combination of the extreme accuracy requirement and the flexibility of the sheets, no machine could be found to do this job, and skilled labor is the only choice.

- **Significant judgment required** addresses the case where good knowledge and judgment is required for doing the job. For example, when sorting the worn parts for useable, rework and scrap, good knowledge is required to do a correct sort; otherwise a good part may be treated as a bad one or vice versa if non-skilled labor is used; when lapping a cylinder valve, significant judgment is required for determining the smoothness of surface.

4.3 Standard Activity Structure (SAS)

In order to present and describe any kind of manufacturing activity in a standard way, a model, "Standard Activity Structure (SAS)", was developed in this thesis.

SAS answers the question "What are the generic requirements to perform an activity?" Four items are identified as the generic requirements to perform an activity in the thesis and called "Activity elements" that are "Input, Control, Doing and Output" as shown in Figure 4.4.

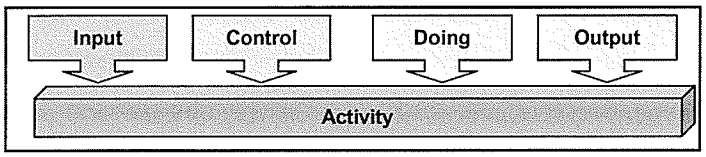


Figure 4.4 Activity Elements

4.3.1 Activity Element "Input"

Input is any resource required to perform an activity, including the physical resource and information.

- The **physical resource** is separated into material and actor.

- **Material** is the consumable and modifiable resource that is transformed to the produced item such as a part, which includes raw material, purchased part, and sub-assembly. Energy, e.g. water, electricity, gas and compressed air are also included here.

- **Actor** is the non-consumable resource that contributes the effort to transform the material, which includes labor, machine, fixture, space and contract (These are adopted and modified from Operation Based Costing (OBC) which is described later).

  - **Labor** is a person to do the job.

  - **Machine** is the equipment to transform the material from one form to another, which could be a mill, drill or an NC machine.

  - **Fixture** is the tool, such as a holder, to assist the machine to function properly.

  - **Space** is the place to perform the job, which could be the shop floor, inventory or transportation area.

    - **Shop floor** is the area to transform the raw material to semi-finished or final product. The activities on the shop floor could be assembly, disassembly, inspecting, shaping, forming, shearing and surface correction. The shop floor is the main area of interest in this thesis. Inventory and transportation area are described only for completeness.

    - **Inventory** is the area to store raw, semi-finished or final products for balancing the production flow between supply and demand. The activities in inventory could be receiving, storage, picking order, packing and shipping.

    - **Transportation area** is the space to deliver the materials and items between sender and receiver. The activities at the transportation area could be loading, moving and unloading.

- **Contract** is the "Outsource" of work to increase the internal production capacity or reduce the cost. Contract is not the main topic in the thesis and only mentioned for completeness.

- The **information** for performing the activity includes "Bill of material" (BOM), specification, operation sheet and shop order.
  - **BOM** is the list of all parts contained in the product.
  - **Specification** is the detail required for defining the part or product, and determining the quality of the finished part or product.
  - **Operation sheet** is a detailed instruction of performing the job in terms of part routing, job sequence and so on.
  - **Shop order** is a form to provide shop floor an authorization to proceed with production in terms of quantity, quality and time.

4.3.2 Activity Element "Control"

Control is the effort to plan, guide and adjust "Doing" through an open or closed control loop.

- The **efforts of planning**, including organizing and meetings, are implemented through the controlling of the work in Doing.
- The **efforts of guiding and adjusting** are implemented through the closed control loop that receives the information of the result of actual execution such as throughput, damage and idle from Output, then adjusts work in Doing.

4.3.3 Activity Element "Doing"

Doing is the execution effort to actually transform the material to the output by the actor under the instruction from Control, which includes setup, run and wait.

- **Setup** is the effort to make the machine, and sometimes the operator, ready to do the job, which includes collecting, removing the last fixture used, installing the next fixture and changing the tools.

- **Run** is the effort to transform the material from one stage to another, such as drilling, cutting and welding.

- **Wait** is doing nothing since something is not ready to run, such as the operator waits for a part.

4.3.4 Activity Element "Output"

Output is the outcome after Doing is executed, which includes the physical item (e.g. part) and related information (e.g. identity, quantity, quality, time and next user).

- **Identity** provides the output identity such as a unique number or name.

- **Quantity** provides the throughput information such as 1000 parts/day.

- **Quality** provides the quality information such as acceptance rate and non-conformance rate.

- **Time** provides the time information such as total time spent for producing one part.

- **Next user** is either an internal or external user.

4.3.5 SAS Model

The concept of "Open / Closed loop" in automatic control theory (C. Benjamin et al. 2002) [9] is used for the modeling. Generally speaking, "Closed control loop" is a mechanism to minimize the bias between the actual performance and the aimed performance by a control signal, which is adjusted or modified based on the significance of the bias that is collected by either off-line or on-line sampling. The more significant the bias is, the stronger the control signal is and the faster the modification is.

Based on this concept, the four activity elements are connected to each other and form a new model called the "Standard Activity Structure (SAS)", as shown in Figure 4.5.

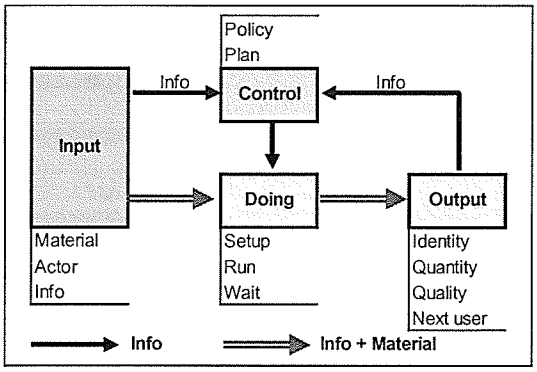


Figure 4.5 Standard Activity Structure (SAS)

SAS includes the material and information flow, which is described as follows:

Everything required for performing an activity enters "Input", which includes the physical resource and information. The planning information from Input and the execution information from Output enter "Control". If differences occur between the planned and actual performance, the adjustment is requested and implemented through "Doing" to achieve the planned output and satisfy the customer in terms of "Quantity, Quality and Time". "Doing" receives the material from Input and information from both Input and Control to execute the setup, run, and wait for producing the required items. Everything that comes out as a result of performing activity is in "Output", which includes the good part, scrap and related information. By this way, SAS describes any activity in a consistent way and reduce the variations in the recognition of an activity.

Conclusions of Chapter:

- **Skilled labor** manufacturing is an expensive approach, and therefore is the least desired approach, and should only be used when absolutely necessary.
- Any activity can be presented by Standard Activity Structure (SAS) model by using four activity elements: "Input", "Doing", "Control" and "Output" since SAS is a model at a generic level.
    - Material (i.e. material, supply, service, contract and tied cost), actor (i.e. labor, machine, fixture and space) and related information such as the quantity of material used in the activity, is described in one place, "Input".

- Time and number of uses are described in one place, "Doing".
- Efforts related to controlling the activity is described in one place, "Control".
- Outcome (i.e. desired output, lower quality output, output to be reworked, legitimate scrap and unplanned scrap) is shown in one place, "Output".

- SAS describes how an activity is performed in terms of material and information flow. The performance of the Output is always checked against the target performance. Once a discrepancy occurs, it is reduced by the Control element in the model.

- SAS reduces the variations in presenting the activity since all activities have the same standard structure. It brings in a more consistent conclusion.

- The use of SAS must follow the "Two-Step" approach, which is "Obtain flowchart based on the process analysis" and "Plug SAS into each activity involved in the flowchart".

5 Chapter V: Three-Step Procedure (3SP)

In order to use skilled labor effectively and efficiently, many issues must be considered. The first issue is whether skilled labor is truly required since better choices in many situations are less skilled labor or machines. The second issue is whether the production process is designed to use skilled labor effectively and efficiently, since many production processes that use skilled labor have been found to be poorly designed. The third issue is whether the actual production process works as well as expected. In order to address these issues, a systematic procedure is created and named as the "Three Step Procedure (3SP)" in this thesis as shown in Figure 5.1, which includes: "**Step 1:** Determine whether to use skilled labor"; "**Step 2:** Define the most suitable specifications for using skilled labor" and "**Step 3:** Attain and maintain the defined productivity".

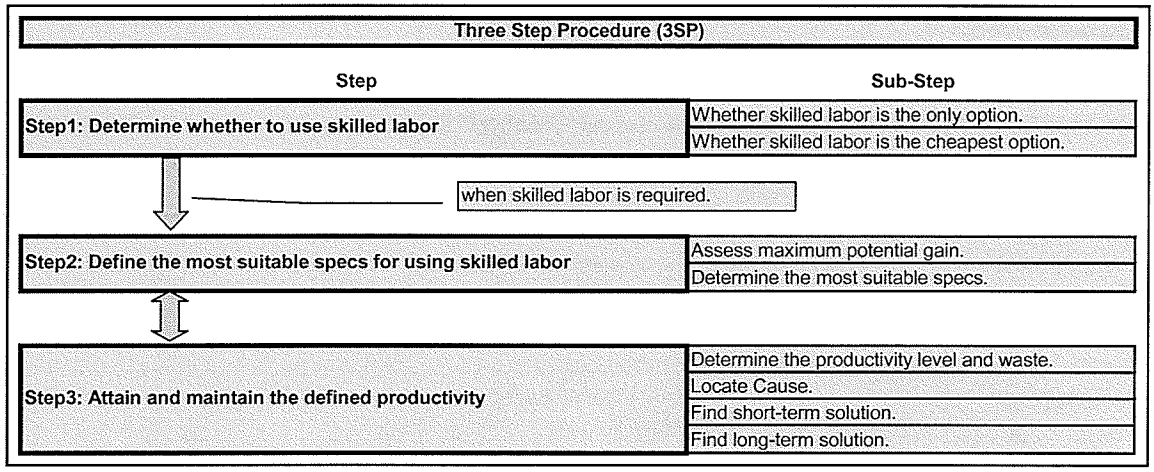


Figure 5.1 Three-Step Procedure (3SP)

5.1 Step 1: Determine whether to Use Skilled Labor

As mentioned before, many production options such as skilled labor, un-skilled labor and machine are used in manufacturing and the question is which one is the best one for performing the required job. In order to do so, two issues are checked, which are: "Whether skilled labor is the only option" and "Whether skilled labor is the cheapest option". If skilled labor is chosen to be used, the issue will go to Step 2 otherwise no further discussion is needed in this thesis.

5.1.1 Whether Skilled Labor Is the Only Option

The reason for checking this issue is to reduce the decision effort since it is unnecessary to go through the cost procedure if skilled labor is the only option to do the required job effectively and efficiently.

A list of cases is identified where skilled labor is the only option, which includes "Small volume of orders; Non existent machine; Unavailable documents; Complex item with small volume; Uncertainty in process; Extreme accuracy, Extensive measurement and adjustment required; and Significant judgment required". For example, an extremely accurate alignment is required when joining two sheets together to avoid "Oil canning" (a situation when two sheets do not fit perfectly together and cause a slightly curved rather than a flat surface, and with slight force the curve pops in or out easily). However, no machine could be found to perform this job since the machine **does not exist** and using skilled labor becomes the only way to do this job. For details refer to Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure.

5.1.2 Whether Skilled Labor Is the Cheapest Option

When more than one option is available to do the job, a cost comparison is necessary. For example, both NC welder and skilled labor are available to do a "Welding" job and the question is which one is the cheapest. When the batch size is small, using skilled labor is usually the cheapest because the setup cost of the NC welder is normally very higher per part welded.

The rules are summarized to reduce the effort during the comparison, which are:

- **Rule 1:** Machinery is always considered as the **first option** to do the job when the unit cost is acceptable since the machine always provides the least production time, the greatest quantity, the best and most consistent quality. Considering whether to use the machine usually depends on the unit cost determined by the production volume.

- **Rule 2:** Non-skilled (un-skilled or semi-skilled) labor is the **second option** to do the job when the worker has the minimum required skill since the wage is medium. But,

it is expected that other costs may be increased, such as longer production time or more defects.

- **Rule 3:** Skilled labor is the **least desired option** to do the job if other options are available because of high labor cost.

- **Rule 4:** Contract is a **possible option** to do the job if the cost is acceptable. This issue will not be discussed in the thesis unless a complete discussion is required.

In summery, in an industrialized country, machinery is always the first option, un-skilled labor is the second option, and skilled labor is the last option. Contract may be an option.

The comparison in this step means to determine whether skilled labor has the least cost, which includes four steps: 1) Analyze production flow, 2) Determine factors to measure, 3) Identify losses and 4) Estimate cost, as briefly described as follows. The details refer to Chapter VI: Production Flow and Measurement, Chapter VII: Matrix of Loss-Cause-Solution (MLCS) and Chapter IX: Costing of Loss and Solution (CLS).

- **Analyze production flow** is to understand how the production is done in terms of information and material flow. The information includes the static information (e.g. aim, task, penalty policy, throughput, scrap, delay and cost) and dynamic information (e.g. where the value is added or lost and how the involved steps are linked).

- **Determine factors to measure** is to decide what to measure for the cost spent for "Quantity, Quality and Time", and are listed as follows by activity elements.

  - **Input**

    - **Material:** Quantity (from actual measure) and unit cost (per piece, from accounting book).

    - **Labor:** Number and unit cost (per unit of time, from accounting book), which includes wages, salary, fringe benefits and support cost.

- **Machine (including tool, fixture and computer):** Quantity, unit cost including the capital cost and maintenance cost (per piece or unit of time, from accounting book) and depreciation period. The maintenance cost can be ignored if it is less than 1% of depreciation cost.

- **Space:** Size and unit cost (per area or per unit of time, from accounting book), which includes the deposit and renting cost.

- **Contracting out:** Quantity and unit cost (per part or unit of time, from accounting book).

- **Tied cost:** Interest paid for the stored material, which depends on the "Interest Rate" (from accounting book), "Time Stored" and "Quantity of Material" (from actual measure).

- **Energy:** Amount of energy used (electricity, water and compressed air, from actual measure) and unit cost (per watt, volume or unit of time, from accounting book).

- **Control**

  - **Penalty:** Payment (determined by the penalty rates and quantity involved) for dissatisfaction of the customer in terms of quantity, quality and time. The penalty is usually pre-set (from accounting book).

  - **Organizing:** Cost for scheduling, meeting and etc, which depends on the "Cost per Unit of Time" (from accounting book), and "Time Spent for Those Efforts" (from actual measure).

- **Doing**

  - **Time:** Time spent for doing the job which includes the planned time (from production statement) and actual time spent (from actual measure).

- **Output**

- **Quantity:** Quantity produced (from actual measure).
- **Quality:** Quality produced such as scraps and reject items (from actual measure).
- **Time:** Time spent to complete the job (from actual measure).
- **Cost:** Total cost, value added and loss (calculated using above information).

The sources for obtaining the above information are "Production Statement", "Accounting Book" and "Actual Measure". The tools used to collect the above information are video, interview and observation. In this step, estimates of times and losses may be used instead of actual measure if the measurement is very difficult.

- **Identify loss** is to get loss information including planned and unplanned losses.
- **Estimate cost** is to evaluate the cost including the cost for loss, as stated in the "Cost Statement".

If skilled labor is chosen, the analysis process will go forward to Step 2 for further evaluation, otherwise no further discussion will be undertaken in this thesis.

5.2 Step 2: Define the Most Suitable Specifications for Using Skilled Labor

After skilled labor is chosen to do the job, it is necessary to know how to use skilled labor to obtain the maximum output rate with the least manufacturing error. Therefore, "Define the most suitable specifications for using skilled labor" is identified as the task of Step2 and discussed under two topics: 1) Assess maximum potential gain and 2) Determine the most suitable specifications.

5.2.1 Assess Maximum Potential Gain

Note that the information related to how the maximum potential gain is achieved is described here for the reader's ease of understanding. This information is not part of this thesis and can be found in many text books or articles. Also most skilled labor

manufacturers have operation designers that are experienced in this area (Nahmias Steven, 2004) [34].

Assess maximum potential gain means to estimate the potential maximum gain with the least loss under the planned condition (e.g. the required materials are always ready for use and the operation is not delayed). The analysis here is based on the ideas of operation designers who are experienced in designing skilled labor manufacturing operations. In order to get the least loss, four general directions are identified in this thesis: 1) Optimize the utilization of resources; 2) Minimize the process time; 3) Minimize the error occurrence and 4) Maximize workplace safety.

- **Optimize the utilization of resources** such as raw material, skilled labor and machine. For example, assign one operator to operate on two or more machines, rather than have one operator per machine; carefully define the used part acceptance level in overhauling process, rather than use an unnecessarily accurate specification that rejects useful parts; have unskilled labor perform some steps to reduce skilled labor involvement; keep defined scrap low, especially related to cutting parts from a piece of material.

- **Minimize the process time** including setup and run. For example, run a larger batch to reduce setup time per part if setup time is long; eliminate unnecessary steps by carefully analyzing the job to determine the minimum work to be done; reduce skilled labor waiting time for parts or tools to become available, or for a machine driven process to finish; use assisting tools to increase process speed.

- **Minimize the error occurrence** since this is very important because some errors always occur when skilled labor is used to perform complex tasks. For example, design the workstation for easy access to check the operation and parts whenever required; set more inspection stations in place if cost effective; provide more instructions for trouble-shooting when an error occurs; use assist tools, fixtures and machines for better accuracy; design the operation and the parts to keep the possibility of mistakes low.

- **Maximize workplace safety**, for example, add sensors to suitable locations of machines to prevent operators' hands from entering the work area during an operation; redesign the workplace using ergonomic techniques to decrease the potential work risk. However, this issue is not a focus in this thesis since it is a more legal issue than cost issue.

5.2.2 Determine the Most Suitable Specifications

After the general structure and techniques for the operation have been worked out, the operation is designed in detail and run to see how well it works. As mentioned earlier, with complex operations using skilled workers, a major consideration is the reduction of operational errors and smooth recovery when errors are created.

If improvements can be made to the operation, an iterative procedure of improving and running is used until a suitable result is achieved. To obtain the best results the following procedures are used: 1) Analyze production flow, 2) Determine factors to measure, 3) Determine production design weak points, reasons for weak points and potential solutions, and 4) Estimate cost.

- **Analyze production flow** is the same as the one in Step 1.
- **Determine factors to measure** is the same as the ones in Step 1.
- **Determine production design weak points, reasons for weak points and potential solutions.**
    - **Production design weak points** are any errors that occur under expected conditions. For example, as expected conditions, everything supporting the job is as it is supposed to be, including material with the correct specifications available at the expected time and operators with the required skill levels performing the operation; a detailed statement of the job is used as a reference, and all inputs to the job, control of the job, and running of the job must fit this detailed job statement. If this statement does not exist, it will have to be created. To find the weak points, all measures are under close observation, noting everything of

importance in production, including: exactly how long each step in the production takes; the likelihood of material being used improperly; and the likelihood of out of specification product being created.

- **Reasons for weak points** are the possible causes for the errors. For example, labor with less than the required skill is used to determine the reusability of a part from the engine to be overhauled may reject a good part or accept a bad one because the labor's skill or training is too low.

- **Potential solutions** are the possible solutions to eliminate the cause. For example,

  - **Use a step improvement approach**, which is to use a very different approach than is presently being used. For example, designing a new product in a way that the manufacturing process will be easier, or that will allow the use of more machinery. This solution is desirable in manufacturing but associated with a high product development cost.

  - **Re-design**

    - The processes to simplify the work, do less work, or wait for less time, by splitting, combining and merging. For example, waiting could be eliminated by changing the operation sequence or production schedule; the distances of a tool movement could be reduced by changing the operation sequence or combining the tasks.

    - The layout to reduce loss, for example, unnecessary travel distance between two machines. Another example is that if a hot gun is used, the operation should always be kept away from a cold environment; e.g. never near doors that may be opened in the winter time.

    - The information system to add extra data, such as information related to loss, cause and solution.

  - **Redefine**

- The process to reduce the overall cost of some operations. For example, since labor intensive operations always have losses caused by the operator, change the operation in a way that slightly increases the time, but reduces the chance of damaging the part.

- The specifications where possible, for example increase the allowance of a hole to allow a bolt to be installed more easily.

- The specification to accept more used parts by carefully considering the maximum wear of used parts that will not hurt the product being rebuilt.

- **Add plan** to consider savings not normally considered, such as energy saving, when defining the operation.

  - **Assist with machine, tool and fixture** to improve the consistency of quantity, quality and time. Machine assistance can add speed and accuracy and reduce "out of specification parts". For example, a fixed caliper is used to make a common measurement rather than requiring the operator's skill and extra time to use an adjustable caliper. The automatic equipment is used as much as possible to perform the load, unload, inspection and locating

- **Estimate cost** is the same as the one in Step 1.

All above determinations can be thought as "Define the process requirement".

5.2.3 Notes for the Determination

One key issue that has to be addressed is that the person to do the above determinations should have significant training and experience with manufacturing operations. The developed procedure must be tested under tightly controlled conditions to determine how well the design actually works. It is an iterative determination process, going between design and test until the best result is found. The testing also uses an extensive video recording, data analysis and discussion with operators to determine what runs smoothly

and what gives problems. The result of this determination is used as the production baseline of measurement for the next step: Step 3.

5.3 Step3: Attain and Maintain the Defined Productivity

After skilled labor is chosen and the most suitable specifications are defined, it is necessary to know how to attain and maintain the defined productivity, which is identified as the aim of Step 3.

Step 3 is supported by four sub-steps: 1) Determine the productivity level and waste; 2) Locate the cause; 3) Find a short-term solution and 4) Find a long-term solution, which are briefly described as follows. The details refer to Chapter VI: Production Flow and Measurement, Chapter VII: Matrix of Loss-Cause-Solution (MLCS), Chapter IX: Costing of Loss and Solution (CLS) and Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

5.3.1 Sub-Step1: Determine the Productivity Level and Waste

In order to improve the productivity that is defined as the "Inverse of cost" in this thesis (Strong, 2003) [44], it is necessary to understand the current productivity level to see whether any **waste** exists.

5.3.1.1 Definition of Waste

From the ecology point of view, everything on the earth has a purpose and no waste exists. Therefore the term "Waste" is a relative concept since waste for one person may not be waste for another. For example, recycled paper is a waste for most industries, but not for the recycling industry since it is the source of its revenues. Generally speaking, waste is any unwanted or undesired material left over after completing an activity such as the transformation of raw materials to semi-finished or finished products. In this thesis, "**Waste**" is defined as "**Any unplanned loss in terms of quantity, quality and time in manufacturing**". The main point in this definition is that the waste is measured against the "Planned" quantity, quality, time and cost. For example, an unplanned idle is a waste, but is not a waste if the idle is planned. Based on this definition, this "Waste" is also referred to as "Pure waste" in some literature.

5.3.1.2 Description of Sub-Step 1

The aim of sub-step 1 is to determine the productivity level with waste in actual production, which includes: 1) Analyze production flow, 2) Determine factors to measure, 3) Identify waste and 4) Estimate cost.

- **Analyze production flow** is the same as the one in Step 1.
- **Determine factors to measure** is the same as the one in Step 1. The tools used to collect the information include interviews with the foreman and operators and independent observation of the operation, and obtaining information from reliable production information system.
- **Identify waste** is to identify the waste roughly in this sub step. For example, **excessive availability, excessive capability and unplanned busy are waste**.
    - **Excessive availability** means the quantity of resources is greater than planned, such as two workers doing a job that actually requires only one worker and causes over payment.
    - **Excessive capability** means the capability of resources is greater than planned, such as a skilled worker is doing a low skilled job and causes an over paid wage.
    - **Unplanned busy** means the time spent is for unnecessary activity, such as doing an inspection twice.
- **Estimate cost** is the same as the one in Step 1 but focusing on the significance of waste.

A detailed "step by step" approach to implement the above sub-step refers to Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

5.3.2 Sub-Step 2: Locate Cause of Waste

Once the waste is roughly identified in the sub-step 1, the cause of waste has to be located, which is defined as the aim of sub-step 2.

5.3.2.1 Definition of Cause

The **cause** of waste is defined in this thesis as **"Any issue to create waste"**. For example, an unskilled worker causes a higher reject rate; the parts received with inconsistent quality causes a longer operation time; a slightly incorrect shape of fixture may cause part damage.

5.3.2.2 Description of Sub-Step 2

In order to provide an exact direction to locate the related causes of waste, a detailed investigation is required, which includes: 1) Analyze production flow and 2) Locate cause of waste.

- **Analyze production flow** is the same as the analysis in Step 1 with the major focus on the cause of waste. For example, for a particular waste such as a waiting time for a part coming to a drilling operation, a specific production flow (A kind of inserted mapping chart to show the detailed linkages between this drilling operation and other operations) is created to show the causes from up stream, which may reveal a labor shortage in the upstream operation resulting in an inability to deliver the required part on time.

- **Locate the cause of waste** is to map waste to the related cause, which sometimes requires a great detailed investigation and data analysis. For example, an inconsistent quantity of the parts received between batches causes extra time to handle the different batch sizes since the resources structured for one batch may not easily handle a significantly large or smaller batch size, and cause an increase in loading and unloading time; lack of a required part causes the operator to wait for the part coming instead of working on the part; a part received with a missing hole causes a reject; A higher fuel price causes a higher material cost. The details refer to Chapter VII: Matrix of Loss-Cause-Solution (MLCS).

5.3.3 Sub-Step 3: Find a Short-Term Solution

Once the low productivity is found and the related cause is located, if the low productivity relates to quality or delivery to the customer, a short term solution must be

found quickly to keep the customer happy. That is defined as the aim of sub-step 3 and includes: 1) Find possible solutions and 2) Costing of solution.

- **Find possible solution** is to obtain a short-term solution to restore as soon as possible, aspects of productivity that satisfy the customer in terms of Quantity, Quality and Time. For example, adding more inspectors at the blocked inspection station to speed up the inspection operation to decrease the level of jam; repair or rework on the defects as soon as possible. The way to find the solution includes an interview with foreman, supervisor, manager, expert; data analysis and simulation. The details refer to Chapter VII: Matrix of Loss-Cause-Solution (MLCS).

- **Estimate cost** is to obtain the cost for assessing whether the solution should be implemented. In the case of a short-term solution, this evaluation can be ignored since the satisfaction of the customer is the highest priority.

A detailed "step by step" approach to implement this sub-step refers to Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

5.3.4 Sub-Step4: Find a Long-Term Solution

Once customer satisfaction has been restored, how to find a long-term solution to maintain the productivity level as long as possible becomes the next task. That is defined as the aim of sub-step4 and includes: 1) Find possible solutions and 2) Costing of solution.

- **Find possible solution** is to obtain a long-term solution to maintain the productivity level as long as possible. For example, when determining the reusability of a part core, a less skilled worker may sort a good part as a bad part, or vice versa. This causes the purchasing of the extra part if a good part is sorted as a bad one or the creation of a defective product if a bad part is sorted as a good one. The "Less skill level" is identified as a root cause in this case, and more training is required as a long-term solution. The way to find this type of solution is the same as in ones in sub-step3. For details refer to Chapter VII: Matrix of Loss-Cause-Solution (MLCS).

- **Estimate cost** is to get the cost for assessing whether the solution should be implemented. In some cases, "Leave the loss as is" may be the best solution if the cost of implementing the solution is too significant. The factors to measure for costing are basically the same as the ones in sub-step1. For details refer to Chapter IX: Costing of Loss and Solution (CLS).

A detailed "step by step" approach to implement this sub-step refers to Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

The **implementation of the solutions** is not a focus of this thesis.

5.4 Flexible Use of 3SP

3SP has three independent steps. As a summary, Step 1 concerns the general structure of the activity and determines which manufacturing method is the most suitable one; Step 2 organizes the activity to make it as productivity as possible and uses this productivity as a benchmark to measure the production; Step 3 looks at the indicators to see whether the activity runs as expected, and if not, finds short-term and long-term solutions to attain and maintain the productivity level. These steps could be used in several different ways. For example, if the issue is to determine which production method is the most suitable way to produce the required items, Step 1, 2 and 3 must be done one by one; If skilled labor is already used, only Step 2 and 3 should be done; If skilled labor is in place and the most suitable specification are already reached, only sub-step 3 (Maintain productivity) in Step 3 should be done.

Conclusions of Chapter:

- **3SP** (Three-Step Procedure) provides a standard procedure to determine whether skilled labor should be used and how to attain and maintain high productivity with skilled labor.

- **3SP** is basically a qualitative procedure to guide the user on how to proceed when the best use of skilled labor is required.

6 Chapter VI: Production Flow and Measurement

As mentioned in chapter I, the procedure for best use of skilled labor is supported by a series of tasks and knowledge. One of these tasks is to build "Production Flow and Measurement", as shown in Figure 6.1 and discussed as follows.

Production Flow and Measurements (PFM), CWS 1							
Production Flow (PF), PFM 1				Measurement (M), PFM 2			
Static Information	PF 1	Dynamic Information	PF 2	What to Measure (WM)	M 1	How to Measure (HM)	M 2
Descriptive Info (Aim, task, throughput, scrap, delay and cost)		Interactive Info (Information flow, material flow and their linkages)		Cost Drivers	WM 1	Time Aspect	HM 1
				Situations to Consider	WM 2	Detail Aspect	HM 2
				Factors to Measure	WM 3	Combination of Aspects	HM 3

Figure 6.1 Production Flow and Measurement (PFM), CWS 1

6.1 Production Flow

In order to understand how production is performed, a flow chart is created to describe information flow and material flow for all activities involved to produce the required item, including the administrative activity.

- **Information flow** includes static information and dynamic information.
    - Static information is descriptive information about production, such as the aim, task, capability, production level, material, penalty policy and unit cost.
    - Dynamic information is interactive information between upstream and downstream to show how the involved activities interact with each other to produce the required item. For example, value added or lost, throughput, scrap and delay.
- **Material flow** shows where the material or part comes from and goes to.

The following flowchart, Figure 6.2, is an example to present how the actual process "Grind and Lap Valves" is done in Aero-Recip (Canada) Ltd, which is one of processes to rebuild the cylinder in the P&W R985 engine. The ring on the valve seat in the cylinder is a soft metal part and needs to be replaced if it is worn and out of specification. When a new ring is installed, it must seal with the valve without gas leaking. Otherwise

significant engine power will be lost, and that is why this process is performed. The planned operation time is also shown in this figure.

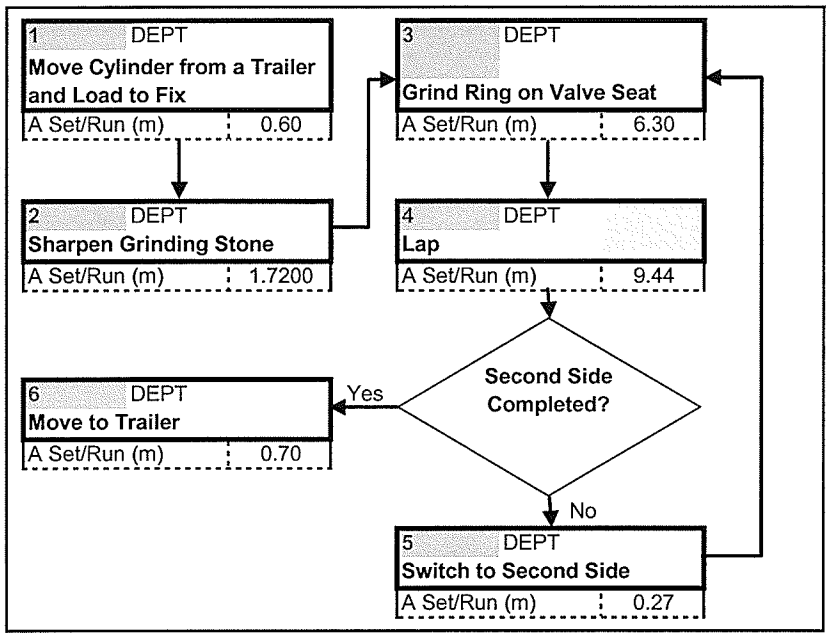


Figure 6.2 Grind and Lap Valves (Cylinder, P&W R985)

In the figure, operator moves a cylinder in which new rings have been installed, from a trailer and loads and secures it on a fixture. He sharpens the sand stone used for grinding to the correct angle if necessary. He grinds the area on the ring where the value will touch (called "Contact area"), checks the result several times until enough material is removed, and then cleans the grinding area with a cloth.

Next, he does a "fine" operation (called "Lapping") to smooth the "contact area" to make sure no air will leak through this area when the valve seals with the ring. The way to do this is: He takes the valve, which is specifically used for the valve seat being lapped, from a case and puts the lapping compound on the contact area on the valve. He takes a pole with a suction cup on the bottom (lapping tool) and mounts it on the flat side of the value seat, and puts the valve on the ring at the valve seat 1, then he starts lapping by rotating the pole. After rotating a while, he cleans the contact area and visually checks the smoothness. If the lapping is not completed, he repeats these pasting, rotating, cleaning and checking steps until the smoothness level, which gives a good seal level, is reached. Then he turns the cylinder to the second side that is valve seat 2 and repeats the above

operations done for valve seat 1. Once both sides are completed, the operator removes the bolts, takes the cylinder off the fixture, and places it on the trailer.

To create a correct flowchart, it is crucial to use a knowledgeable person, obtain management approval and get all involved parties to agree to the flowchart. The tools used in creating the flowchart include observation, video, interviews, questionnaire, process analysis and data analysis.

6.2 Measurement

In manufacturing, different people usually use different ways to measure the same issue and can obtain different conclusions. To reduce this subjectivity, some standard measurement methods in terms of "What and how to Measure" are developed in the thesis and discussed under the topics of "Cost Driver", "Situations to Consider", "What to Measure" and "How to Measure".

6.2.1 Cost Driver

The term "Cost driver" is widely used in the thesis with a specific meaning as defined in this section.

All types of measurement in this thesis will ultimately be shown by the "Dollar" value, which is the cost determined by the "Cost Driver". As described before, many cost drivers are presented in publications.

In this thesis, the **cost drivers** are defined as "Input Price, Quantity, Quality and Time" (PQQT) since they are independent contributors to the cost, as shown in Figure 6.3.

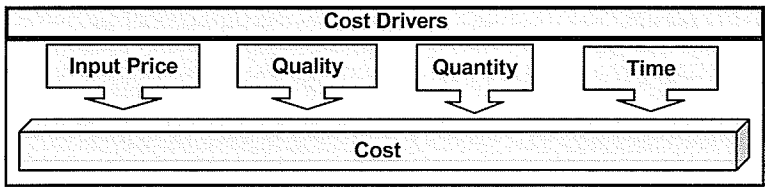


Figure 6.3 Cost Drivers (Input Price, Quantity, Quality and Time)

- **Input price** reflects the price aspect in Input. For example, a high fuel price.

- **Quantity** reflects how many resources and how much effort are used to perform the activity. For example, 10 parts are required; $20m^2$ are required for WIP storage.

- **Quality** reflects how good the resources are and how well the efforts are performed. For example, two damaged parts are received and a part is scrapped after inaccurate cutting.

- **Time** reflects the moment and duration to perform the job. For example, 1 minute for setup and 5 minutes for drilling.

6.2.2 Situations to Consider

When measuring productivity, three questions are of major concern: 1) What is the "Baseline" for measuring productivity? 2) What is the current productivity level? 3) What are the causes and solutions to low productivity?

- **Baseline** is the benchmark to reflect how well a production process can do, and is called "The most suitable specification for using skilled labor". When determining the baseline, the production is run as smoothly as possible under the defined conditions. For example, the material is always available with required specifications; the machine and fixture are always maintained to the specifications; and the operator is always well trained. For the method to determine the baseline refer to Step 2 in 3SP.

- **Current productivity level** is the existing productivity level. The space between the existing productivity and baseline is the opportunity for improvement. For example, the existing cutting operation needs 15 minutes, while the baseline shows 10 minutes. 5 minutes is the difference between the existing productivity and baseline, and the opportunity for improvement. The details refer to Sub-Step 1 of Step 3 in 3SP.

- **Cause and solution** are the cause of loss and solution to reduce the loss. For example, a longer assembly time can be caused by unavailable parts when required, which can be solved by keeping enough items in stock. The details refer to Sub-Step 2, 3 and 4 of Step 3 in 3SP.

6.2.3 What to Measure

"What to measure" means "What factor to measure", which reflects the productivity and could "Allow costing", while keeping within a "Reasonable cost" for costing.

- **Allow costing** means that the factor can be used for estimating cost, either for a complete activity or a portion of the activity. The factor, at the top level, will reflect the aspects of **Extra input cost** (e.g. high fuel price), **Quantity** (e.g. number of use of fixture, square feet of storage used), **Quality** (e.g. rate of scrap creation) and **Time** (e.g. time spent for setup). Some possible factors are material, operators, machines, fixtures, space, contractor and payment for penalty.

- **Reasonable cost for costing** means the cost for costing should be acceptable, which depends on what factor to measure and how to measure. If the cost of measuring is high, the factor to measure should be changed. For example, measure the different factors simultaneously; measure as few factors as possible; use a good educated guess to obtain a start point for measuring; use automatic detector.

Factor measurement information can be obtained from the "Production statement", "Accounting book" or "Actual measure". These factors can be modified to fit any specific case, as shown as follows by the headings of "for Step 2", "for Step 3", "Activity Elements" and "Cost Drivers".

- **For Step 2 (Define the most suitable process for using skilled labor):**
  - **Input related** (Information is from accounting book):
    - **Material:** Quantity and unit cost.
    - **Labor:** Number and unit cost (including wages, salary, fringe benefits and support cost).
    - **Machine** (e.g. Tool/Fixture/Computer System)**:** Quantity, unit cost and depreciation period including "Capital cost (including hardware cost)" and "Maintenance cost (including software cost)".

- **Space:** Size and unit cost (including deposit, renting and lease period).
- **Contract:** Quantity and unit cost.
- **Money tied to product:** Interest paid for the stored material.
- **Energy cost:** Amount and unit cost (including electricity, water and compressed air).

- **Control related** (Information is from accounting book):
  - **Penalty:** Payment for dissatisfaction of the customer in terms of quantity, quality and time. The penalty rates are usually pre-set.
  - **Organizing:** Cost for scheduling, meeting, etc.
- **Doing related** (Information is from accounting book and plan): Time for the planned Doing.
- **Output related** (Information is from test measure): Quantity and cost of throughputs

- **For Step 3 (Attain and maintain the defined productivity):** The costs in this step are beyond Step 2 and based on actual production measurement.
  - **Input related** (Information is from accounting book):
    - **Material:** Quantity and unit cost related to loss (e.g. "out of specification" material).
    - **Labor:** Number and unit cost related to loss (e.g. over skilled labor).
    - **Machine** (Including Tool/Fixture/Computer System)**:** Quantity and unit cost related to loss (e.g. over capability machine).
    - **Space:** Size and unit cost related to loss (e.g. oversize space).

- **Control related** (Information is from accounting book):
  - **Penalty:** Payment for the penalty for customer dissatisfaction (e.g. late delivery).
  - **Organizing:** Cost related to loss created in scheduling, meeting, etc (e.g. duplicated planning).
- **Doing related** (Information is from actual measure):
  - **Unplanned busy:** Time for unplanned Doing (e.g. longer time for changing tool).
  - **Idle:** Time for waiting instead of working on something.
- **Output related** (Information is from actual measure):
  - **Quantity and unit cost related to loss** (e.g. excessive throughput).

6.2.4 How to Measure

Once the factors to measure are determined in the last section, which are from "Production Statement", "Accounting Book" or "Actual Measure", how to measure them becomes a question. "How to measure" means "Aspects to measure", which are considered as **Time** and **Detail** in the thesis since they are the common aspects to be viewed in the production, which are associated with very different costs of measurement.

6.2.4.1 Time Aspect

"Time" means the **moment** and **duration** to measure.

- **Moment** means **when to start** measure, which could be **scheduled measure** and **random measure**.
  - **Scheduled measure** is a planned measuring, which is used for a **routine check** such as a daily check of whether the work place is cleaned.

- **Random measure** is an unplanned measuring, which is used for a **special check** such as a one-time check of whether the worker sleeps during the midnight shift.

- **Duration** means how **long the measure lasts**, which could be **snapshot measure** and **continuous measure**.
  - **Snapshot measure** is a one-time measuring, which is used for understanding how the activity is performed **at a specific moment** such as the final step in the assembly line.
  - **Continuous measure** is a non-stop measuring, which is used for understanding how the activity is performed **for a specific period** such as a month, a quarter or a year.

6.2.4.2 Detail Aspect

"Detail" means **overall** and **detailed** level of information to measure.

- **Overall measure** means the rough measure, which is used to understand how the activity is performed **in general**. For example, to understand how the company uses its resources (e.g. material, labor and space), an overall measure at the company level is used.

- **Detail measure** means the detailed measure, which is used for understanding how the activity is **exactly** performed **in detail**. For example, to investigate the cause of "Longer process time", the detailed measure at the operation level is used and the result shows that unskilled labor is used and takes more time to complete the job.

6.2.4.3 Combination of Aspects

In reality, the aspects of time and detail are usually measured simultaneously. Based on this, eight combinations can be obtained and measured as shown in Figure 6.4.

In the figure, the X-axis presents the **moment to measure** (i.e. "Scheduled vs. Random"), the Y-axis presents the **detail to measure** (i.e. "Overview vs. Detailed") and the Z-axis presents the **duration to measure** (i.e. "Snapshot vs. Continuous").

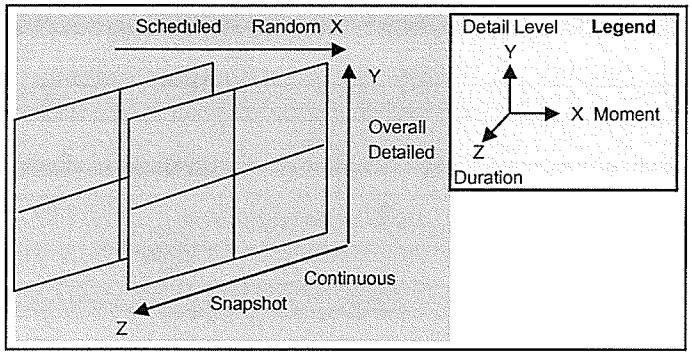


Figure 6.4 Aspects to Measure

The 8 combinations are: 1) Scheduled snapshot overall measure; 2) Scheduled snapshot detailed measure; 3) Scheduled continuous overall measure; 4) Scheduled continuous detailed measure; 5) Random snapshot overall measure; 6) Random snapshot detailed measure; 7) Random continuous overall measure; 8) Random continuous detailed measure. They are explained as follows by using the "Scheduled" measure since the "Random" measure has 4 similar explanations.

- **Scheduled snapshot overall measure** provides an overview picture on how the activity is performed at a scheduled moment like the month end. For example, the wrong parts were produced last month; scrap was created last week. This measure has a low cost since it is a one-time measure.

- **Scheduled snapshot detailed measure** reveals a detailed picture on whether the activity is done as required at a scheduled moment. For example, the parts were missed in inventory in December. This measure has a medium cost since it requires more resources to perform the measurement.

- **Scheduled continuous overall measure** tells an overview picture on how the activity is performed during a scheduled period like a winter. For example, the excess materials are used each month in the past five years; the daily average number of non-conformance parts is produced in the last year. This measure has a high cost since it requires more time and resources to perform the measurement.

- **Scheduled continuous detailed measure** tells a detailed picture on whether the activity is performed as required during a scheduled time frame. Some examples are listed as follows:

  - Variable operation time over the last six months that may reveal a poor plan or training; Variable quality over the last 12 months that may show a poor fixture issue.

  - Time for correction such as repair and rework, for fitting, for handling unforeseen problems, for unnecessary operations such as double inspections, double requests, over maintenance, unnecessary moving and unnecessary training, and for an expedited operation.

  - Waiting time for each part for a month, to determine the pattern of part timing.

  This measurement has the highest cost since it requires the most effort to perform.

Conclusions of Chapter:

- A **hierarchical category structure** is used to present the actual manufacturing issues for an easy measure and understanding. The categories include the first level of "No waste vs. waste", the second level of "Activity elements (i.e. Input, Control, Doing and Output)" and the third level of "Cost drivers (i.e. Quantity, Quality and Time)".

- The **factors** identified in the chapter are basically the generic information required for assessing effectiveness and efficiency (EE). They could be adjusted to fit the specific situations concerned.

- **Eight measurement combinations** are defined based on the aspects of "Time" and "Detail", which could be ultimately measured by a "**Dollar**" value.

7 Chapter VII: Matrix of Loss-Cause-Solution (MLCS)

When identifying a loss, the assumption is that the production specifications are designed correctly, and are sufficiently tested for the given and assumed production requirements. A loss occurs when one or more of the production requirements are no longer correct. For examples, when a less skilled operator than required is used, more parts than expected may be damaged; or the purchase cost of a material may be higher than planned.

As mentioned in chapter I, the systematic approach for effective and efficient use of skilled labor is supported by a series of tasks and knowledge. One of them is to "Determine Linkages between the Loss-Cause-Solution", which is discussed under four issues in this chapter: 1) Loss, 2) Cause, 3) Solution and 4) Linkage between Loss, Causes and Solutions as shown in Figure 7.1.

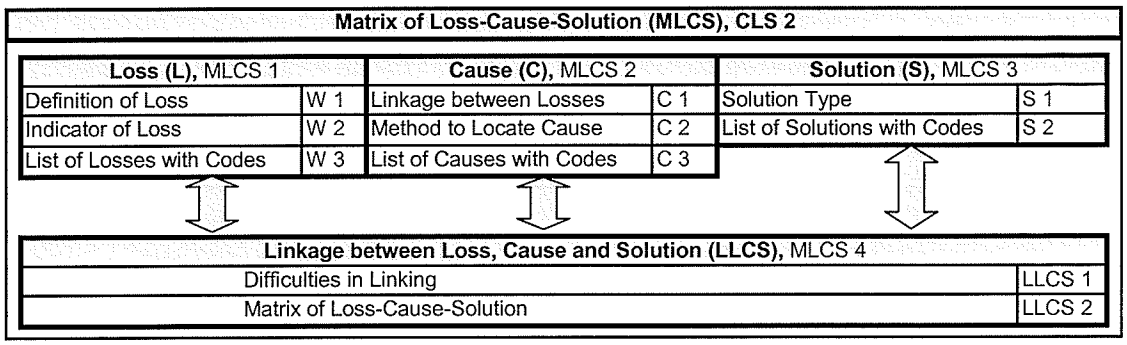


Figure 7.1 Matrix of Loss-Cause-Solution (MLCS), CLS 2

7.1 Loss (L)

The "Loss" in this section is addressed by the topics: "Definition of Loss", "Indicator of Loss", "A List of Losses" and "Code of Loss".

7.1.1 Definition of Loss

A "Loss" can be defined as "The condition of being deprived or bereaved of something or someone" [2]. In this thesis, **loss** is defined as **"Any reduction in a dollar value or extra cost increased"** such as a damaged part and an increasing time in assembling an engine. If the loss is unplanned, it is defined as "Waste" in this thesis.

In reality, a loss usually shows up in many ways and is hard to identify in a systematic way. In order to develop a systematic method to identify loss, a categorization system is required, which is created in this thesis. It consists of "Indicator of Loss", "Activity Element" and "Cost Driver". The "Indicator of Loss" is used to group the losses at a high level, which is discussed in detail in the next section. The "Activity Element" is the basic element to perform a job that is "Input, Control, Doing and Output" (refer to Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure for details). The "Cost driver" is the basic driver to generate the cost that is "Quantity, Quality and Time" (refer to Chapter VI: Production Flow and Measurement for details). The reason for using "Activity Element" and "Cost Driver" is to categorize the loss for costing.

7.1.2 Indicator of Loss

Through investigation and research, the "Indicator of loss" is summarized in this thesis as "Extra cost, Excessive Availability, Excessive Capability, Penalty, Unplanned Busy, Idle, Over Throughput, Disappearance, Reparable Damage, Un-reparable Damage and Obsolescence".

- **Extra cost** indicates the cost of Input is more than planned. For example, a high fuel cost is not expected in the original plan and causes more Input cost.

- **Excessive availability** indicates the quantity of Input is more than planned. For example, two workers are assigned to do a job that only requires one worker and causes more labor cost.

- **Excessive capability** indicates the capability of Input is more than planned. For example, the operator's skill level is higher than required and causes a higher wage.

- **Penalty** indicates the payment for customer dissatisfaction in terms of "Quantity, Quality and Time", for example, the payment for poor quality and more late delivery parts than normal.

- **Unplanned busy** indicates the time spent for unnecessary activities, such as duplicated inspections and un-required rework.

- **Idle** indicates the manufacturing resources are waiting for "Output" from upstream more often or longer than planned. For example, an operator waits for a part arriving later than planned.

- **Over throughput** indicates the quantity of output is more than planned. For example, two more expensive aero engines are produced than planned, which may mean extra cost for producing and storing those two engines.

- **Disappearance** indicates the output was lost after Doing. For example, a plastic part may disappear after a chemical cleaning process since it dissolved in the solvent.

- **Reparable damage** indicates the output is "Out of Specification" but repairable. For example, a part is broken when it is pulled off the engine core but it is reparable.

- **Un-reparable damage** indicates the output is permanently "Out of Specification" and un-repairable. For example, the part property is permanently changed after over heating.

- **Obsolescence** indicates the output is no longer used as time elapses or the style is changed and degrades the value.

7.1.3 A List of Losses

20 Losses are listed in Figure 7.2 as a starting point for a manufacturing company to identify its losses.

They are explained as follows under the headings of "Activity Element", "Cost Driver" and "Indicator of Loss". This list can be modified to accommodate some specific situations in a company, for example, a specific loss can be added to the list or dropped from the list.

The sources to obtain the losses are "Production Statement", "Accounting Book" and "Actual Measure".

- **Input**

- **Input price**
  - **Extra price (indicator):** Extra input cost. For example, extra fuel cost.
- **Quantity**
  - **Excessive availability (indicator):** Extra materials, parts, assemblies, operators, machines, fixtures, spaces and heating are available. For example, 100 aero engines are available while only 80 engines are required, which causes an extra cost for purchasing and storing them.
- **Quality**
  - **Excessive capability (indicator):** Over capable materials; Over skilled labors; Over capable machines. For example, an expensive NC machine is used to do a "Cutting" operation that can be done by a simple machine.

- **Control**
  - **Quantity, Quality or Time**
    - **Penalty (indicator):** Penalty payment for poor quality product or late delivery.

- **Doing**
  - **Time**
    - **Unplanned busy (indicator):** Too many correction operations (e.g. repair and rework); too many fitting, adjusting and measure operations; duplicated operations (e.g. requesting the same parts twice); over inspection or maintenance; too many rush operations (e.g. expedite inspection).
    - **Idle (indicator):** Waiting without doing anything. For example, the operator waits for a late arriving part instead of working on the part.

- **Output**

- **Quantity**
  - **Over throughput (indicator):** Extra items produced; Wrong items produced.
  - **Disappearance (indicator):** Material is excessively consumed in a mill operation; Part is destroyed during the chemical cleaning process.
- **Quality**
  - **Repairable damage (indicator):** Material, fixture or tool is damaged but repairable.
  - **Un-repairable damage (indicator):** Material, fixture or tool is damaged beyond repair.
  - **Obsolescence (indicator):** Out of style.

Output, Doing, Control, Input, Time, Quality, Quantity, Input price, Penalty, Excsv. capability, Excsv. availability, Extra price, Disappear, Over throughput, Idle, Un-necessary busy, Obsolescence, Un-repairable damage, Repairable damage

Activity Element				Cost Driver				Loss Indicator											5th/6th Digit	Code	ID	Examples
1st Digit				2nd Digit				3rd and 4th Digits														
1	2	3	4	1	2	3	4	01	02	03	04	05	06	07	08	09	10	11				
1				1				01											01	110101	01	Extra input cost (e.g. extra fuel cost).
1					2				02										01	120201	02	Excessive material, part, operator, machine, fixture or space available.
1						3				03									01	130301	03	Over skill labor, over capability machines etc.
	2					3					04								01	230401	04	Penalty payment for poor quality product or late delivery.
		3					4					05							01	340501	05	Correction such as repair and rework.
		3					4					05							02	340502	06	Over fitting, adjusting and measure.
		3					4					05							03	340503	07	Duplicated operations (e.g. duplicated lapping).
		3					4					05							04	340504	08	Over inspect and maintenance (e.g. maintenaint to higher level than required).
		3					4					05							05	340505	09	Unplanned rush operation (e.g. expedite weldding).
		3					4					05							06	340506	10	Handle unforeseen production problems.
		3					4						06						01	340601	11	Wait (e.g. operator is waiting for part coming late).
			4		2									07					01	420701	12	More parts produced than planned.
			4		2									07					02	420702	13	Wrong item produced.
			4		2										08				01	420801	14	Inputs consumed excessively.
			4		2										08				02	420802	15	Parts, machines, fixtures or tools are destroyed.
			4			3										09			01	430901	16	Part, machine, fixture or tool is damaged, but repairable.
			4			3										09			02	430902	17	Rejected or returned.
			4			3										09			03	430903	18	Off specs (e.g. oil canning).
			4			3											10		01	431001	19	Part, machine, fixture or tool is damaged and un-repairable (e.g. property changed).
			4			3												11	01	431101	20	Out of style.

Figure 7.2 A List of Losses and Their Codes

The losses in the above table are also coded for the purpose of quick reference and correct mapping. The coding system is discussed in the next section.

7.1.4 Code of Loss

A six-digit code is also created in Figure 7.2 to allow an easy link between loss and cause.

- The 1st digit represents the **activity elements** (i.e. Input, Control, Doing and Output) and is coded as 1, 2, 3 or 4.
- The 2nd digit represents the **cost drivers** (i.e. Input price, Quantity, Quality and Time) and is coded as 1, 2, 3 or 4.
- The 3rd and 4th digits represent the **loss indicators** and are coded as 01, 02 … or 11.
- The 5th and 6th digits represent the **detailed loss** and are coded as 01, 02, …

For example, the code "430902" represents the loss "Rejected or returned (Repairable)" which is under "Output" (1st digit = 4, "430902"), "Quality" (2nd digit = 3, "430902"), loss indicator "Repairable damaged" (3rd and 4th digits = 09, "420902") and second loss in this category (5th and 6th digits = 02, "430902").

7.2 Cause (C)

A **cause** is defined in this thesis as **"Any issue that can create a loss in any part of a production process"**. For example, in the case where an unskilled worker causes a high reject rate; the part received with inconsistent quality causes a longer operation time; or a slightly incorrect shape of a fixture may cause the part to be damaged. In order to reduce the loss, the related causes must be located, which are addressed under the topics: "Linkage between Losses", "Method to Locate Cause", "A List of Causes" and "Code of Cause".

7.2.1 Linkage between Losses

Usually a loss upstream causes a loss downstream. This loss travels with the material or parts as they move from operation to operation. The parts could be changed from the planned cost, quality, quantity or time. Some of these changes could add cost to a part that is transferred to the following operations. Other changes, such as quality, could also create more problems in the following operations. The concept is illustrated by a process that has 5 operations as shown in Figure 7.3. Note that although equations are used here, they are only used for illustration. They cannot be used to give a solid mathematical output unless many more variables are considered.

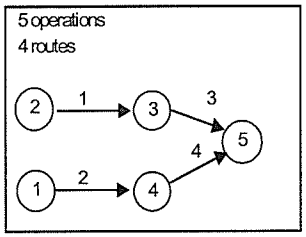


Figure 7.3 A Process with 5 Operations

Each operation is identified by a numbered cycle. The travel between operations is presented by a numbered arrow and a five digital array. A "0" value in the array means "No loss", "1" means "Full loss". The value between 0 and 1 means a portion of loss. For example, the array [0, 1, 0, 1, 0] means that full loss occurs in operation 2 and 4, and no loss occurs in operation 1, 3 and 5. The array [0, 0.1, 0, 0.2, 0] means that the losses in this process are contributed by operation 2 at a 10% loss and by operation 4 at a 20% loss. This concept can be formulized as an equation (6-1).

$$L_n = \sum_{i=1}^{n} \alpha_i L_i \qquad n = 1, 2, 3, 4 \ldots \qquad (6\text{-}1)$$

Where:

$L > 0$ for some losses, $L = 0$ for no loss.

L_n = Loss after the activity of concern. $n = 1, 2, 3, 4 \ldots$

L_i = Loss from the ith activity, $i = 1, 2 \ldots, n$ (All upstream activities before the activity of concern).

α_i = Contribution factor of loss L_i to the loss L_n. $\alpha_i = 0$ for no contribution from L_i to L_n, $\alpha_i \neq 0$ for a contribution from L_i to L_n.

Therefore the equation (6-1) is interpreted as: "**Loss after the ith activity is the sum of the losses from all previous and current activities adjusted by the contribution factors**". To use a different phrase, all losses upstream produce losses downstream and may be augmented by combining with other losses with a final outstanding loss.

The loss transferred between activities is unified as a "Dollar" value no matter the original physical loss type such as out of spec material, damaged material or over-skilled labor.

When equation (6-1) is applied in SAS (Standard Activity Structure) (refer to Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure for the details), the linkages between losses are shown in Figure 7.4.

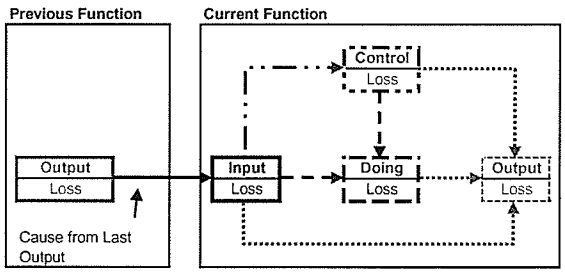


Figure 7.4 Linkages between Losses in SAS

- The loss **after "Input"** is the loss from "Output" of the previous activity (Black arrowed line) and the loss created in "Input", such as an expensive part received.

- The loss **after "Control"** is the loss from "Input" (**Blue** arrowed dot line) and the loss created in "Control", such as unnecessary meetings.

- The loss **after "Doing"** is the loss from "Input" (**Brown** arrowed dot line), "Control" (**Brown** arrowed line) and the loss created in "Doing", such as a longer time spent on the process than necessary.

- The loss **after "Output"** is the loss from "Input" (**Red** arrowed dot line), "Control" (**Red** arrowed dot line), "Doing" (**Red** arrowed dot line) and the loss created in "Output", such as a damaged part. It is the total value lost after performing the entire activity, as shown in Figure 7.5.

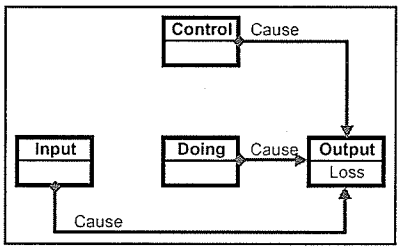


Figure 7.5 Causes of Loss in Output are from "Input, Control and Doing"

Therefore, the loss in the upstream end can be thought as the cause of loss in the downstream process. This is the relationship between loss and cause.

7.2.2 Method to Locate Cause

The method to locate the immediate cause and the real or root cause of a problem consists of several techniques that can be combined to support logic and insight. A list of many possible methods including the collection, recording and analysis of information is discussed as follows.

- Use video camera to collect information; Use automatic devices such as scanner, automatic identification and recognition device (radio frequency data terminal, voice headset, light and computer aids and smart card), bar coding system (bar code, bar code reader, bar code printer), optical character recognition (radio frequency tag, magnetic strip, machine vision) and digital cameras to capture the required information.

- Interviews with operator, supervisor and management team to find the problematic spots.

- Inspect for any unusual issue in order to find any problem related to quantity, quality and time issue of producing the parts. For example, check whether the correct actors were used and the required maintenance level kept up to date.

- Analyze data or use simulation to find more information such as the pattern of "Loss over Time".

7.2.3 A List of Causes

When a loss exists, some specification or situation must have changed from that defined and tested in Step 2. As a starting point 26 possible causes are listed in Figure 7.6 and are referenced to "Activity Element" and "Cost Driver".

- **Input:**
    - **Input price:**
        - **High input price.** For example, a high fuel price causes a high input cost.

- **Quantity:**
  - **Large variations in quantity.** For example, the inconsistent quantity of the part received between batches requires extra time for handling the different batch sizes since the resources used for one batch may not efficiently handle another batch and use more time.
  - **No/low availability.** For example, lack of a required part causes the operator to wait for the part instead of work on the part.
  - **A higher fuel cost causes the higher cost of material.** This cause is one of the examples of "Out of Control" by industrial engineering.
- **Quality:**
  - **Wrong design specification.** For example, a tight allowance of a hole, which was originally defined with a loose allowance, may increase the time required to install a bolt.
  - **Wrong workplace layout.** For example, a long distance between two machines, which was not original designed, causes unnecessary movement.
  - **Large variation in quality.** For example, the inconsistent quality of parts received varies between batches and causes extra time to fit, adjust and measure since the way of processing for one quality level may not be suitable for another quality level.
  - **Damaged material received.** For example, a damaged part received causes the extra processes to repair it or obtain another good one.
  - **"Out of specification" material received.** For example, a part received with a missing hole causes the extra process to solve this problem.

- **Too close to specification limit.** For example, the specification of a received part is very close to the limit and causes more time for fitting during assembly.
- **Breakdown of actors.** For example, a broken down machine causes an operator to wait.
- **"Out of specification" actors.** For example, a slightly incorrect shape of fixture may cause damage to a part.
- **Low efficient actors.** For example, a tool that was substituted for a similar but better tool is difficult to use and may cause a longer time.
- **Less capability.** For example, unskilled labor, substituted for skilled labor, may cause damage to the parts when dismantling the engine core, which results in the need to buy extra parts to replace the damaged ones.

  - **Time:**
    - **Large variation in time.** For example, an inconsistent milling time from one part to another part may cause either late delivery or a jam in the next operation.

- **Control:**
  - **Quantity:**
    - **No plan.** For example, no energy saving plan may be the cause for extra gas and fuel consumption.
    - **Missing process.** For example, an inspection process that was originally designed as part of the whole process, was removed, and causes many reworks, since many defects are not checked out until they are caught at the final inspection. This results in many efforts already put into the previous operations that are wasted now.

- **Quality:**
  - **Mixed process route.** For example, two processes sharing the same operation cause one process to wait for another process to be completed.
  - **Poor WIP control.** For example, poor communication between the shop floor and inventory causes a long waiting time for the shop floor to get the requested parts since the worker on the shop floor does not know that the requested parts are already available in the inventory.
  - **Poor information system.** For example, a mistake on the worksheet causes the wrong items to be produced that are not able to be used for the next operation.
  - **Low adjustability in control.** For example, a work order has to be planned two weeks in advance and any change is very difficult once the plan is set, which may cause a late delivery of the required items.
  - **Low pay.** For example, a low wage discourages the worker to do a better job, which indicates a poor management decision in making wage policy. This topic will not be discussed further in the thesis.
  - **Poor setting.** For example, a wrong temperature setting causes a part to be over heated which may change the physical properties of the part.

- **Doing:**
  - **Quantity:**
    - **Missing doing.** For example, a tool preparation operation is designed as a part of the process, but is not performed and causes extra time to collect the required tools to do the job.

- **Less doing.** For example, inadequate maintenance of a machine causes "Out of spec" parts to be produced since the machine's specifications have slightly changed after a long run.

- **Quality:**
  - **Wrong doing.** For example, a wrong force applied by the worker when detaching the part from the engine core may causes damage to the part core.

- **Time:**
  - **Late doing.** For example, a charge-back is requested after the valid time for charging back has expired. This situation causes a needless loss of money.
  - **Early doing.** For example, an early doing leads to an early completion and causes a waiting period for the next operation to take the part away once the WIP buffer is full.

Activity Element			Cost Driver				3rd/4th Digit	Code	ID	Example
1st Digit			2nd Digit							
Input	Control	Doing	Input price	Quantity	Quality	Time				
1	2	3	1	2	3	4				
1			1				01	1101	01	High input price
1				2			01	1201	02	Large variation in quantity (e.g. the quantity of part received varies between batches).
1				2			02	1202	03	No/low availability (e.g. lack of required part).
1					3		01	1301	04	Wrong design specification (e.g a tight allowance of hole).
1					3		02	1302	05	Wrong workplace layout (e.g. long distance between two machines).
1					3		03	1303	06	Large variation in quality (e.g. the quality of parts received varies between batches).
1					3		04	1304	07	Damaged material received (e.g. a damaged part received).
1					3		05	1305	08	"Out of specification" material received (e.g. a part with missing hole received).
1					3		06	1306	09	Too close to specification limit (e.g. the specification of received part is very close to up limit).
1					3		07	1307	10	Breakdown of actors (e.g. a shutdown machine).
1					3		08	1308	11	"Out of specification" actors (e.g. a slightly incorrect shape of fixture).
1					3		09	1309	12	Low efficient actors (e.g. a substituted tool is difficult to use).
1					3		10	1310	13	Less capability (e.g. an unskilled labor).
1						4	01	1401	14	Large variation in time (e.g. an inconsistent milling time from one part to another part).
	2			2			01	2201	15	No plan (e.g. no energy saving plan).
	2			2			02	2202	16	Missing process (e.g. an inspection process is not designed as a part of process in the first place).
	2				3		01	2301	17	Mixed process route (e.g. two processes share the same operation).
	2				3		02	2302	18	Poor WIP control (e.g. a poor communication between shop floor and inventory).
	2				3		03	2303	19	Poor information system (e.g. a mistake on the worksheet).
	2				3		04	2304	20	Low adjustability in control (e.g. work order was planned 2 weeks in advance and is difficulty to change).
	2				3		05	2305	21	Low payment (e.g. a low wage discourages the worker to do a better job).
	2				3		06	2306	22	Poor setting (e.g. a wrong setting of temperature).
		3		2			01	3201	23	Missing doing (e.g. a preparation operation is designed as a part of process, but is not performed).
		3		2			02	3202	24	Less doing (e.g. an inadequate maintenance of machine).
		3			3		01	3301	25	Wrong doing (e.g. a wrong force applied by the worker when detaching the part from engine core).
		3				4	01	3401	26	Late / Early doing (e.g. a charge-back is requested after the valid time for charging back has expired).

Figure 7.6 A List of Causes and Their Codes

7.2.4 Code of Cause

A four-digit code is also created in Figure 7.6 for tracking loss to the cause, and to the solution.

- The 1st digit represents the **activity elements** (i.e. Input, Control and Doing) and is coded as 1, 2 or 3.
- The 2nd digit represents the **cost drivers** (i.e. Input price, Quantity, Quality and Time) and is coded as 1, 2, 3 or 4.
- The 3rd and 4th digits represent the **possible causes** identified and are coded as 01, 02, ...

For example, the code "3201" represents the cause "Missing doing" which is under "Doing" (1st digit = 3, "3201"), "Quantity" (2nd digit = 2, "3201") and the first cause in this category (3rd and 4th digits = 01, "3201").

7.3 Solution (S)

Once a loss is identified and causes are located, the next thing to do is to find the solution. The solution is defined in this thesis as **"Any way to eliminate the causes of loss and reduce loss"** and is addressed in this section under the topics: "Solution Type", "A List of Solutions" and "Code of Solution".

7.3.1 Solution Type

The solutions found in this thesis are grouped into the solution types, i.e. short-term solution and long-term solution.

- The **Short-Term solution** is the solution aimed at restoring the customer confidence as soon as possible by correcting the problems in terms of product quantity, quality and timeliness requested by a customer. For example, rework on the fixture to a greater accuracy to reduce the chance of using the wrong reference location in drilling. This type of solution may not solve the root cause, and a similar loss may occur again in the future. In addition, this solution usually requires an extra cost to

pay for the extra resources needed; however satisfying customer requirements is of greater concern than cost. Short term solutions are listed in the next section.

- The **Long-Term solution** is the solution required to maintain the defined productivity for the long-term. For example, train the low skilled worker, who was incorrectly assigned to the job, to a level that he can perform the job correctly. Achieving a long-term solution can take one of four routes: 1) Get the situation returned to the defined specifications; 2) Go back to Step 2 to redefine the specifications; 3) Go back to Step 1 to reassess whether to use other production resources such as machinery and unskilled labor etc; 4) Leave the situation as is.

  - **Get the situation returned to the defined specifications.** This means to restore the productivity to the level as defined in the original specifications. Some ways to restore the productivity are listed in the next section.

  - **Go back to Step 2 to redefine the specifications.** The actual production situation and the original specifications may not fit each other any more, which results in the need to either restore the production situation or redefine the original specifications. If redefining of the specifications is the choice, the issue is sent back to Step 2 as a package for redefining the specifications including the selection of new materials. For example, the original production specifications may have been changed by the production department and lower skilled labor is used to do a welding job and increases the defects. The company cannot afford to hire skilled labor to do the job because of a significant drop in order volume, so the solution is to send the operation for analysis to Step 2 to redefine the operation specifications to use lower skilled labor along with the addition of a part time inspector to keep the quality at the required level.

  - **Go back to Step 1 to reassess whether to use other production resources such as machinery and unskilled labor etc.** For the case that both above routes do not work, another possible solution is to send the operation for analysis back to Step 1 and reassess whether skilled labor should be used. Maybe other resources,

such as machinery, unskilled labor or contracting out, can be used for the required production.

- **Leave the situation as is.** Finally "Leave the situation as is" may be the best solution if the cost for implementing the solution is significantly higher than the loss. This is a unique example of sending the operation back to Step 2 for analysis.

7.3.2 A List of Solutions

Sixteen solutions are listed in Figure 7.7 as a starting point for a manufacturing company to find solutions, and can be modified to accommodate a specific situation in a company. They are grouped by "Solution Type" and "Activity Element".

- **Short-Term Solution:**
  - **Input:**
    - **Share resources that are not fully used through internal or external use.** For example, assign skilled labor who runs the milling machine to do the loading/unloading for a drilling machine as well; contract out the spare expensive machine; cross use of the space such as for both receiving and shipping.
    - **Use alternatives if effective.** For example, use a little lower level skilled labor to do the job if he can fulfill the task done by skilled labor, but with more inspection.
  - **Control:**
    - **Add more resources at a blocked spot in the process.** For example, add more inspectors at the blocked inspection station to avoid the jam for completing the process on time.
  - **Doing:**

- **Repair or Rework.** For example, once the defect is found, the immediate action is to repair or rework it; rework on the fixture to the original specifications for a correct position to drill.

- **Long-Term Solution** (Here are the examples of restoring the productivity to the level originally defined. These solutions are done by the supporting groups in the company instead of production groups):

  - **Input:**

    - **Reduce the travel distance to** original defined by moving the operations around for less personnel and vehicle travel time.

    - **Use efficient resources**, such as skilled labor or equipment (e.g. Forklift, AGV, machine, fixture or tool), as original defined.

    - **Provide more training and instructions** as originally defined to **do the job.** For example, by providing a complete BOM that was originally available, skilled labor can more accurately determine which used part should be replaced and which one could be reused; by a sign, picture, drawing or video that was originally available, skilled labor can assemble a complex part with fewer mistakes.

    - **Keep reasonable inventory level** as originally defined by

      - Reducing obsolete inventory or excessive materials through "On sale", "Degraded use" and so on.

      - Purchasing more materials when prices drop.

    - **Be sure the capability of resources matches with the job requirement.** For example, skilled labor is used only when absolutely required because of the high wage. For example a dentist should do the job of filling teeth while the technician does the preparation job; a complex machine is set up by a skilled worker, while operated by a semi-skilled worker for his lower wage.

- **Backup resources** as originally defined (e.g. material, machine or labor).

- **Control:**

  - **Control tightly operation on quantity, quality and time** as originally defined for a better, smooth, and simpler production. The following issues are controlled:

    - The availability of resources (e.g. parts, labor and contracting out) required for keeping the job moving.

    - The job schedule in terms of available orders, deliveries and resources.

    - The quality of "Input" (e.g. material and part) to the job, "Output" from the job.

    - The job sequence.

    - The throughput.

  - **Run correct batch size** as originally defined to reduce the unit cost.

  - **Prepare** for the job by using 5S as originally defined, such as periodically pre-arrange, document, learn and clean. For example, the tools, materials, and work locations should always be well defined and organized for the job. All support machines and fixtures should always be well maintained for the expected function.

  - **Balance workflow** by WIP storage as originally defined to slow down or speed up the jobs.

  - **Improve communication** as originally defined by

    - Using automatic devices as originally defined to reduce the errors of data input.

    - Using an automatic paperless system for a quick response.

- Using a reminding mechanism between inventory and shop floor.

- **Doing:**

  - **Eliminate non-value added activities** as originally defined, such as adjusting, measurement, duplication, manual work and bottleneck operation.

Solution Type		Activity Element			3rd/4th Digit	Code	ID	Example
1st Digit		2nd Digit						
Short Term	Long Term	Input	Control	Doing				
1	2	1	2	3				
1		1			01	1101	01	Share resources with other users if possible.
1		1			02	1102	02	Use alternatives if effective.
1			2		01	1201	03	Add more resources at a blocked spots in the process.
1				3	01	1301	04	Rework or Repair.
	2	1			01	2101	05	Reduce the travel distance.
	2	1			02	2102	06	Use efficient resources wherever possible.
	2	1			03	2103	07	Provide more training and instructions for doing the job.
	2	1			04	2104	08	Keep reasonable inventory level.
	2	1			05	2105	09	Match the capability of resources with the job requirement.
	2	1			06	2106	10	Backup resources such as materials, machines and labor.
	2		2		01	2201	11	control tightly the operation on quantity, quality and time.
	2		2		02	2202	12	Run correct batch size whenever possible.
	2		2		03	2203	13	Prepare for doing the job (e.g. S5 strategy).
	2		2		04	2204	14	Balance workflow by WIP storage.
	2		2		05	2205	15	Improve the communication.
	2			3	01	2301	16	Eliminate non-value added activities wherever possible.

Figure 7.7 A List of Solutions and Their Codes

7.3.3 Code of Solution

For easy tracking from the loss, cause to solution, a coding system is created that consists of four-digits in Figure 7.7.

- The 1st digit represents the **solution type** (i.e. Short-term, Long-term solution) and is coded as 1 or 2.

- The 2nd digit represents the **activity element** (i.e. Input, Control and Doing) and coded as 1, 2 or 3.

- The 3rd and 4th digits represent the **possible solutions** and are coded as 01, 02, …

For example, the code "1301" represents the solution "Rework or Repair" which is under "Short-term" (1st digit = 1, "1301"), "Doing" (2nd digit = 3, "1301") and the first solution in this category (3rd and 4th digits = 01, "1301").

Generally speaking, the solutions mentioned in this thesis will reduce the production time, improve the quality of work and items produced, reduce the losses and finally decrease the cost.

In addition, the above solutions are not limited to the reduction of the big loss. In some cases, a simple solution could quickly be put in place with a small investment to achieve the required reduction of loss. In other cases, "Leave as is" may be the best way if the cost of implementing the solution is more expensive than the cost of loss. The details of costing refer to Chapter IX: Costing of Loss and Solution (CLS).

7.4 Linkage between Loss, Cause and Solution

In the course of finding the solutions, the linkages between loss, cause and solution must be known and clearly shown, which is discussed in this section under the topics: "Difficulties in Linking" and "Matrix of Loss-Cause-Solution".

7.4.1 Difficulties in Linking

The usual situation in reality is that the solutions found may not reduce the losses because of the difficulties in the course of mapping loss to cause, and further to solution. They are summarized in this thesis as: "Subjective Matter", "Limited Recognition" and "Multiple Linkages".

- **Subjective matter** addresses the fact that the linking process can be very human oriented. For example, different individuals may conclude that there are different causes for the same loss while only one cause actually exists.

- **Limited recognition** addresses the limited ability of a person to locate the root cause. For example, for the loss "Waiting instead of working on the part", the direct cause is "No part available when required", the indirect cause is "Late replenishment of inventory", the further indirect cause is "Low inventory level" and the further indirect causes can be sought until the root cause is found or may not be able to be found.

- **Multiple linkages** address the situation where the links between the loss, cause and solution are "One to one; One to many; Many to one; or Many to many". For example:

  - Nothing gets through the plant unless expedited (loss) since the customer order exceeds its production capacity (direct cause). The further cause is either too many customer orders are brought into the plant (indirect cause) or the low production capacity (indirect cause).

  - The operators on the shop floor find they have not enough time to follow the production routines, which creates a delay (loss) caused by having to deal with expedited orders (direct cause). Further analysis indicates that expedited orders are caused by a low capability of production (indirect cause).

  - The labor has to wait (loss) for the parts arrival since they are not available when required (direct cause), which is further caused by a late inventory replenishment (indirect cause).

7.4.2 Matrix of Loss-Cause-Solution

In order to clearly show the linkages between losses, causes and solutions, a matrix is used as shown in Figure 7.8 (Simplified version).

		Causes		
ID	Losses	Input Related	Control Related	Doing Related
1	Excessive availability	x	x	x
2	Excessive capability	x	x	x
3	Wrong incentive	x	x	x
4	Un-necessary busy	x	x	x
5	Idle	x	x	x
6	Over throughput	x	x	x
7	Disappear	x	x	x
8	Reparable damaged	x	x	x
9	Un-reparable damaged	x	x	x
10	Obsolete	x	x	x
	Solutions	Input Related	Control Related	Doing Related
1	Input Related	x	x	x
2	Control Related	x	x	x
3	Doing Related	x	x	x

Figure 7.8 Matrix of Loss-Cause-Solution (Simplified)

The above figure consists of two parts: "Loss-Cause" and "Solution-Cause". The losses are all possible ones grouped by the loss indicators; the causes and solutions are all possible ones grouped by the activity elements. The linkage between them is indicated

by the letter "x". A detailed version is shown in Figure 7.9 and illustrated by the following examples.

- A damaged part (loss # 16) is caused by "Wrong Doing" (extra force, direct cause) by "Less capability actor" (unskilled labor, indirect cause), or caused by "Missing process" (missing mistake proofing mechanism, indirect cause), which can be solved by "More training" (long-term-solution # 7) or "Bring back the checking mechanism" (long-term solution).

- In determining the usability of used parts, a good part is rejected (loss # 14) by "Less capability actor" (Semi-skilled labor, direct cause) who does not know how to inspect the used parts properly and needs more training (long-term solution # 7) or use another skilled labor for the inspection on part time bases (short-term solution # 3).

- In a bus assembly line, a hot glue operation works well in the summer, but not always in winter. The gun does not work properly from time to time throughout the day (loss # 17) when a large door nearby is open and cold air flows in (direct cause), which is caused by an improper location of workplace (indirect cause). In this case, the location is still the same as originally designed, but the weather changes over time, and the room temperature does not fit the temperature assumption of design. The possible solutions could be: 1) Go back to Step 2 to redefine the specifications, such as to move the operation away from the door or move the traffic that normally goes through the door to another door; 2) Use efficient resources (long-term solution # 6) to eliminate the cause "Low efficient actors" (cause # 11), or 3) Control tightly the operation on quantity, quality and time (long-term solution # 11), for example, to live with the issue but instruct labor not to glue when the door is open, but this solution may result in the bottleneck because of this slow glue operation.

- Many defects (loss # 15) are produced by a worn and less accurate NC mill (direct cause), which could be solved by using another more accurate machine (long-term solution # 6), or overhauling this NC machine to its original condition (long-term solution), or redesigning the operation in a way to compensate the machine's

			Causes																										
			Input														Control								Doing				
		Loss Type / Solution Type	High input price	Large variation in quantity	No/Low availability	Wrong design specs	Wrong workplace layout	Large variation in quality	Damaged materials are received	"Out of spec" matl received	Too close to spec limit	Breakdown of actors	"Out of spec" actors	Low efficient actors	Less capability	Large variation in time	No plan	Missing process	Mixed process route	Poor WIP control	Poor information system	Low adjustability in control	Low payment	Poor setting	Missing doing	Less doing	Wrong doing	Late/Early doing	
ID	Losses		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	
1	Extra input cost (e.g. extra fuel cost).	01	x					x												x									1
2	Excessive material, part, operator, machine, fixture or space available.	02		x													x			x	x	x							2
3	Over skill labor, over capability machines etc.	03						x												x									3
4	Penalty payment for poor quality product or late delivery.	04			x							x		x													x		4
5	Correction such as repair and rework.	05								x					x			x						x	x	x	x		5
6	Over fitting, adjusting and measure.	05				x	x	x			x			x	x														6
7	Duplicated operations (e.g. duplicated requests).	05			x					x				x	x		x			x	x				x				7
8	Over inspect, maintenance, unnecessary training (e.g. inspect twice).	05				x		x		x	x			x	x		x												8
9	Unplanned rush operation (e.g. expedite weldding).	05		x								x																	9
10	Handle unforeseen production problems.	05		x				x																					10
11	Wait (e.g. operator is waiting for part coming late).	06			x		x					x	x	x	x	x	x	x	x	x	x		x	x				x	11
12	More parts produced than planned.	07			x			x									x												12
13	Wrong item produced.	07																		x	x	x		x			x		13
14	Inputs consumed excessively.	08		x		x	x	x		x	x	x	x	x	x	x				x							x		14
15	Parts, machines, fixtures or tools are destroyed.	08				x	x			x			x		x									x			x		15
16	Part, machine, fixture or tool is damaged, but repairable.	09				x	x	x		x			x		x									x			x		16
17	Rejected or returned.	09				x		x	x	x	x		x		x	x			x	x					x	x	x		17
18	Off specs (e.g. oil canning).	09				x		x	x	x	x		x		x								x		x	x	x		18
19	Part, machine, fixture or tool is damaged and un-repairable (e.g. property changed).	10				x	x	x		x			x		x									x			x		19
20	Out of style.	11		x																								x	20
ID	Solutions		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	
1	Share resources with other users if possible.	L		x	x			x	x	x		x		x	x				x										1
2	Use alternatives if cost effectively.	S	x	x	x				x			x		x	x		x					x							2
3	Add more resources at a blocked spots in the process.	S			x						x	x	x	x	x										x	x		x	3
4	Rework or Repair defects immediately.	S								x														x	x	x	x		4
5	Reduce the travel distance.	L					x									x												x	5
6	Use efficient resources wherever possible.	L										x	x	x	x													x	6
7	Provide more training and instructions for doing the job.	L											x	x	x												x		7
8	Keep reasonable inventory level.	L	x	x	x			x																					8
9	Match the capability of resources with the job requirement.	L											x	x	x												x		9
10	Backup resources such as materials, machines and labors.	L		x	x															x	x			x				x	10
11	Control tightly the operation on quantity, quality and time.	L		x				x								x	x			x								x	11
12	Run batch whenever possible.	L																										x	12
13	Prepare for doing the job (e.g. S5 strategy).	L														x				x									13
14	Balance workflow by WIP storage.	L														x				x								x	14
15	Improve the communication.	L		x	x			x								x				x			x					x	15
16	Eliminate non-value added activities wherever possible.	L																							x	x	x		16
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	

Figure 7.9 Matrix of Loss-Cause-Solution (Detailed)

inaccuracy (long-term solution, back to Step 2) or contracting out the operation (short-term solution, back to Step 1).

If more statistical information is required, it can be extracted from this matrix, for example, the number of causes associated with a particular loss or the number of solutions for a particular cause.

- **Number of causes associated with a particular loss** is shown in Figure 7.10. In which, the loss of "Rejected or returned parts" is associated with 13 causes including "Too close to specification limit, Damaged materials received and Large variation in quality".

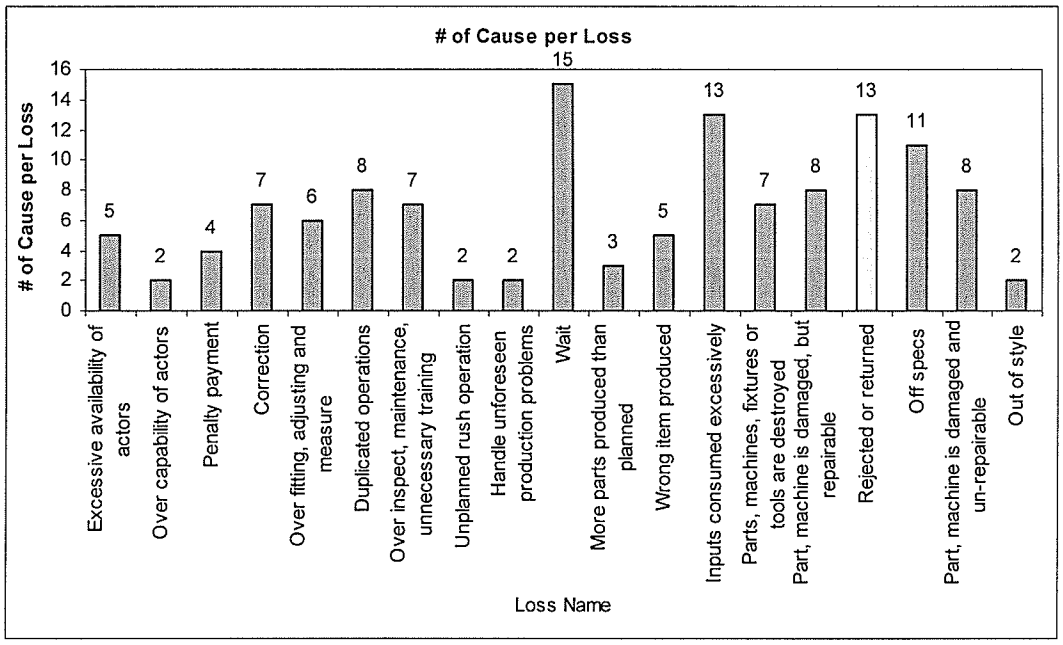


Figure 7.10 Number of Cause per Loss

- **Number of solutions for a particular cause** is shown in Figure 7.11. In which, 6 solutions including "Use alternatives if cost effective, Keep reasonable inventory level and Provide more training and instructions for doing the job" are for eliminating the cause "No/Low availability".

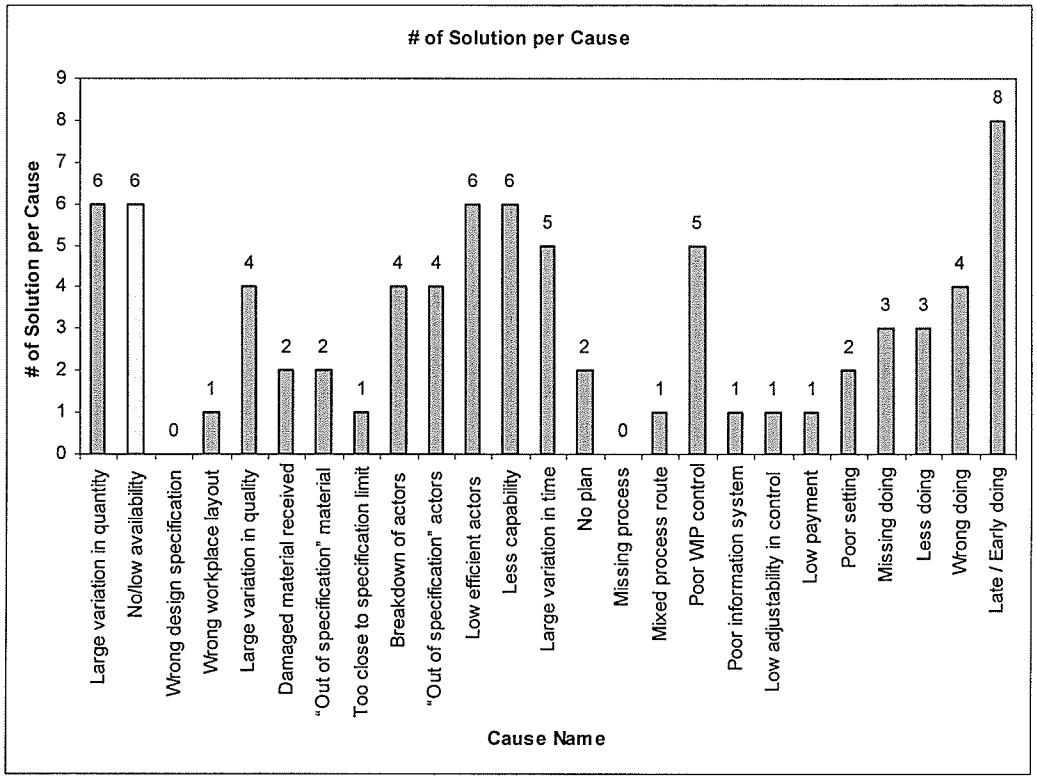


Figure 7.11 Number of Solution per Cause

Once the above matrix is established, the process comes to the implementation period. The first question will be "Is it worthwhile to be implemented in terms of cost?" which will be discussed in Chapter IX: Costing of Loss and Solution (CLS).

Conclusions of Chapter:

- **MLCS** (Matrix of Loss-Cause-Solution) provides a list of losses, causes and solutions and their linkages, which can be used as a starting point for company managers to do their own work. The company can adjust this list to fit its situation.

- A coding system for loss, cause and solution has also been developed for easy tracking.

8 Chapter VIII: Function Based Costing (FBC)

As mentioned before, neither Activity Based Costing (ABC) nor Operation Based Costing (OBC) provides a generic structure to describe how an activity or operation is performed in terms of information and material flow. Also neither tool provides a step by step approach in terms of how to use them to measure the cost. In order to remove the above disadvantages, a new cost module, "Function Based Costing (FBC)", was developed in this thesis. A "Function" means "An assigned action, activity or duty" (American Heritage Dictionary, 2000) [2]. Assigned indicates the function has a defined purpose. From now on, the term "Activity" and "Function" have the same meaning in this thesis.

Generally speaking, FBC integrates OBC with the concept of activity in ABC by defining a generic activity structure, standard cost information and standard costing flow, and by providing a step by step approach to use it.

More specifically, FBC first defines an activity in a generic way by four elements required to perform an activity (refer to the next section for details), and then defines a set of standard cost information for each activity element. Furthermore it defines a standard costing flow to show how each cost is calculated and related to each other. Finally a step by step approach for using FBC is provided in order to reduce the subjectivity level by separating the analysis into two steps: "Production flow analysis" and "Costing analysis". Whatever actual activities are included in the flow analysis, FBC is attached to each activity for costing. The major contribution to the cost analysis from FBC is the **standardization** of activity structure, cost information and costing flow, discussed as follows.

8.1 Standard Activity Structure (SAS)

In reality, a production activity can be represented in many ways and this usually results in different conclusions. But at a generic level, the activity can be described in a standard way, which is called the Standard Activity Structure (SAS) as mentioned before. SAS describes how the activity is performed by showing material and information flow, and

reduces the subjectivity level in recognition of the activity. Four activity elements, Input, Control, Doing and Output", are defined in SAS, which are the basic requirements to perform an activity, as shown in Figure 8.1 that repeats Figure 4.5. The details refer to Chapter IV: Skilled Labor Manufacturing and Standard Activity Structure.

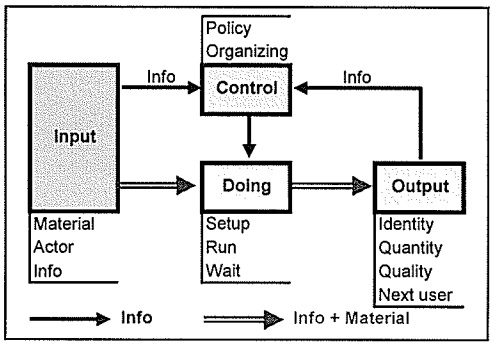


Figure 8.1 Standard Activity Structure (SAS)

8.2 Standard Cost Information (SCI)

Cost information in FBC is standardized for each activity element in SAS. This standard cost information can be adjusted or redefined to fit the specific industry or emphasize specific information. For example, in the manufacturing industry, eight cost elements in OBC [11] can be adopted in FBC; in the service industry, other cost elements may be used to emphasize its specific cost characteristics. The specific information emphasized in FBC could be any "waste" created by each activity element or whole operation, which is the difference between the costs of Step 2 (the standard for the operation) and Step3 (the operation as it runs in production).

8.2.1 Standard Cost Information for "Input"

Standard cost information for Input includes (headings): Input items, Cost per item, Unit cost, Quantity, Planned, Waste and % Waste, as shown in Figure 8.2.

Input item covers "Material" and "Actor", which are shown by "Material ($/piece)" and "Actor ($/piece or hour)".

- **Material ($/piece)** includes the raw material, semi-finished parts and finished parts, etc. For the purpose of costing, the material cost is usually added to the top of "Cost of Doing".

- **Actor ($/piece or hour)** includes contract, tied cost (interest paid for the stored material), labor, machine, fixture, space and energy.

The above Input items are measured by Cost/Item, Unit cost, Quantity, Planned, Waste and % Waste. **Planned** cost is the cost as planned. **Waste** is the unplanned cost such as the unexpected damaged parts received from upstream or over wages, i.e. wages that are greater than planned. **% Waste** is the percentage of waste in total value, which is obtained by an analysis process and provides a place to address any waste from Upstream and in Input.

Cost of Input						
Input Items	Cost / Item	Unit Cost	Quantity	Planned	Waste	% Waste
Material ($/piece)						
Material						
Total (Material)						
Actor ($/piece or hour)						
Contract						
Tied Cost						
Labor						
Machine						
Fixture						
Space						
Energy						
Water						
Electricity						
Compress Air						
Total (Actor)						

Figure 8.2 Standard Cost Information for "Input"

8.2.2 Standard Cost Information for "Control"

Standard cost information for Control includes (headings): Control item, Cost per item, Unit cost, Quantity, Planned, Waste and % Waste", as shown in Figure 8.3.

Cost of Control						
Control Items	Cost / Item	Unit Cost	Quantity	Planned	Waste	% Waste
Control ($/piece or hour)						
Penalty						
Organizing Cost						
Total (Control)						

Figure 8.3 Standard Cost Information for "Control"

Control item covers the management related issues such as "Penalty" and "Organizing" which are shown by "Control ($/piece or hour)".

- **Penalty** is the payment for customer's dissatisfaction related to timing, quality and quantity.
- **Organizing** is the effort to manage, guide or regulate "Doing", such as meeting, planning and supervising.

The above Control items are measured the same way as Input. This also provides a user a place to address any waste created by the Control effort.

8.2.3 Standard Cost Information for "Doing"

Standard cost information for Doing includes (headings): Settings, Doing item, Cost per item, Unit cost, Time, Planned, Waste and % waste, as shown in Figure 8.4.

Doing ID, Name

Number of Setups	
Batch Size	
Same Labor for Run and Setup?	

Cost of Doing						
Doing Item	Cost / Item	Unit Cost	Time (h)	Planned	Waste	% Waste
Setup						
Busy						
Idle						
Run						
Busy						
Idle						
Waste from Actor/Control						
Setup (Busy)						
Run (Busy)						
Cost of Doing						

Figure 8.4 Standard Cost Information for "Doing"

Settings set "Number of setups", "Batch size" and "Whether using "Same labor for run and setup".

Doing item has three groups "Setup", "Run" and "Waste from actor/control".

- Setup is the effort to make the machine, and sometimes operator, ready to do the job, which includes collecting, removing the last fixture used, installing the next fixture and changing tools.
- Run is the effort to transform the material from one stage to another, such as drilling, cutting and welding.
- Waste from actor/control is the waste created by Actor and Control such as the extra wage.

The above Doing items are measured by Cost/Item, Unit cost, Time, Planned and Waste. **Time** is the time spent for "Doing", which is further separated into "Busy" and "Idle". **Planned** value is the Value added after Doing. **Waste** is any waste from Actor (Input), Control and Doing.

8.2.4 Standard Cost Information for "Output"

Standard cost information for Output includes (headings): Output item, Cost (Planned and Waste), as shown in Figure 8.5.

Cost of Output per Part			
Output Item	Cost	Planned	Waste
Total Cost			
Material ($/piece)			
Actor ($/piece)			
Control ($/piece)			
Cost of Doing			

Figure 8.5 Standard Cost Information for "Output"

Output item is basically the "Total cost" that is broken down to Material ($/piece), Actor ($/piece), Control ($/piece) and the Cost of Doing. Each piece of cost is also shown by Planned and Waste cost.

8.2.5 Cost Information in "Summary"

The standard cost information for Output can be viewed in many ways. One of ways used in this thesis is from the angles of "Loss" and "Waste" as shown in Figure 8.6.

Summary (per Part)			
Output Item	Cost	Planned	Waste
Total Cost			
Value Added			
Value Loss			
Material (Waste, $/piece)			
Actor (Waste, $/piece)			
Control (Waste, $/piece)			
Waste in Cost of Doing			
Waste in Output			
Over throughput			
Damaged (Repairable)			
Damaged (Non-repairable)			
Obsolete			

Figure 8.6 Cost Information in "Summary" (per Part)

Total cost shown in the table is contributed by "Value added" and "Value loss".

- **Value added** is the planned costs to perform the activity.

- **Value loss** is the waste from Material, Actor, Control, Doing and Output. The waste from Output is further narrowed down to Over throughput, Damaged (Repairable), Damaged (Non-repairable) and Obsolete. Over throughput is more than planned Output; Damaged (Repairable) is damaged Output but repairable; Damaged (Non-repairable) is damaged output that cannot be repaired; Obsolete is an Out of date style or degraded specifications. This loss provides a direction to where improvement should be started.

The above standard cost information can be refined to fit a specific industry to emphasize its specific concerns.

8.3 Standard Costing Flow (SCF)

The standard costing flow (SCF) presents the relationship (how they are calculated) between the costs for each activity element, as shown in Figure 8.7.

The "Cost of Output" is contributed by the "Piece work" from Input and Control, and the "Cost of Doing". The cost in Summary is another cost view that shows "Value added" and "Value loss" since the loss is a main concern in this thesis.

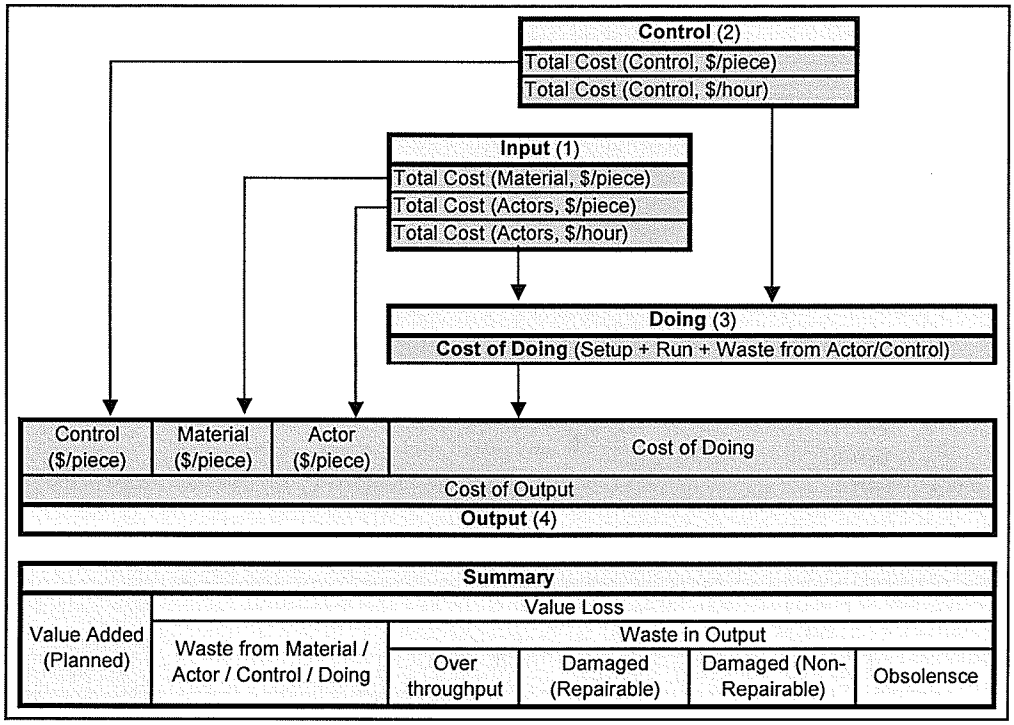


Figure 8.7 Costing Flow in FBC

- **Cost of Output** is contributed to by "Cost per piece of material, actor and control, and Cost of Doing".
  - **Cost per piece of material, actor and control** is the cost per piece from Input and Control directly.
  - **Cost of Doing** is the cost determined by the time spent for Doing.
- **Summary** is another view of "Cost of Output" by focusing on the "Value added" and "Value loss", as explained in the last section.

8.4 FBC

When each activity in SAS is attached with its own standard cost information, it becomes "Function Based Costing (FBC)" as shown Figure 8.8.

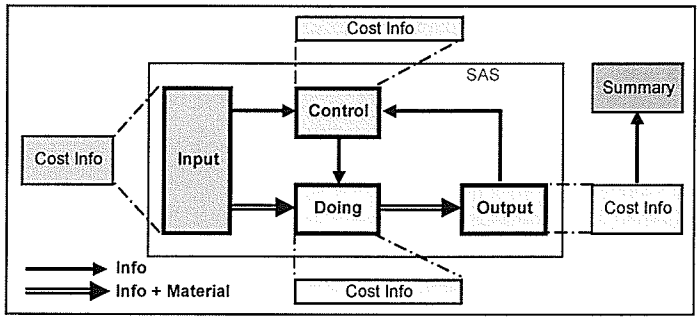


Figure 8.8 Function Based Costing (FBC)

8.5 Way to Use It

FBC must be used in a proper way to estimate the cost; otherwise, the process analysis issue will be mixed with the costing procedure and increase the complexity in costing, such as how to define the scope of the activity and what the exact content of the activity is, etc.

Therefore the use of FBC is separated into two steps: 1) Build production flowchart and 2) Plug FBC module into each activity in the production flowchart. This is illustrated by the following simple example.

- **Build production flowchart**. For example, in order to assemble a part, 5 operations are required as shown in Figure 8.9. Each operation is presented by a numbered circle. The travel between operations is presented by the numbered arrows. Operation 5 is the final assembly operation that joins the operations 3 and 4.

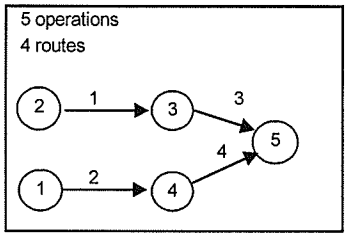


Figure 8.9 A Process with 5 Operations

- **Plug FBC module into each activity in the production flowchart.** Based on Figure 8.9, each activity (operations 1 to 5) is substituted by the FBC module; for example, Figure 8.10 shows that operation 5 is replaced by the FBC module. The cost information of the Output in the preceding operation is the cost information of Input

in the next operation. This way can clearly show each intermediate cost and final cost. A detailed example refers to Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

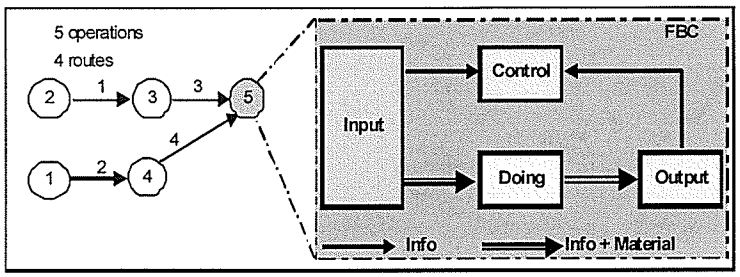


Figure 8.10 Operation 5 Replaced by the FBC Module

Conclusions of Chapter:

- A new costing module, **FBC** (Function Based Costing) created in this thesis, improves ABC and OBC by adding a standard activity structure, standard cost information and standard costing flow, and reduces the subjectivity involved in the costing procedure.

- The information is described separately for each activity element. For example, the material and actor used are described in "Input"; the time and number of uses of actors are described in "Doing"; the efforts related to controlling and customer satisfaction are described in "Control"; and the creations after performing the activity, such as desired output, planned scrap and unplanned scrap, are described in "Output".

- **Waste** is immediately shown by separating it from the legitimate costs in each activity element. The types of waste can be easily compared to help direct the short-term effort and determine where improvement could do the most good.

- FBC could be **assembled** to simulate any manufacturing activity (e.g. step, operation and process). The tables and calculation structures in FBC can be adjusted to emphasize any concern without hurting the overall structure of FBC.

- The use of FBC is not limited to manufacturing. It can also be used in other industries such as banking, health or government, which have many defined repetitive processes.
- The correct use of FBC makes the costing process clearer and simpler.

9 Chapter IX: Costing of Loss and Solution (CLS)

In the course of identifying the loss and finding the solution, it is necessary to know the significance of the loss and the cost of the solution. In order to do so, "Loss, Solution and Costing" are integrated in this chapter as a new module: "Costing of Loss and Solution" (CLS)", which can be independently used in practice. It is discussed under the topics: "Structure of CLS" and "Cost Statement".

9.1 Structure of CLS

CLS consists of three modules: 1) Production Flow and Measurement (PFM), 2) Matrix of Loss-Cause-Solution (MLCS) and 3) Costing (C), as shown in Figure 9.1.

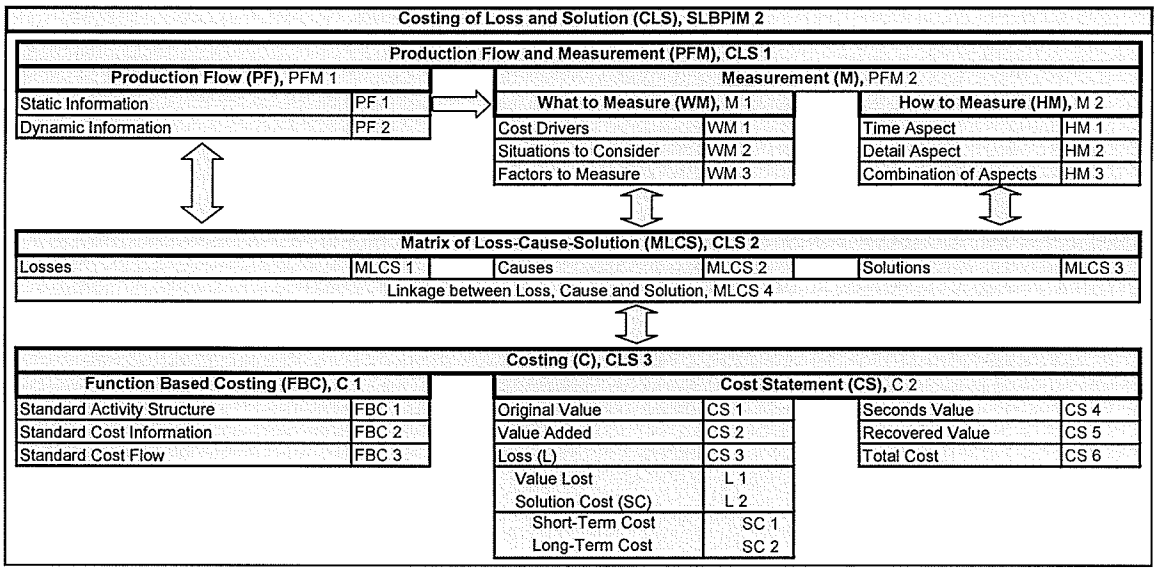


Figure 9.1 Costing of Loss and Solution (CLS)

- **Production Flow and Measurement (PFM)** provides a picture of how the job is performed at the overall level or at a detailed level; what factors should be measured; and how to measure. The details refer to Chapter VI: Production Flow and Measurement.

- **Matrix of Loss-Cause-Solution (MLCS)** provides a list of losses, causes, solutions and the linkages between them. The details refer to Chapter VII: Matrix of Loss-Cause-Solution (MLCS).

- **Costing (C)** provides a cost statement for the issue of concern, which is a new creation in this thesis and is discussed in the next section.

9.2 Costing (C)

Any production issue in this thesis will be ultimately measured by a "Dollar" value, no matter what dimension the issue falls in, such as "Quantity, Quality and Time". For example, the hours spent to do a job are in the dimension of "Time", which could be finally measured by a dollar value based on the wage. The costing process is based on "Function Based Costing (FBC)" and "Cost Statement".

9.2.1 FBC

FBC is a cost module to provide a standard tool to estimate the cost in any manufacturing environment. The information from this model includes the "Value added", "Loss" and "Total cost". The details refer to Chapter VIII: Function Based Costing (FBC).

9.2.2 Cost Statement

The "Cost statement" is a new creation in this thesis and provides the user with a relatively complete cost picture for the issue of concern. It covers all cost information related to production and customer satisfaction in terms of "Quantity, Quality and Time", which is presented by: 1) Original value, 2) Value added, 3) Loss (Value lost + Solution cost (Short-term cost + Long-term cost)), 4) Seconds value, 5) Recovered value, and 6) Total cost, as shown in Figure 9.2.

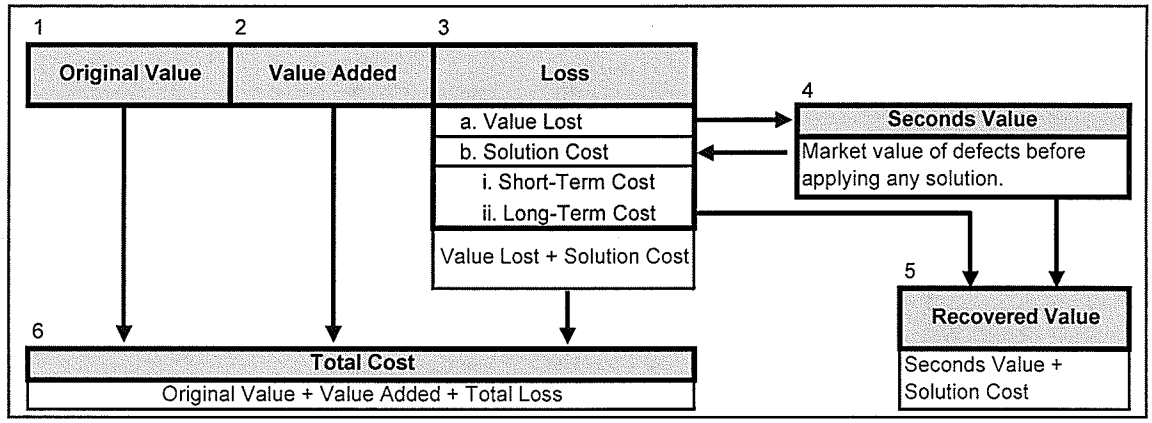


Figure 9.2 Cost Statement

- **Original value** is the value of the "Inputs", which could be the cost of new material purchased or old product to be rebuilt, for example, the original value of an old cylinder is $500.

- **Value added** is the value increased through performing the activity such as a drilling operation. This is the source of profit.

- **Loss** is any value of output decreased after performing the activity, which includes the value of loss in regular production and the cost for solution.

  - The **value loss in regular production** is the value decreased during performing the regular activity such as the scraps in milling.

  - The **cost for solution** is the cost of implementing the solution, which is the sum of "Short-term solution cost" and "Long-term solution cost". The reason for solution cost being a sort of loss is that the solution may not be required if the related loss does not occur in the first place.

    - **Short-term solution cost** is the cost to implement the short-term solution such as repair or rework.

    - **Long-term solution cost** is the cost to implement the long-term solution such as training. This cost is usually allocated to all beneficiaries of the solution, for example, the cost of training is allocated to the cost of labor since his skill level is improved through training.

- **Seconds value** is the market value of defects (As it is). For example, assume the original value of a part is $100, the value added by the operation is $10 and the total value is $110. The value of seconds is $0 if the part is totally scrapped, or $60 if the part could be sold for $60. The seconds value is determined by the sales team and is not discussed in this thesis.

- **Recovered value** is the value restored through solution such as repair, which is the sum of "Seconds value" and "Solution cost". This value can be used to determine whether the solution should be implemented. For example, the value of seconds is

$80, but the regular price for a good product is $100. The cost to repair the seconds is $30, so the recovered value is $110 (Seconds value + repairing cost). The question here is "Do you sell the product as seconds at $80 vs. at a regular price of $100 after spending $30 for repairing?" Assuming the product can be sold at $100, the possible loss will be $20 for seconds ($100 -$80) and $10 for repaired product ($110 - $100). Thus the repairing operation should be implemented, since it has the least loss in this case.

- **Total cost** is the sum of "Original value", "Value added" and "Loss". This cost will be used for making decisions.

9.3 Workflow in CLS

The workflow of the CLS model is shown in detail in Figure 9.3.

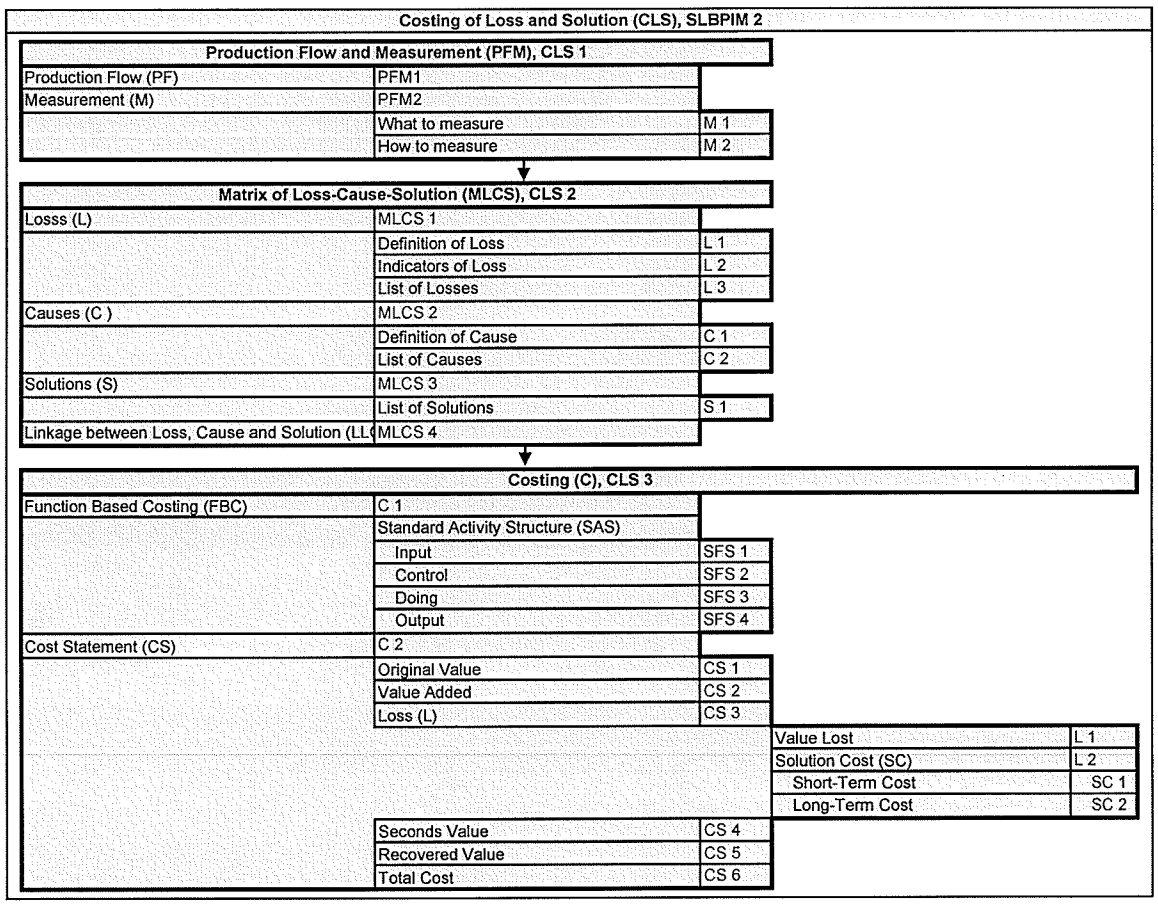


Figure 9.3 Workflow in CLS

Once a costing is required, the issue is assessed by the module "Production Flow and Measurement (PFM)" for obtaining a production flow that describes how the production is performed, and determining what factors to measure and how to measure in terms of time and detail. Then the issue is assessed by the module "Matrix of Loss-Cause-Solution (MLCS)" for identifying the loss, locating the causes and finding the possible solutions. The losses and solutions found are assessed for their significance in terms of the cost by the module "Costing (C)", which are used in a "Cost statement". The application of CLS will be shown in Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM).

Conclusions of Chapter:

- **CLS** (Costing of Loss and Solution) provides a standard procedure to estimate the cost of loss and solution.
- The cost information is presented in a "**Cost statement**" that includes the normal cost, seconds cost, lost cost, solution cost and final total cost in producing an item.
- Each cost item in the cost statement is clearly defined.
- The relationship between each cost item in the cost statement is clearly shown to provide the information of how they are dependent on each other and calculated.

10 Chapter X: Skilled Labor Based Productivity Improvement Model (SLBPIM)

This chapter integrates all the models, techniques and concepts developed or reviewed in the previous chapters, and creates a comprehensive production analysis model. This model and its method of use are illustrated using three examples. The chapter discusses the model and its uses under the headings "Model SLBPIM", "Analysis flow inside SLBPIM" and "Checklist for Implementing SLBPIM".

10.1 Model SLBPIM

The comprehensive model, "Skilled Labor Based Productivity Improvement Model (SLBPIM)", is created in the thesis, which consisted of two main modules: "Three-Step Procedure (3SP)" and "Costing of Loss and Solution (CLS)", as shown in Figure 10.1 (Simplified version).

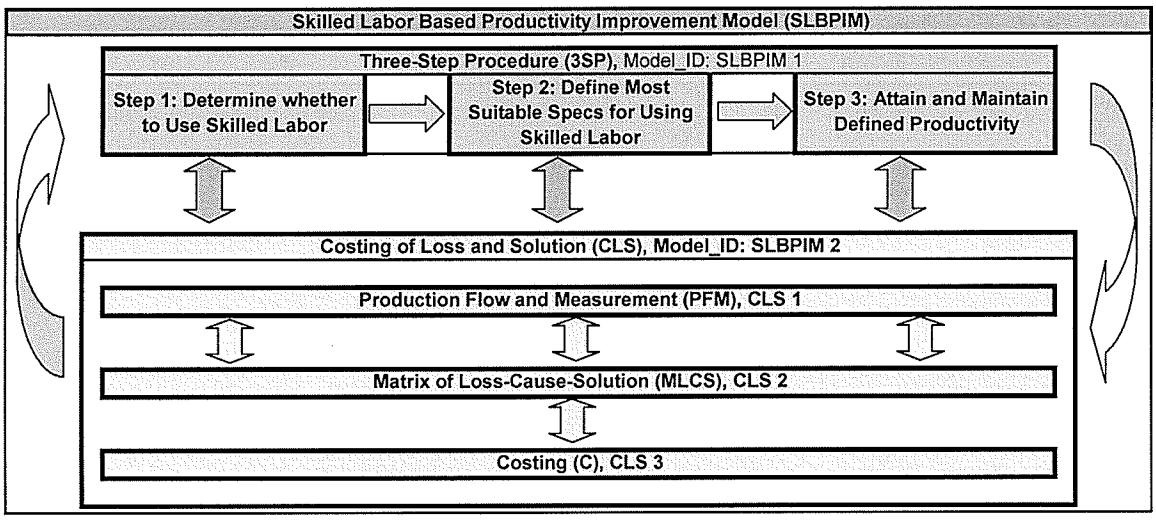


Figure 10.1 Skilled Labor Based Productivity Improvement Model (SLBPIM)

- **Three-Step Procedure (3SP)** provides a standard procedure to determine whether skilled labor should be used and how to attain and maintain the defined productivity if it is used. The three steps in 3SP are: "**Step1:** Determine whether to use skilled labor", "**Step2:** Define the most suitable specification for using skilled labor" and "**Step3:** Attain and maintain the defined productivity". The details refer to Chapter V: Three-Step Procedure (3SP).

- **Costing of Loss and Solution (CLS)** provides a standard cost procedure with a complete cost statement that includes total cost, loss and profit. The details refer to Chapter IX: Costing of Loss and Solution (CLS).

A detailed version of SLBPIM is shown in Figure 10.2.

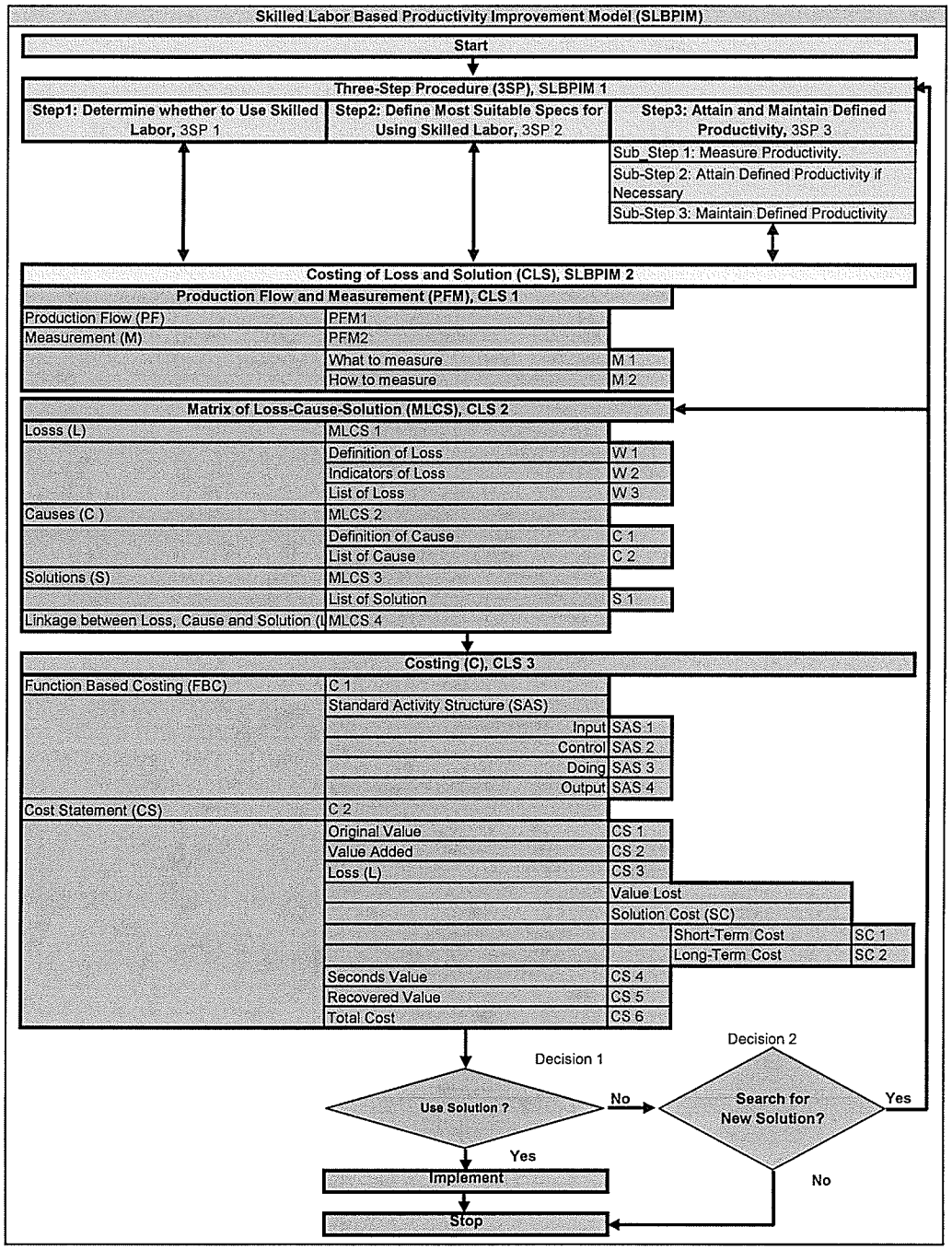


Figure 10.2 SLBPIM (Detailed Version)

10.2 Analysis Flow inside SLBPIM

The analysis flow provides a fairly detailed idea on how to make decisions related to the best use of skilled labor. There are two situations that are suitable for analysis: 1) For "New production process"; 2) For "Existing production process". The flow for "New process" is the basic flow, and the flow for "Existing process" enters this basic flow at some decision point, as shown in Figure 10.3.

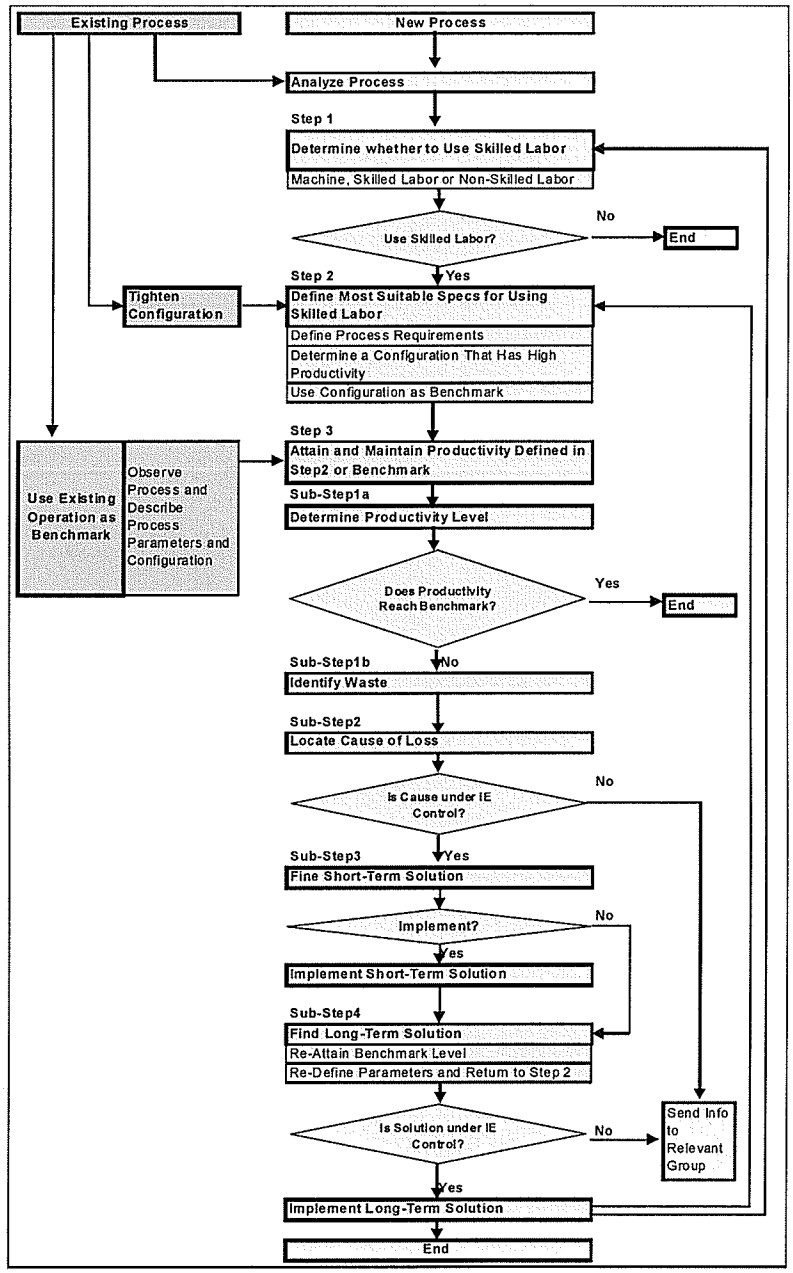


Figure 10.3 Analysis Flow inside SLBPIM

The possible decision points for the "Existing process" to enter the main flow are: 1) "Analyze process" if required; 2) "Define the most suitable specs for using skilled labor" if "Tightened configuration" is required; 3) "Attain and maintain the defined productivity" if "Use existing operation as benchmark" can be done.

Events for "New production process" are: 1) Analyze process; 2) Step 1: Determine whether to use skilled labor; 3) Step 2: Define the most suitable specifications for using skilled labor; 4) Step 3: Attain and maintain the defined productivity defined in Step 2, which is the benchmark. The following are short descriptions for the above events and for the details refer to Chapter VI: Production Flow and Measurement and Chapter V: Three-Step Procedure (3SP).

- **Analyze process** to understand the process designed, for example, product name, production volume, planed time and throughput.

- **Determine whether to use skilled labor** by comparing with other production alternatives such as unskilled labor, machine or contract. Two routes are involved in this determination: 1) Whether skilled labor is the only option; and 2) Whether skilled labor is the cheapest option. If skilled labor is not selected, no further discussion is required in this thesis; otherwise the issue goes to the next decision point.

- **Define the most suitable specifications for using skilled labor** in terms of effectiveness and efficiency. These **specifications** represent "No unnecessary losses exist related to quantity, quality and time while performing the activity", which means the maximum potential gain. These specifications can be considered the process requirements to be achieved and used as benchmarks to assess the productivity of the actual production.

- **Attain and maintain the defined productivity defined in step2 or benchmark** is supported by four tasks: 1) Determine the productivity level and identify the loss; 2) Locate the cause; 3) Find a short-term solution and 4) Find a long-term solution.

- **Locate the cause** is to map the loss to related cause(s), which may require a detailed investigation. For example, an unskilled worker causes a high reject rate; the part

received with inconsistent quality causes a longer operation time; a slightly incorrect shape of fixture causes the part to be damaged.

If the causes located are under the control of the Industrial Engineer, the issue goes to the next decision point; otherwise it is handled over to relevant groups for further decision. For example, a cause of "Higher wage" is handled over to a union for further decision.

- **Find a short-term solution** in order to satisfy the customer as soon as possible in terms of the quantity, quality and time that the customer requests. For example, if the inspection slows down the production flow, an additional inspector should be in position to speed up the inspection operation.

- **Find a long-term solution** in order to maintain the defined productivity for a long-term. For example, train the low skilled worker, who should not have been assigned to do the job, to a level that he can perform the job effectively and efficiently. The long-term solutions can be classified as four possible routes: 1) Return the situation to the specifications as defined; 2) Go back to Step2 to redefine the specifications; 3) Go back to Step1 to reassess whether using other production alternatives such as machine and unskilled labor etc; 4) Leave as is.

The details of the implementation of the solutions are very important, but too big and extensive to be covered in the thesis since they are beyond the thesis's scope.

10.3 Checklist for Implementing SLBPIM

A checklist is created from SLBPIM to help implement the model step by step, as shown in Figure 10.4. This list can be modified to accommodate any new situation if necessary.

Skilled Labor Based Productivity Improvement Model (SLBPIM)			
3SA			
Three-Step Procedure (3SP), SLBPIM 1			
3SP 1	**Step1: Determine Whether to Use Skilled Labor**		
3SP 2	**Step2: Define Most Suitable Specs for Using Skilled Labor**		
3SP 3	**Step3: Attain & Maintain Defined Productivity**		
	Sub_S 3.1	Sub-Step 1: Measure Productivity	
	Sub_S 3.2	Sub-Step 2: Attain Defined Productivity if Necessary	
	Sub_S 3.3	Sub-Step 3: Maintain Defined Productivity	
CLS			
Costing of Loss and Solution (CLS), SLBPIM 2			
Production Flow and Measurement (PFM), CLS 1			
PFM1	Production Flow (PF)		
PFM2	Measurement (M)		
	M 1	What to Measure	
	M 2	How to Measure	
Matrix of Loss-Cause-Solution (MLCS), CLS 2			
MLCS 1	Loss (L)		
	W 1	Definition of Loss	
	W 2	Indicators of Loss	
	W 3	List of Losses	
MLCS 2	Cause (C)		
	C 1	Definition of Cause	
	C 2	List of Causes	
MLCS 3	Solution (S)		
	S 1	List of Solutions	
MLCS 4	Matrix of Loss-Cause-Solution (MLCS)		
Costing (C), CLS 3			
C 1	Function Based Costing (FBC)		
	Standard Activity Structure (SAS)		
		SAS 1	Input
		SAS 2	Control
		SAS 3	Doing
		SAS 4	Output
C 2	Cost Statement (CS)		
	CS 1	Original Value (OV)	
	CS 2	Value Added (VA)	
	CS 3	Loss (L)	
		L 1	Value Lost (VL)
		L 2	Solution Cost (SC)
			SC 1, Short-Term Cost (STC)
			SC 2, Long-Term Cost (LTC)
	CS 4	Seconds Value (SV)	
	CS 5	Recovered Value (RV)	
	CS 6	Total Cost (TC)	
Decision 1	**Use Solution?**		
Decision 2	**Search for Another Solution?**		
Implement	**Implement**		
Stop	**Stop**		

Figure 10.4 Checklist for Implementing SLBPIM

Conclusions of Chapter:

- SLBPIM (Skilled Labor Based Productivity Improvement Model) is a standard tool to analyze whether skilled labor can be used effectively. The tool includes determining whether to use skilled labor, defining the most suitable specification to use skilled labor, measuring the productivity, attaining and maintaining the defined productivity.

- SLBPIM **integrates** all concepts and models developed in this thesis to provide a series of tables and calculation structures, which include both quantitative and qualitative methods and steps.

- It is the first time that a model solves the subject of "how to best use skilled labor", which coordinates both subjective and objective approaches through a smooth analysis flow.

- This model provides the user or analyzer a general direction and detailed steps when considering the best use of skilled labor.

- This model can be used not only in manufacturing to improve its productivity, but also probably in other industries such as banking, health or government.

11 Chapter XI: Examples of Using SLBPIM

This chapter demonstrates how SLBPIM can be used to solve real production problems. Three cases are presented. The first case is to determine whether skilled labor is the best option to perform the job at the process level, which is a task of Step 1 in 3SP. The second case is to determine the best batch size at the process level, which is a task of Step 2 in 3SP. The third case is to determine the productivity level and waste at the product level, which is a task of sub-steps 1 of Step 3 in 3SP.

These examples are derived from the situations encountered during work with Bristol Aerospace and Aero-Recip. The analysis was done much late, after the thesis concepts were developed.

11.1 Case 1: Determine whether Skilled Labor is the Best Option

The task in this case is to determine whether skilled labor is the best option to perform the job at a process level, which is a task of Step 1 in 3SP.

11.1.1 Description of Situation

The process used in this case is "Grind and Lap Valves, Cylinder, P&W R985", which is one of processes to rebuild the cylinder in the P&W R985 engine in Aero-Recip (Canada) Ltd. The ring on the valve seat in the cylinder is a soft metal part and needs to be replaced if it is worn and out of specification. When a new ring is installed, it must seal with the valve without gas leaking. Otherwise significant engine power will be lost. In order to obtain the required seal level, the process of "Grind and Lap Valves" is performed as shown in Figure 11.1 that repeats Figure 6.2.

The operations in this process are: operator moves a cylinder in which new rings have been installed, from a trailer and loads and secures it on a fixture. He sharpens the sand stone used for grinding to the correct angle if necessary. He grinds the area on the ring where the valve will touch (called "Contact area") and checks the result several times until enough material is removed, and then cleans the grinding area with a cloth.

Next, he does a "fine" operation (called "Lap") to smooth the "contact area" to make sure no gas will be leaked through this area when the valve seals with the ring. The way to do this is: He takes the valve, which is specifically used for the valve seat being lapped, from a case and puts the lapping compound on the contact area on the valve. He takes a pole with a suction cup on the bottom (lapping tool) and mounts it on the flat side of the value seat, and puts the valve on the ring of the valve seat 1, then he starts lapping by rotating the pole. After rotating a while, he cleans the contact area and visually checks the smoothness. If the lapping is not completed, he repeats these pasting, rotating, cleaning and checking steps until the smoothness level which gives a good seal level is reached. Then he turns the cylinder to the second side that is valve seat 2 and repeats the above operations done for valve seat 1. Once both sides are completed, the operator removes the bolts and takes the cylinder off the fixture and places it on the trailer.

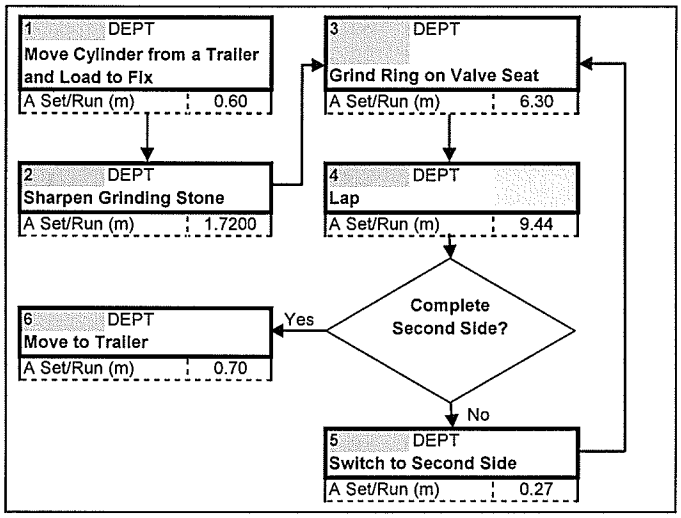


Figure 11.1 Process of "Grind and Lap Valves, Cylinder, P&W R985"

Some pictures of the operations are shown in Figure 11.2. The first picture, "1.MPG", shows the operator taking the cylinder from a trailer; the second picture, "2.MPG", shows the operator doing the grinding operation and the third picture, "3.MPG", shows the operator switching the cylinder to the second side.

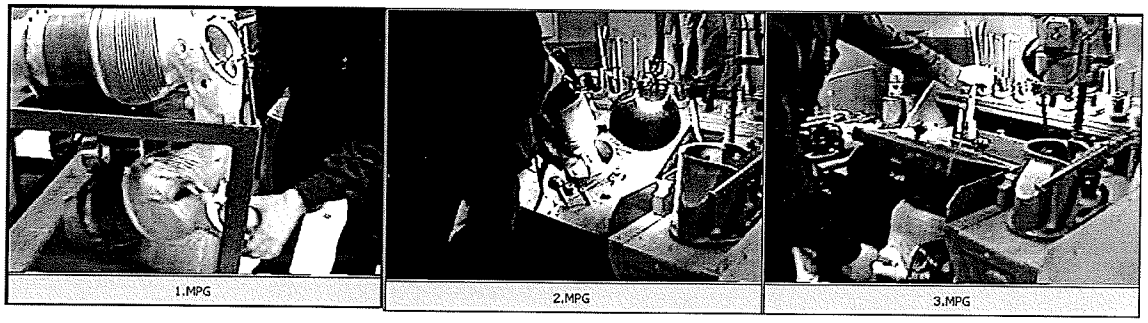


Figure 11.2 Some Pictures to Grind and Lap Valves

Many methods could be used to perform the above process, and the three method types considered here are machine, semi-skilled labor and skilled labor.

A machine is usually the first option to do a job since it creates the least damage and requires the least time once it is correctly setup and maintained. However in this case, available automatic lapping machines are designed for high volume and are very expensive, so for small volume, the unit cost is very high. Since only 670 cylinders are rebuilt each year, the machine is not a practical option.

Semi-skilled labor may be used to perform this process because of the lower wage. But semi-skilled labor may create more damage or require more time to complete the job because of lower skill. This greater damage and longer production time may finally add more cost than the cost saved by the lower wage. For example, semi-skilled labor may remove too much material during grinding, which would require the ring to be replaced again; the lapping time may be longer since the semi-skilled labor may not grind the value seat enough, which would require more lapping time, and the lapping time might be further increased by the semi-skilled labor asking for advice or checking the lapping smoothness too often.

Skilled labor can also be used in this case. Although skilled labor requires a higher wage, it could create less damage and require less production time, leading to lower production cost. For example, compared with semi-skilled labor, a skilled labor spends less time to do the lapping since he knows exactly what he is supposed to do. A skilled labor may still accidentally damage the ring during grinding because of human error, but the damage will happen less often.

11.1.2 Detailed Steps of Determination

The detailed steps to fulfill the task are shown in the following checklist of using SLBPIM. It provides the detailed cost information and process time required for cost estimation, such as unit cost, amount of material consumed, setup time and run time, which is extracted from the accounting book or an educated guess (e.g. damage rate of the final parts) by experienced personnel who understand the process of interest, and know the related cost very well. The "Yes" or "No" in the right-most column in the checklist indicates whether the item should be performed or not.

Skilled Labor Based Productivity Improvement Model (SLBPIM)				
3SP				
Three-Step Procedure (3SP), SLBPIM 1				
3SP 1	**Step1: Determine Whether to Use Skilled Labor**			**Yes**
The task is to determine whether skilled labor is the best method to perform the process of "Grind and Lap Valves, Cylinder, P&W R985". The methods to be compared are "Semi-skilled labor" and "Skilled labor".				
CWS				
Costing of Loss and Solution (CLS), SLBPIM 2				
Production Flow and Measurement (PFM), CLS 1				
PFM 1	Production Flow (PF)		Process, "Grind and Lap Valves, Cylinder, P&W R985"	**Shop Floor**
Please refer to the above description of Figure 11.1 for the details.				
PFM 2	Measurement (M)			**Yes**
		What to Measure	Cost	**Yes**
		How to Measure	Scheduled, snap shot, and detailed level measure	**Yes**
Matrix of Loss-Cause-Solution (MLCS), CLS 2				
MLCS 1	Loss (L)			
	L 1	Definition of Loss		**Yes**
	L 2	Indicators of Loss		**Yes**
	L 3	List of Losses		**Yes**
MLCS 2	Causes (C)			
	C 1	Definition of Cause		**Yes**
	C 2	List of Causes		**Yes**
MLCS 3	Solutions (S)			
	S 1	List of Solutions		**No**
MLCS 4	Linkage between Loss, Cause and Solution (LLCS)			**No**
Costing (C), CLS 3				
C 1	Function Based Costing (FBC)			
	Standard Activity Structure (SAS)			
		SAS 1	Input	**Yes**
		SAS 2	Control	**Yes**
		SAS 3	Doing	**Yes**
		SAS 4	Output	**Yes**
1. The cost information in "Input".				

The information here is mainly from the accounting book including the material cost and actor cost required for costing of this process, as shown in table 1.

Table 1. Cost Information in "Input" (Case 1)

Cost of Input												
Input Items	Cost / Item		Unit Cost		Quantity		Planned		Planned Loss		% Planned Loss	
Manufacturing Methods	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor
Material ($/piece)	Cost per Piece											
Material	$500	$500	$500	$500	1.0	1.0	$500	$500	$0.00	$0.00	0.00	0.00
Total (Material)	$500	$500					$500	$500	$0.00	$0.00		
Actor-3 ($/h)	For Run (Cost per Time)											
Labor 2	$60.00	$70.00	$40.00	$70.00	1.5	1.0	$60.00	$70.00				
Machine	$0.50	$0.50	$1.00	$1.00	0.5	0.5	$0.50	$0.50				
Fixture	$0.50	$0.50	$1.00	$1.00	0.5	0.5	$0.50	$0.50				
Space	$4.00	$4.00	$0.01	$0.01	400.0	400.0	$4.00	$4.00				
Tied Cost	$0.01	$0.01	$0.01	$0.01	1.0	1.0	$0.01	$0.01				
Energy	$4.55	$4.30	$0.05	$0.05			$4.55	$4.30	$0.00	$0.00		
Water	$0.95	$0.90	$0.01	$0.01	95	90	$0.95	$0.90				
Electricity	$1.70	$1.60	$0.02	$0.02	85	80	$1.70	$1.60				
Compressed Air	$1.90	$1.80	$0.02	$0.02	95	90	$1.90	$1.80				
Total (Actors-3)	$69.56	$79.31					$69.56	$79.31	$0.00	$0.00		

Material: $500 for both methods, which is the value of cylinder core.

Total cost per hour from Actor: $69.56 for semi-skilled labor and $79.31 for skilled labor, in which

- Labor: $60/h for 1.5 workers (one full time worker and one worker available to help and answer questions while working on another process) in semi-skilled labor method and $70/h for 1 worker in skilled labor method. Note: if the labor available to help the semi-skilled labor is skilled, less assistance time would be required, but at a higher cost per hour. The total cost would be about the same.
- Machine: $0.5/h for 0.5 machine used in semi-skilled labor or skilled labor since this machine is shared with another process.
- Fixture: $0.5/h for 0.5 fixture used in semi-skilled labor or skilled labor since the fixture is shared with another process.
- Space: $4/h for 400 sq ft used for machine and trailer etc in semi-skilled labor or skilled labor.
- Energy: $4.55/h for semi-skilled labor method and $4.3/h for skilled labor since the semi-skilled labor is less efficient in using energy.

2. The cost information in "Control".

The information here is the cost for penalty and organizing, which is mainly from the accounting book as shown in table 2. The penalty is for late delivery or poor quality to the customer. The organizing cost is for administration such as meetings.

Table 2. Cost Information in "Control" (Case 1)

Cost of Control												
Control Items	Cost / Item		Unit Cost		Quantity		Planned		Planned Loss		% Planned Loss	
Manufacturing Methods	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor
Control-2 ($/h)	Cost per Time											
Penalty												
Organizing Cost	$10.00	$10.00	$10.00	$10.00	1.0	1.0	$10.00	$10.00				
Total (Control-2)	$10.00	$10.00					$10.00	$10.00	$0.00	$0.00		

Total cost per hour from "Control": $10 for both methods, in which

- Penalty (paid for late delivery): $0.
- Organizing cost (e.g. meeting): $10/h for both methods.

3. The cost information in "Doing".

The information here is mainly from the actual measures in terms of time spent, and from Input and Control in terms of unit cost. The information is grouped by "Setup and Run", and further by "Planned and Planned loss", as shown in table 3.

Table 3. Cost Information in "Doing" (Case 1)

Settings	Semi-Skilled	Skilled Labor
Number of Setups	1	1
Batch Size	1	1
Same Labor for Setup and Run?	y	y

Cost of Doing												
Doing Items	Cost / Item		Unit Cost		Time (h)		Planned		Planned Loss		% Planned Loss	
Manufacturing Methods	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor
Setup	**$8.59**	**$7.59**	**$79.56**	**$89.31**	**0.108**	**0.085**	**$7.80**	**$7.59**	**$0.80**	**$0.00**	9.3%	0.0%
Busy	$7.80	$7.59	$79.56	$89.31	0.098	0.085	$7.80	$7.59				
Idle	$0.80	$0.00	$79.56	$89.31	0.010	0.000			$0.80	$0.00	100.0%	
Run	**$27.05**	**$24.11**	**$79.56**	**$89.31**	**0.340**	**0.270**	**$23.87**	**$22.33**	**$3.18**	**$1.79**	11.8%	7.4%
Busy	$23.87	$22.33	$79.56	$89.31	0.300	0.250	$23.87	$22.33				
Idle	$3.18	$1.79	$79.56	$89.31	0.040	0.020			$3.18	$1.79	100.0%	100.0%
Planned Loss from A-3 / C	**$0.00**	**$0.00**			**0.398**	**0.335**			**$0.00**	**$0.00**		
Setup (Busy)	$0.00	$0.00	$0.00	$0.00	0.098	0.085			$0.00	$0.00		
Run (Busy)	$0.00	$0.00	$0.00	$0.00	0.300	0.250			$0.00	$0.00		
Cost of Doing	**$35.64**	**$31.71**			**0.448**	**0.355**	**$31.66**	**$29.92**	**$3.98**	**$1.79**	11.2%	5.6%

Settings for Doing:

- # of Setups is 1 for both methods.
- Batch size is 1 for both methods.
- Same labor does both Setup and Run.

Cost of Doing: $35.64 for semi-skilled labor and $31.71 for skilled labor, in which

- Planned: $31.66 for semi-skilled labor and $29.92 for skilled labor.
- Planned loss: $3.98 for semi-skilled labor and $1.79 for skilled labor. This loss is from the idle time. More loss and more busy time is from semi-skilled labor because of lower skill.

Cost of Setup: $8.59 for semi-skilled labor and $7.59 for skilled labor, in which

- Planned: $7.80 for semi-skilled labor and $7.59 for skilled labor.
- Planned loss: $0.80 for semi-skilled labor and $0 for skilled labor.

Cost of Run: $27.05 for semi-skilled labor and $24.11 for skilled labor, in which

- Planned: $23.87 for semi-skilled labor and $22.33 for skilled labor.
- Planned loss: $3.18 for semi-skilled labor force and $1.79 for skilled labor.

Cost of Planned Loss from A-3/C (from too much cost per unit for Input): $0 for both methods.

4. The cost information in "Input + Control + Doing".

The information here is from actual measurement where possible and from an educated guess by a skilled production organizer where the actual measure can not be done, as shown in table 4. "Cost (up to and including Doing)" is the sum of "Cost of Doing" and "Passing through cost (Material, Actor-1 and Control-1)". The passing through cost is "Unit" based and not used in "Time" based costing such as Table 3.

Table 4. Cost Information in "Input + Control + Doing" (Case 1)

Cost (Input / Control / Doing)								
Doing + Control + Input	Cost / Item		Planned		Planned Loss		% Planned Loss	
Manufacturing Methods	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor
Material	$500	$500	$500	$500	$0	$0	0.0%	0.0%
Actor-1	$0	$0	$0	$0	$0	$0		
Control-1	$0	$0	$0	$0	$0	$0		
Cost of Doing	$35.64	$31.71	$31.66	$29.92	$3.98	$1.79	11.2%	5.6%
Cost (up to and including Doing)	$535.64	$531.71	$531.66	$529.92	$3.98	$1.79	0.7%	0.3%

Cost (up to and including Doing): $535.64 for semi-skilled labor and $531.71 for skilled labor, in which

- Planned: $531.66 for semi-skilled labor and $529.92 for skilled labor.
- Planned loss: $3.98 for semi-skilled labor and $1.79 for skilled labor.

Cost of Doing: $35.64 for semi-skilled labor and $31.71 for skilled labor.

Material: $500 for all methods.

5. The cost information in "Summary".

The information here is from actual measures by separating "Value added" and "Value loss", as shown in table 5. The value loss is the planned loss that is added to the cost of production, because this is what is planned. This is assumed to be the normal production and the losses are expected to happen. The Planned losses can be stated separately as well as stated with total cost.

The cost in Table 5 dose not include a "Solution Cost" as this only occurs in Step 3 in 3SP when a solution must be found to a production problem that reduces productivity from the planned level.

Table 5. Cost Information in "Summary" (Case 1)

Allocation of Total Cost (per Part)								
Output Items	Cost / Item		Planned		Planned Loss		% Planned Loss	
Manufacturing Methods	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor	Semi-Skilled	Skilled Labor
Total Cost	$535.64	$531.71	$527.38	$527.79	$8.26	$3.91		
Value Added	$527.38	$527.79	$527.38	$527.79				
Value Loss	$8.26	$3.91			$8.26	$3.91		
Material (Planned Loss)	$0.00	$0.00			$0.00	$0.00		
Actor-1 (Planned Loss)	$0.00	$0.00			$0.00	$0.00		
Control-1 (Planned Loss)	$0.00	$0.00			$0.00	$0.00		
Planned Loss from Doing	$3.98	$1.79			$3.98	$1.79		
Planned Loss in Output	$4.29	$2.13			$4.29	$2.13		
Over throughput								
Damaged (Repairable)	$4.29	$2.13			$4.29	$2.13	0.8%	0.4%
Damaged (Non-repairable)								
Obsolete								

Total cost per part: $535.64 for semi-skilled labor and $531.71 for skilled labor, in which,

- Value added (Planned): $527.38 for semi-skilled labor and $527.79 for skilled labor.
- Value loss (Planned loss): $8.26 for semi-skilled labor and $3.91 for skilled labor, in which
  - Planned loss from Doing: $3.98 for semi-skilled labor and $1.79 for skilled labor.
  - Planned loss in Output (Damaged, repairable): $4.29 for semi-skilled labor (0.8% of final items or 1 item in 125 are damaged) and $2.13 for skilled labor (0.4% of final items or 1 item in 250 are damaged).

C 2	Cost statement (CS)			Yes
	CS 1	Original Value (OV)		Yes
	CS 2	Value Added (VA)		Yes
	CS 3	Loss (L)		Yes
		L 1, Value Lost (VL)		Yes
		L 2, Solution Cost (SC)		No
		SC 1	Short-Term Cost (STC)	No
		SC 2	Long-Term Cost (LTC)	No
	CS 4	Seconds Value (SV)		No
	CS 5	Recovered Value (RV)		No
	CS 6	Total Cost (TC)		Yes

6. The cost statement is shown in table 6.

Table 6. Cost Statement (Case 1)

Code	Cost Statements	Cost	
		Semi-Skilled	Skilled Labor
CS 1	**Original Value**	$500.00	$500.00
CS 2	**Value Added**	$527.38	$527.79
CS 3	**Planned Loss (PL)**	$8.26	$3.91
	W 1, Value Lost	$8.26	$3.91
	W 2, Solution Cost (SC)	$0.00	$0.00
	SC 1, Short-Term Cost	$0.00	$0.00
	SC 2, Long-Term Cost	$0.00	$0.00
CS 4	**Seconds Value**	$0.00	$0.00
CS 5	**Recovered Value**	$0.00	$0.00
CS 6	**Total Cost**	**$535.64**	**$531.71**

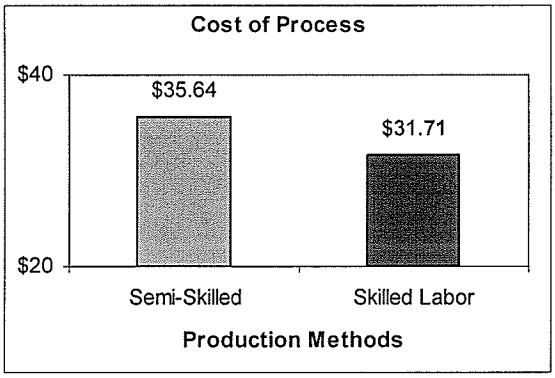
Total cost: $535.64 for semi-skilled labor and $531.71 for skilled labor, in which,

- Original value: $500 for both methods.
- Value added: $527.38 for semi-skilled labor and $527.79 for skilled labor.
- Planned loss: $8.26 for semi-skilled labor and $3.91 for skilled labor, in which
  - Value lost: $8.26 for semi-skilled labor and $3.91 for skilled labor.
  - Solution cost: $0 in this case.
- Seconds value and Recovered value: $0 in this case since repairs must always be made to bring the valve seal to specification.

Decision 1	**Use Solution?**	**Check**
Decision 2	**Search for New Solution?**	**No**

Comparison and result

- Skilled labor is chosen since this method has the lowest cost of process of $31.71 as shown as follows.



- Although the semi-skilled labor method has a lower cost in Input vs. skilled labor, semi-skilled labor generates more planned loss because he requires a longer process time and creates more damage in Output, which ultimately creates a higher cost per final part. Otherwise the semi-skilled labor might be used.

Implement	**Implement**	**Yes**
Stop	**Stop**	**Yes**

11.2 Case 2: Define the Most Suitable Specifications for Using Skilled Labor

Once skilled labor has been chosen to perform the process of "Grind and Lap Valves, Cylinder, P&W R985" in Case 1, the next step is to define the most suitable specifications for using skilled labor. One specification is the "best batch size" for the least cost, which is presented in this case. The aim of this case is to determine the **best batch size** at the process level, which is a task of Step 2 in 3SP.

11.2.1 Description of Situation

The process used in this case is "Grind and Lap Valves, Cylinder, P&W R985" as shown in Figure 11.1 and described in Case 1.

The yearly throughput is 35 "P&W R985" engines, which indicates that about 7 working days are available to rebuild an engine since only one workstation is used to assemble this type of engine in this company. From case 1, the process time to do "Grinding and Lapping" is 0.355 hours including 0.085 h for Setup and 0.25 h for Run. The current batch size used in this company is 9 since each engine of this type has 9 cylinders. The questions here are: Is this size the best batch size? Can other sizes be used such as 5 and 18?

Generally speaking, the advantage of a batch production is a lower unit cost since the cost of common operations such as Setup can be shared by the multiple operations such as Run. But one possible disadvantage is that waiting for enough parts to start the batch may increase the chance that the rebuilt engine will be completed later than planned and a penalty may be charged directly by the customer, or charged indirectly through decreased repeat business. The present batch size is the number of cylinders in a complete engine, which varies related to engine type. One thought would be to use 5 as a standard for all engine types, which might reduce organizing cost in 'Control'. Another idea would be to use two engines worth which in this case would be 18 cylinders.

For the case of 5 cylinders, a batch would often have to wait for parts from another engine which would cause the operation to start later than for the use of one engine's worth of cylinders as the batch size. For the case of 2 engines' worth of cylinders, the decreased cost caused by increased batch size has to be considered relative to the potential increase in cost because of an increased chance of lateness waiting for a second engine.

The batch sizes tested in this case are 5, 9 and 18, which corresponds with Run time of 1.25h, 2.25h and 4.5h per batch, and Setup time of 0.085h per batch in all cases.

11.2.2 Detailed Steps of Determination

The detailed steps to fulfill the task are shown in the following checklist of using SLBPIM. It provides the detailed cost information and process time required for the cost estimation, such as unit cost, amount of material consumed, setup time and run time, which are extracted from the accounting book or an educated guess (e.g. damage rate of the final parts) by experienced personnel who understand and know the designated process and knows the related cost very well. The "Yes" or "No" in the right-most column in the checklist indicates whether the item should be performed or not.

Skilled Labor Based Productivity Improvement Model (SLBPIM)		
3SP		
Three-Step Procedure (3SP), SLBPIM 1		
3SP 1	Step 2: Define the most suitable specification of using skilled labor.	Yes
The task is to determine the "**Best batch size**" to perform the process of "Grind and Lap Valves, Cylinder,		

P&W R985". The batch sizes to test are 5, 9 and 18.

CWS

Costing of Loss and Solution (CLS), SLBPIM 2				
Production Flow and Measurement (PFM), CLS 1				
PFM 1	Production Flow (PF)		Process, "Grind and Lap Valves, Cylinder, P&W R985"	**Shop Floor**
Please refer to case 1 for the details.				
PFM 2	Measurement (M)			**Yes**
		What to Measure	Cost	**Yes**
		How to Measure	Scheduled, snap shot, and detailed level measure	**Yes**
Matrix of Loss-Cause-Solution (MLCS), CLS 2				
MLCS 1	Loss (L)			
	L 1	Definition of Loss		**Yes**
	L 2	Indicators of Loss		**Yes**
	L 3	List of Losses		**Yes**
MLCS 2	Causes (C)			
	C 1	Definition of Cause		**Yes**
	C 2	List of Causes		**Yes**
MLCS 3	Solutions (S)			
	S 1	List of Solutions		**No**
MLCS 4	Linkage between Loss, Cause and Solution (LLCS)			**No**
Costing (C), CWS 3				
C 1	Function Based Costing (FBC)			
	Standard Activity Structure (SAS)			
		SAS 1	Input	**Yes**
		SAS 2	Control	**Yes**
		SAS 3	Doing	**Yes**
		SAS 4	Output	**Yes**

1. The cost information in "Input".

The information here is mainly from the accounting book including the material cost and actor cost required for costing of this process, as shown in table 1.

Table 1. Cost information in "Input" (Case 2)

	Cost of Input																	
Input Items	Cost / Item			Unit Cost			Quantity			Planned			Planned Loss			% Planned Loss		
Batch Size	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18
Material ($/piece)	Cost per Piece																	
Material	$2,500	$4,500	$9,000	$500	$500	$500	5	9	18	$2,500	$4,500	$9,000	$0	$0	$0	0.00	0.00	0.00
Total (Material)	$2,500	$4,500	$9,000							$2,500	$4,500	$9,000	$0	$0	$0			
Actor-3 ($/h)	For Run (Cost per Time)																	
Labor 2	$70.00	$70.00	$70.00	$70.00	$70.00	$70.00	1.0	1.0	1.0	$70.00	$70.00	$70.00						
Machine	$0.50	$0.50	$0.50	$1.00	$1.00	$1.00	0.5	0.5	0.5	$0.50	$0.50	$0.50						
Fixture	$0.50	$0.50	$0.50	$1.00	$1.00	$1.00	0.5	0.5	0.5	$0.50	$0.50	$0.50						
Space	$4.00	$4.00	$4.00	$0.01	$0.01	$0.01	400	400	400	$4.00	$4.00	$4.00						
Tied Cost	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	1.0	1.0	1.0	$0.01	$0.01	$0.01						
Energy	$4.30	$4.30	$4.30	$0.05	$0.05	$0.05				$4.30	$4.30	$4.30	$0.00	$0.00	$0.00			
Water	$0.90	$0.90	$0.90	$0.01	$0.01	$0.01	90	90	90	$0.90	$0.90	$0.90						
Electricity	$1.60	$1.60	$1.60	$0.02	$0.02	$0.02	80	80	80	$1.60	$1.60	$1.60						
Compressed Air	$1.80	$1.80	$1.80	$0.02	$0.02	$0.02	90	90	90	$1.80	$1.80	$1.80						
Total (Actors-3)	$79.31	$79.31	$79.31							$79.31	$79.31	$79.31	$0.00	$0.00	$0.00			

Material: $2,500 for batch size 5, $4,500 for batch size 9 and $9,000 for batch size 18, which is the value of cylinder cores.

Total cost per hour from Actor: $79.31/h for all batch sizes, in which

- Labor: $70/h for all batch sizes.

- Machine: $0.5/h for all batch sizes.
- Fixture: $0.5/h for all batch sizes.
- Space: $4/h for 400 sq ft used for machine and trailer etc for all batch sizes
- Energy: $4.3/h for all batch sizes.

2. The cost information in "Control".

The information here is the cost for penalty and organizing, which is mainly from the accounting book as shown in table 2. The penalty is for the late delivery or poor quality to customer. The organizing cost is for administration such as meetings.

Table 2. Cost Information in "Control" (Case 2)

Cost of Control																		
Control Items	Cost / Item			Unit Cost			Quantity			Planned			Planned Loss			% Planned Loss		
Batch Size	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18
Control-2 ($/h)	Cost per Time																	
Penalty	$10.50		$15.00	$15.00	$15.00	$15.00	0.70		1.00	$10.50		$15.00						
Organizing Cost	$8.00	$10.00	$10.00	$8.00	$10.00	$10.00	1.00	1.00	1.00	$8.00	$10.00	$10.00						
Total (Control-2)	$18.50	$10.00	$25.00							$18.50	$10.00	$25.00	$0.00	$0.00	$0.00			

Total cost per hour from "Control": $18.50/h for batch size 5, $10/h for batch size 9 and $25/h for batch size 18, in which

- Penalty (paid for late delivery): $10.50/h for batch size of 5, sometimes waiting for cylinders from the next engine to start the batch; $0 for batch size of 9 since no delay occurs; and $15/h for batch size of 18, waiting for 2 engines before starting the batch. The $/h here is a management decision based on the average performance.
- Organizing cost (e.g. meeting, supervision): $8.00/h for batch size of 5 assuming an administration efficiency increase; $10.00/h for batch sizes of 9 and 18 cylinders.

3. The cost information in "Doing".

The information here is mainly from the actual measure in terms of time spent, and from Input and Control in terms of unit cost. The information is grouped by "Setup and Run", and further by "Planned and Planned loss", as shown in table 3.

Table 3. Cost Information in "Doing" (Case 2)

Settings	5	9	18
Number of Setups	1	1	1
Batch Size	5	9	18
Same Labor for Setup and Run?	y	y	y

Cost of Doing																		
Doing Items	Cost / Item			Unit Cost			Time (h)			Planned			Planned Loss			% Planned Loss		
Batch Size	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18	5	9	18
Setup	$8.3	$7.6	$8.9	$97.8	$89.3	$104.3	$0.085	$0.085	$0.085	$8.3	$7.6	$8.9	$0.0	$0.0	$0.0	0.0%	0.0%	0.0%
Busy	$8.3	$7.6	$8.9	$97.8	$89.3	$104.3	$0.085	$0.085	$0.085	$8.3	$7.6	$8.9						
Idle	$0.0	$0.0	$0.0	$97.8	$89.3	$104.3	$0.000	$0.000	$0.000				$0.0	$0.0	$0.0			
Run	$132.0	$215.2	$492.3	$97.8	$89.3	$104.3	$1.350	$2.410	$4.720	$122.3	$200.9	$469.4	$9.8	$14.3	$22.9	7.4%	6.6%	4.7%
Busy	$122.3	$200.9	$469.4	$97.8	$89.3	$104.3	$1.250	$2.250	$4.500	$122.3	$200.9	$469.4						
Idle	$9.8	$14.3	$22.9	$97.8	$89.3	$104.3	$0.100	$0.160	$0.220				$9.8	$14.3	$22.9	100%	100%	100%
Planned Loss from A-3 / C	$0.0	$0.0	$0.0				$1.335	$2.335	$4.585				$0.0	$0.0	$0.0			
Setup (Busy)	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.085	$0.085	$0.085				$0.0	$0.0	$0.0			
Run (Busy)	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$1.250	$2.250	$4.500				$0.0	$0.0	$0.0			
Cost of Doing	$140.4	$222.8	$501.2				$1.435	$2.495	$4.805	$130.6	$208.5	$478.3	$9.8	$14.3	$22.9	7.0%	6.4%	4.6%

Settings for Doing:

- # of Setup is 1 for all batch sizes.
- Batch size is 5, 9 and 18.
- Same labor does both Setup and Run for all batch sizes.

Cost of Doing: $140.4 for batch size 5, $222.8 for batch size 9 and $501.2 for batch size 18, in which

- Planned: $130.6 for batch size 5, $208.5 for batch size 9 and $478.3 for batch size 18.
- Planned loss: $9.8 for batch size 5, $14.3 for batch size 9 and $22.9 for batch size 18. This loss is from the idle time. The larger the batch size, the longer idle and the more loss.

Cost for Setup: $8.3 for batch size 5, $7.6 for batch size 9 and $8.9 for batch size 18, which are for planned. Planned loss does not occur in Setup. The different setup cost per batch is because the total cost per hour from "Control" (i.e. cost for Penalty and Organizing) is different from each other.

Cost for Run: $132.0 for batch size 5, $215.2 for batch size 9 and $492.3 for batch size 18, in which

- Planned: $122.3 for batch size 5, $200.9 for batch size 9 and $469.4 for batch size 18.
- Planned loss: $9.8 for batch size 5, $14.3 for batch size 9 and $22.9 for batch size 18.

4. The cost information in "Input + Control + Doing".

The information here is from actual measure where possible and from an educated guess by a skilled production organizer where the actual measure can not be done, as shown in table 4. "Cost (up to and including Doing)" is the sum of "Cost of Doing" and "Passing through cost (Material, Actor-1 and Control-1)". The passing through cost is "Unit" based and not used in "Time" based costing such as Table 3.

Table 4. Cost Information in "Input + Control + Doing" (Case 2)

Cost (Input / Control / Doing)												
Doing + Control + Input	Cost / Item			Planned			Planned Loss			% Planned Loss		
Batch Size	5	9	18	5	9	18	5	9	18	5	9	18
Material	$2,500	$4,500	$9,000	$2,500	$4,500	$9,000	$0	$0	$0	0.0%	0.0%	0.0%
Actor-1	$0	$0	$0	$0	$0	$0	$0	$0	$0			
Control-1	$0	$0	$0	$0	$0	$0	$0	$0	$0			
Cost of Doing	$140	$223	$501	$131	$209	$478	$9.78	$14.29	$22.95	7.0%	6.4%	4.6%
Cost (up to and including Doing)	$2,640	$4,723	$9,501	$2,631	$4,709	$9,478	$9.78	$14.29	$22.95	0.4%	0.3%	0.2%

Cost (up to and including Doing): $2,640 for batch size 5, $4,723 for batch size 9 and $9,501 for batch size 18, in which

- Planned: $2,631 for batch size 5, $4,709 for batch size 9 and $9,478 for batch size 18.
- Planned loss: $9.78 for batch size 5, $14.29 for batch size 9 and $22.95 for batch size 18.

Cost of Doing: $140 for batch size 5, $223 for batch size 9 and $501 for batch size 15.

Material: $2,500 for batch size 5, $4,500 for batch size 9 and $9,000 for batch size 18.

5. The cost information in "Summary".

The information here is from actual measure by separating "Value added" and "Value loss", as shown in table 5. The value loss is the "Planned loss" that are all added to the cost of production, because this is what is planned. This is assumed to be the normal production and the losses are expected to happen. The Planned losses can be stated separately as well as stated with total cost.

The cost in Table 5 does not include the "Solution Cost" as this occurs in Step 3 of 3SP, where losses are not always anticipated.

Total cost per part: $528.07 for batch size 5, $524.76 for batch size 9 and $527.84 for batch size 18, in which,

- Value added (Planned): $515.55 for batch size 5, $512.68 for batch size 9 and $516.01 for batch size 18.
- Value loss (Planned loss): $12.52 for batch size 5, $12.08 for batch size 9 and $11.83 for batch size 18, in which
  - Planned loss from Doing: $1.96 for batch size 5, $1.59 for batch size 9 and $1.27 for batch size 18.
  - Planned loss in Output (Damaged, repairable, 2% of final items are damaged in all batch size):

$10.56 for batch size 5, $10.50 for batch size 9 and $10.56 for batch size 18.

Table 5. Cost Information in "Summary" (Case 2)

Allocation of Total Cost (per Part)												
Output Items	Cost / Item			Planned			Planned Loss			% Planned Loss		
Batch Size	5	9	18	5	9	18	5	9	18	5	9	18
Total Cost	**$528.07**	**$524.76**	**$527.84**	**$515.55**	**$512.68**	**$516.01**	**$12.52**	**$12.08**	**$11.83**			
Value Added	**$515.55**	**$512.68**	**$516.01**	**$515.55**	**$512.68**	**$516.01**						
Value Loss	**$12.52**	**$12.08**	**$11.83**				**$12.52**	**$12.08**	**$11.83**			
Material (Planned Loss)	$0.00	$0.00	$0.00				$0.00	$0.00	$0.00			
Actor-1 (Planned Loss)	$0.00	$0.00	$0.00				$0.00	$0.00	$0.00			
Control-1 (Planned Loss)	$0.00	$0.00	$0.00				$0.00	$0.00	$0.00			
Planned Loss from Doing	$1.96	$1.59	$1.27				$1.96	$1.59	$1.27			
Planned Loss in Output	$10.56	$10.50	$10.56				$10.56	$10.50	$10.56			
Over throughput												
Damaged (Repairable)	$10.56	$10.50	$10.56				$10.56	$10.50	$10.56	2.0%	2.0%	2.0%
Damaged (Non-repairable)												
Obsolete												

C 2	Cost statement (CS)		Yes
	CS 1	Original Value (OV)	Yes
	CS 2	Value Added (VA)	Yes
	CS 3	Loss (L)	Yes
		L 1, Value Lost (VL)	Yes
		L 2, Solution Cost (SC)	No
		SC 1 Short-Term Cost (STC)	No
		SC 2 Long-Term Cost (LTC)	No
	CS 4	Seconds Value (SV)	No
	CS 5	Recovered Value (RV)	No
	CS 6	Total Cost (TC)	Yes

6. The cost statement is shown in table 6.

Table 6. Cost Statement (Case 2)

		Cost		
Code	Cost Statements	5	9	18
CS 1	**Original Value**	$500.00	$500.00	$500.00
CS 2	**Value Added**	$515.55	$512.68	$516.01
CS 3	**Planned Loss (PL)**	$12.52	$12.08	$11.83
	W 1, Value Lost	$12.52	$12.08	$11.83
	W 2, Solution Cost (SC)	$0.00	$0.00	$0.00
	SC 1, Short-Term Cost	$0.00	$0.00	$0.00
	SC 2, Long-Term Cost	$0.00	$0.00	$0.00
CS 4	**Seconds Value**	$0.00	$0.00	$0.00
CS 5	**Recovered Value**	$0.00	$0.00	$0.00
CS 6	**Total Cost**	**$528.07**	**$524.76**	**$527.84**

Total cost: $528.07 for batch size 5, $524.76 for batch size 9 and $527.84 for batch size 18, in which,

- Original value: $500 for all batch sizes.
- Value added: $515.55 for batch size 5, $512.68 for batch size 9 and $516.01 for batch size 18.
- Planned loss: $12.52 for batch size 5, $12.08 for batch size 9 and $11.83 for batch size 18, in which
  - Value lost: $12.52 for batch size 5, $12.08 for batch size 9 and $11.83 for batch size 18.

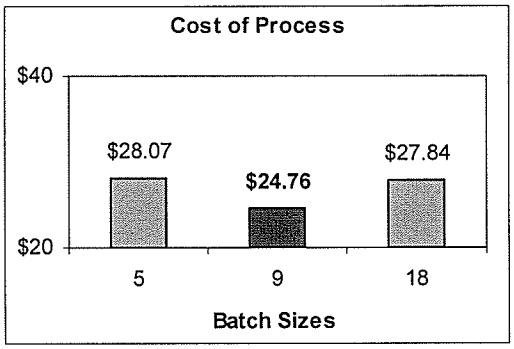
- Solution cost: $0 for all batch sizes.

- Seconds value and Recovered value: $0 for all batch sizes since no waste in this case.

Decision 1	**Use Solution?**	**Check**
Decision 2	**Search for Another Solution?**	**No**

Comparison and result

- The best batch size is 9 since it has the lowest cost of process of $24.76 as shown as follow.



- The least cost batch size is 9, the cylinders of one engine. The other thoughts of improving organizational efficiency or increasing batch size are found to be less cost effective because of penalty costs for late delivery of rebuilt engines.

Implement	**Implement**	**Yes**
Stop	**Stop**	**Yes**

11.3 Case 3: Determine Productivity Level and Waste

In order to understand how well a production process or system is doing, the productivity and waste must be known. This is obtained through Sub-step 1 of Step 3 in 3SP.

11.3.1 Description of Situation

The case presented here is to determine the productivity level and waste at a product level. The product used in this case is "P&W R985 engine" that is rebuilt in Aero-Recip (Canada) Ltd., is shown in Figure 11.3, and has a rebuild rate of 35 engines per year.

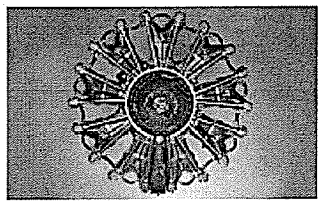


Figure 11.3 "P&W R985" Engine

The processes to rebuild the engine are shown in Figure 11.4.

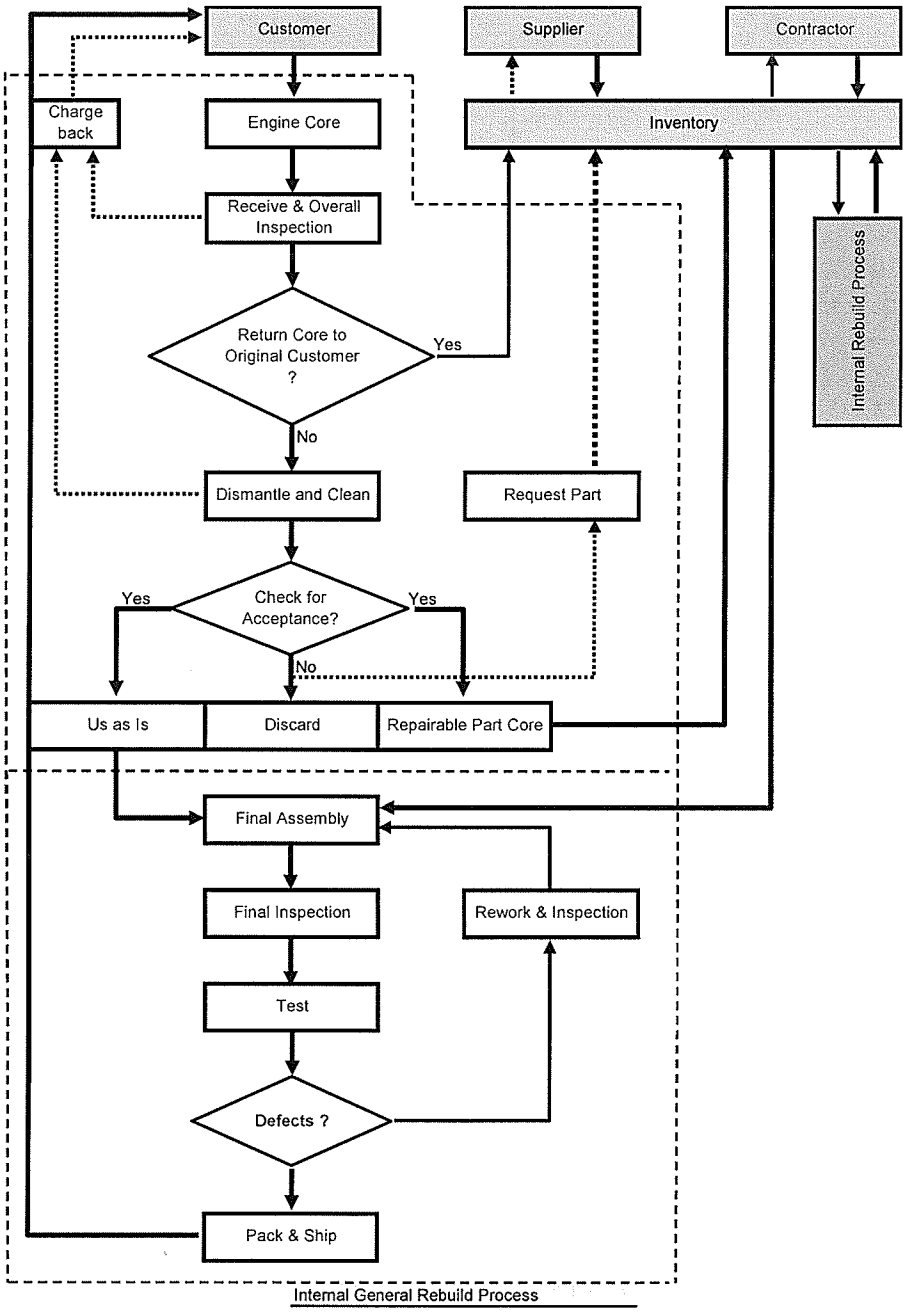


Figure 11.4 Production Flowchart of P&W R985 Engine

The company receives an engine core (Used engine for rebuilding) sent by a customer, and roughly checks this engine core in order to issue a chargeback if some parts are found missing or damaged, or to return the engine core to the owner if the engine is not repairable. The engine core is then dismantled. The dismantled parts are then cleaned through either a physical or a chemical process and inspected for reusability, with three possible outcomes: 1) "Use as is (UAI)" parts that can be used again and sent to the final

assembly station; 2) Reparable part cores that is sent to the inventory for assigning to either an internal rebuilding process or an external contractor for repair, and the rebuilt parts sent back to the final assembly station through inventory; and 3) Discarded parts that require an replacement that triggers a request to inventory for the purchase of new parts that are sent to final assembly station.

Once all required parts are ready, the engine is assembled, inspected and sent to another facility for testing. If the test fails, the engine is repaired and tested again. When all the test specifications are satisfied, the engine is packed and shipped to the customer. The flow diagram is shown in Figure 11.4. A dotted line shows Information flow and a solid line shows Material flow.

11.3.2 Detailed Steps for Determination

The actual productivity level is assessed by comparing it with the "Best specs of using skilled labor" that was determined in Step 2 of 3SP. In this case, the total engine cost of $17,797 was defined in Step 2 as a benchmark without waste, and the total present engine cost is estimated as $18,211 with the waste of $523. This includes the value of the engine core for both case, the value added of $17,797 in benchmark case and $17,688 in the present production case, and the waste of $0 in benchmark case and $523 in the present production case.

The detailed steps to fulfill the task are shown in the following checklist of using SLBPIM. It provides the detailed cost information and process time required for cost estimation, such as unit cost, amount of material consumed, setup time and run time, which are extracted from the accounting book or by an educated guess (e.g. damage rate of the final parts) by experienced personnel who understand the process and know the related cost very well.

The values in the table are for the whole rebuild process, which are the average of the values of all the operations in the process. For example, the quantity of labor used to rebuild the engine is averaged to 2 fulltime skilled laborers although some of the operations may use 1 worker and some other ones use 3 workers; the space used for this

engine is averaged to 800 ft^2 which is allocated for this type of engine including the assembly station.

The extra cost or waste for the ongoing operation relative to the benchmark study of Step 2 in 3SP, is shown on the table row where it occurred. This waste can be tracked to the waste occurrence in a related detailed operation table. For example, over paid wages (waste) is shown in the "Input" table; the penalty (waste) is shown in the "Control" table. This location information of waste can help a great deal in determining exactly what caused each waste.

The "Yes" or "No" in the right-most column in the checklist indicates whether the item should be performed or not.

Skilled Labor Based Productivity Improvement Model (SLBPIM)				
3SP				
Three-Step Procedure (3SP), SLBPIM 1				
Sub step 1 in 3SP 3	**Sub-step 1 in Step 3: Determine the productivity level and waste**			**Yes**
The task is to determine the actual productivity level and waste in rebuilding P&W R985 engines.				
CWS				
Costing of Loss and Solution (CLS), SLBPIM 2				
Production Flow and Measurement (PFM), CLS 1				
PFM1	Production Flow (PF)		Product, "Rebuild P&W R985 Engine"	**Shop Floor**
Please refer to Figure 11.4 for details.				
PFM2	Measurement (M)			**Yes**
		What to Measure	Cost	**Yes**
		How to Measure	Scheduled, snap shot, and detailed level measure	**Yes**
Matrix of Los-Cause-Solution (MLCS), CLS 2				
MLCS 1	Loss (L)			
	L 1	Definition of Loss		**Yes**
	L 2	Indicators of Loss		**Yes**
	L 3	List of Losses		**Yes**
MLCS 2	Causes (C)			
	C 1	Definition of Cause		**Yes**
	C 2	List of Causes		**Yes**
MLCS 3	Solutions (S)			
	S 1	List of Solutions		**Yes**
MLCS 4	Linkage between Loss, Cause and Solution (LLCS)			**Yes**
Costing (C), CLS 3				
C 1	Function Based Costing (FBC)			
	Standard Activity Structure (SAS)			
		SAS 1	Input	**Yes**
		SAS 2	Control	**Yes**
		SAS 3	Doing	**Yes**
		SAS 4	Output	**Yes**

1. The cost information in "Input".

The information here is mainly from the accounting book including the material cost and actor cost required for costing of this process, as shown in table 1.

Table 1. Cost Information in "Input" (Case 3)

Cost of Input												
Input Items	Cost / Item		Unit Cost		Quantity		Planned		Waste		% Waste	
Manufacturing Methods	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status
Material ($/piece)	Cost per Piece											
Material	$6,197	$6,197	$6,197	$6,197	1.0	1.0	$6,197	$6,197				
Total (Material)	$6,197	$6,197					$6,197	$6,197	$0.000	$0.000		
Actor-3 ($/h)	For Run (Cost per Time)											
Labor 2	$150.00	$150.76	$75.00	$75.38	2.0	2.0	$150.00	$150.01		$0.754		0.005
Machine	$1.00	$1.00	$1.00	$1.00	1.0	1.0	$1.00	$1.00				
Fixture	$0.50	$0.50	$1.00	$1.00	0.5	0.5	$0.50	$0.50				
Space	$8.00	$8.00	$0.01	$0.01	800.0	800.0	$8.00	$8.00				
Tied Cost	$1.00	$1.00	$1.00	$1.00	1.0	1.0	$1.00	$1.00				
Energy	$43.00	$43.00	$0.05	$0.05			$43.00	$43.00	$0.000	$0.000		
Water	$9.00	$9.00	$0.01	$0.01	900	900	$9.00	$9.00				
Electricity	$16.00	$16.00	$0.02	$0.02	800	800	$16.00	$16.00				
Compressed Air	$18.00	$18.00	$0.02	$0.02	900	900	$18.00	$18.00				
Total (Actors-3)	$203.50	$204.26					$203.50	$203.51	$0.000	$0.754		

Material: $6,197 in both cases, which is the value of engine core.

Total cost per hour from Actor: $203.5 in the best specs case and $204.26 in the actual case.

- Labor: $150/h in the best specs case and $150.76/h in the actual case with a union agreement by 0.5% of over paid wages defined as waste. In the entire process, some operations use 1 worker and some other ones use 2 workers. But as an average, 2 workers are used in this rebuilding process.
- Machine: $1/h in both cases. Fixture: $0.5/h in both cases.
- Space: $8/h for 800 sq ft in both cases, which is the workspace allocated for assembling this type of engine
- Energy: $43/h in both cases.

2. The cost information in "Control"

The information here is the cost for penalty and organizing, which is mainly from the accounting book as shown in table 2. The penalty is for the late delivery or poor quality to customer. The organizing cost is for administration such as meetings.

Table 2. Cost Information in "Control" (Case 3)

Cost of Control												
Control Items	Cost / Item		Unit Cost		Quantity		Planned		Waste		% Waste	
Manufacturing Methods	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status
Control-2 ($/h)	Cost per Time											
Penalty		$2.50		$2.50		1.0		$0.00		$2.50		1.000
Organizing Cost		$1.00		$1.00		1.0		$0.00		$1.00		1.000
Total (Control-2)	$0.00	$3.50					$0.00	$0.00	$0.00	$3.50		

Total cost per hour from "Control": $0 in the best specs case and $3.50 in the actual case, in which

- Penalty: $0 in the best specs case and $2.5/h in the actual case paid for late delivery defined as waste. The $/h charged is a management decision based previous history.
- Organizing cost: $0 in the best specs case and $1/h in the actual case paid for some unnecessary meetings defined as waste.

3. The cost information in "Doing".

The information here is mainly from the actual measurement in terms of time spent, and from Input and Control in terms of unit cost. The information is grouped by "Setup and Run", and further by "Planned and waste", as shown in table 3.

Table 3. Cost Information in "Doing" (Case 3)

Settings	Best Specs	Actual Status
Number of Setups	1	1
Batch Size	1	1
Same Labor for Setup and Run?	y	y

Cost of Doing												
Doing Items	Cost / Item		Unit Cost		Time (h)		Planned		Waste		% Waste	
Manufacturing Methods	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status
Setup	$407	$416	$204	$208	2.0	2.0	$407	$416	$0.00	$0.00	0.000	0.000
Busy	$407	$416	$204	$208	2.0	2.0	$407	$416				
Idle	$0	$0	$204	$208	0.0	0.0			$0.00	$0.00		
Run	$11,193	$11,531	$204	$208	55.0	55.5	$11,193	$11,427	$0.00	$103.88	0.000	0.009
Busy	$11,193	$11,427	$204	$208	55.0	55.0	$11,193	$11,427				
Idle	$0	$104	$204	$208	0.0	0.5			$0.00	$103.88		1.000
Waste from A-3 / C	$0	$242			57.0	57.0			$0.00	$242.47		1.000
Setup (Busy)	$0	$9	$0	$4	2.0	2.0			$0.00	$8.51		1.000
Run (Busy)	$0	$234	$0	$4	55.0	55.0			$0.00	$233.96		1.000
Cost of Doing	$11,600	$11,946			57.0	57.5	$11,600	$11,600	$0.00	$346.35	0.000	0.029

Settings for Doing:

- # of Setup is 1 in both cases.
- Batch size is 1 in both cases.
- Same labor does both Setup and Run in both cases.

Cost of Doing: $11,600 in the best specs case and $11,946 in the actual case, in which

- Planned: $11,600 in both cases.
- Waste: $0 in the best specs case and $346.35 in the actual case, which is caused by idle time (e.g. when a worker waits for tool to be repaired).

Cost for Setup: $407 in the best specs case and $416 in the actual case, which are the planned cost. No waste in Setup.

Cost for Run: $11,193 in the best specs case and $11,531 in the actual case, in which

- Planned: $11,193 in the best specs case and $11,427 in the actual case.
- Waste: $0 in the best specs case and $103.88 in the actual case.

Waste from Actor / Control: $0 in the best specs case and $242 in the actual case, which is from overpaid wage, penalty and organizing cost.

4. The cost information in "Input + Control + Doing".

The information here is from actual measurement where possible and from an educated guess by a skilled production organizer where the actual measurement cannot be done, as shown in table 4. "Cost (up to and including Doing)" is the sum of "Cost of Doing" and "Passing through cost (Material, Actor-1 and Control-1)". The passing through cost is "Unit" based and not used in "Time" based costing such as Table 3.

Cost (up to and including Doing): $17,797 in the best specs case and $18,143 in the actual case, in which

- Planned: $17,797 in both cases.
- Waste: $0 in the best specs case and $346 in the actual case.

Cost of Doing: $11,600 in the best specs case and $11,946 in the actual case.

Material: $6,197 in both cases.

Table 4. Cost Information in "Input + Control + Doing" (Case 3)

Cost (Input / Control / Doing)								
Doing + Control + Input	Cost / Item		Planned		Waste		% Waste	
Manufacturing Methods	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status
Material	$6,197	$6,197	$6,197	$6,197	$0	$0	0.0%	0.0%
Actor-1	$0	$0	$0	$0	$0	$0		
Control-1	$0	$0	$0	$0	$0	$0		
Cost of Doing	$11,600	$12,147	$11,600	$11,799	$0	$348	0.0%	2.9%
Cost (up to and including Doing)	$17,797	$18,344	$17,797	$17,996	$0	$348	0.0%	1.9%

5. The cost information in "Summary".

The information here is from actual measurement by separating "Value added" and "Value loss", as shown in table 5. The cost in Table 5 does not include the "Solution Cost" as this occurs in Step 3 of 3SP, where waste is not always anticipated.

Table 5. Cost Information in "Summary" (Case 3)

Allocation of Total Cost (per Part)								
Output Items	Cost / Item		Planned		Waste		% Waste	
Manufacturing Methods	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status	Best Specs	Actual Status
Total Cost	$17,797	$18,143	$17,797	$17,688	$0	$455		
Value Added	$17,797	$17,688	$17,797	$17,688				
Value Loss	$0	$455			$0	$455		
Material (Waste)	$0	$0			$0	$0		
Actor-1 (Waste)	$0	$0			$0	$0		
Control-1 (Waste)	$0	$0			$0	$0		
Waste from Doing	$0	$346			$0	$346		
Waste in Output	$0	$109			$0	$109		
Over throughput								
Damaged (Repairable)		$91				$91		0.5%
Damaged (Non-repairable)		$18				$18		0.1%
Obsolete								

Total cost per part: $17,797 for the best specs case and $18,143 for the actual case, in which,

- Value added (Planned): $17,797 in the best specs case and $17,688 in the actual case.
- Value loss (Waste): $0 in the best specs case and $455 in the actual case, in which
  - Waste from Doing: $0 in the best specs case and $346 in the actual case.
  - Waste in Output: $0 in the best specs case and $109 in the actual case, in which
    - Damaged (repairable): $91 in the actual case since 0.5% of the final items were damaged.
    - Damaged (non-repairable): $18 in the actual case since 0.1% of the final items were damaged.

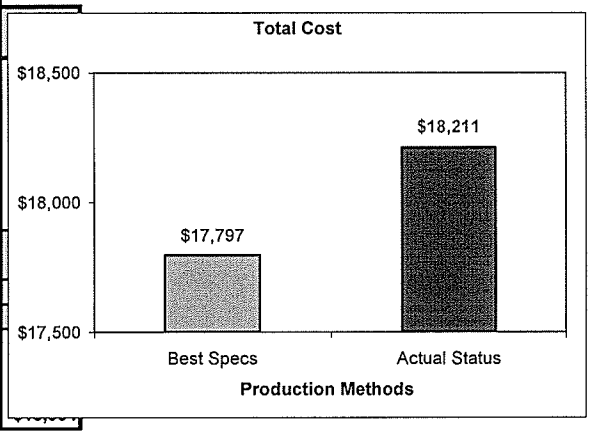
C 2	Cost statement (CS)			Yes
	CS 1	Original Value (OV)		Yes
	CS 2	Value Added (VA)		Yes
	CS 3	Loss (L)		Yes
		L 1, Value Lost (VL)		Yes
		L 2, Solution Cost (SC)		Yes
		SC 1	Short-Term Cost (STC)	Yes

	SC 2	Long-Term Cost (LTC)	Yes
CS 4	Seconds Value (SV)		No
CS 5	Recovered Value (RV)		Yes
CS 6	Total Cost (TC)		Yes

6. The cost statement is shown in table 6.

Table 6. Cost Statement (Case 3)

Code	Cost Statements	Cost: Best Specs	Cost: Actual Status
CS 1	**Original Value**	$6,197	$6,197
CS 2	**Value Added**	$17,797	$17,688
CS 3	**Waste (W)**	$0	$523
	W 1, Value Lost	$0	$455
	W 2, Solution Cost (SC)	$0	$68
	SC 1, Short-Term Cost	$0	$46
	SC 2, Long-Term Cost	$0	$23
CS 4	**Seconds Value**	$0	$0
CS 5	**Recovered Value**	$0	$68
CS 6	**Total Cost**	$17,797	$18,211



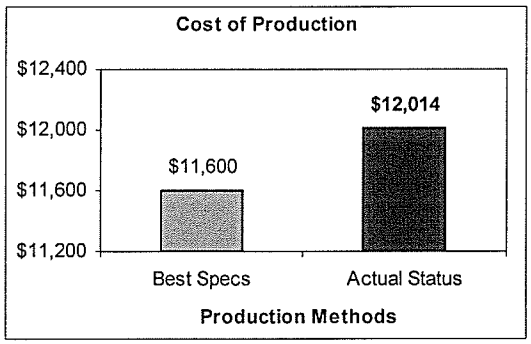
Total cost: $17,797 in the best specs case and $18,211 in the actual case, in which,

- Original value: $6,197 in both cases.
- Value added: $17,797 in the best specs case and $17,688 in the actual case (Less value added by $109).
- Waste: $0 in the best specs case and $523 in the actual case, in which
  - Value lost: $0 in the best specs case and $455 in the actual case.
  - Solution cost: $0 in the best specs case and $68 in the actual case (Solution cost is worth 15% of value lost, in which 10 % is for short-term solutions such as extra repairs and 5% is for long-term solutions such as training).
- Seconds value: $0 in both cases.
- Recovered value: $0 in the best specs case and $68 in the actual case, which is the Sum of Solution cost and Seconds value). The value recovered is the damaged repairable items.

Decision 1	**Use Solution?**	**Check**
Decision 2	**Search for Another Solution?**	**No**

Comparison and result

- Actual case has the highest cost of production of $12,014 as shown as follow.



- The higher cost of production in the actual case ($12,014) is contributed by the higher cost in Input, Control and Doing. The reasons for the higher cost are the lower value added ($109) and waste ($523), in which
  - Value lost is $455 more than the best specs case.
    - Waste from Doing (e.g. overpaid wage and idle etc.) is $346 more than the best specs case.
    - Waste from Output (e.g. damaged parts) is $109 in the actual case, while $0 in the best specs case.
  - Solution cost (e.g. repair and training) is $68 more than the best specs case.

Implement	**Implement**	**Yes**
Stop	**Stop**	**Yes**

Conclusions of Chapter:

- The feasibility of using SLBPIM is demonstrated.
- The tables and calculation structures in SLBPIM can be modified to emphasize any concerns a particular manufacturer has without hurting the overall structure of SLBPIM.

12 Chapter XII: Conclusions and Recommendations

The conclusions and recommendations are addressed in this chapter.

12.1 Conclusions

The main achievements and the conclusions are presented in this section.

12.1.1 Main Achievements

As a practical research thesis, the main achievements are summarized as follows:

- Created a standard approach, called as "**Skilled Labor Based Productivity Improvement Model (SLBPIM)**", to make the analysis and decisions more objectively in the use of skilled labor in manufacturing. This model integrates all concepts and procedures developed in this thesis, which are imbedded in the following two modules: "3 Step Procedure (3SP)" and "Costing of Loss and Solution (CLS)".
    - **3 Step Procedure (3SP)** is a standard procedure, which is a qualitative procedure, to guide how to determine whether skilled labor should be used in production, and how to attain and maintain the defined productivity if skilled labor is used. At each decision point of this procedure, a quantitative model "CLS" is used to determine the exact cost information.
    - CLS stands for **"Costing of Loss and Solution"** that is a costing procedure to provide a complete "Cost statement" for the issues of concern, which includes the total cost and cost of loss or waste. CLS further consists of sub modules: "Matrix of Loss-Cause-Solution (MLCS)" and "Function Based Costing (FBC)".
        - **Matrix of Loss-Cause-Solution (MLCS)** is a module to categorize, group and link the losses, to causes and to solutions in a matrix format, which can be used as a starting point for a company to launch its own investigation.
        - **Function Based Costing (FBC)** is a costing tool to reduce the subjectivity level existing in current costing tools such as Convention Costing (CC),

Activity Based Costing (ABC) and Operation Based Costing (OBC), by standardizing the activity structure, cost information and costing flow.

- Illustrated how to use **SLBPIM** for solving a real production problem by providing three extensive examples. By following these examples, the users are able to perform their own analysis.

12.1.2 Conclusions

The main conclusions are presented as follows.

- The field investigations indicate that skilled labor manufacturing is still a popular production method in developed countries, but they may be moved offshore if the productivity is not improved. Therefore how to improve the productivity is still a very important topic and is worth further research.

- Among the production methods, skilled labor is the **least desired** method that should only be used when absolutely required, since it is slow and has a high cost.

- This thesis is the first to create a model, SLBPIM, to explore the subject of "The best use of skilled labor in manufacturing", and integrate both quantitative and qualitative approaches and provides an analysis at a detailed and overview level.

  - The 3 Step Procedure (3SP) in the model provides a standard guideline of how skilled labor can be best used.

  - Costing of Loss and Solution (CLS) in the model provides a detailed costing tool that can be used in any step in 3SP.

    - CLS provides **waste** information by separating it from the legitimate costs. The types of waste can be easily compared to help direct short term action and determine where an improvement could do the most good.

- SLBPIM provides a series of tables and calculation structures, which include both quantitative and qualitative methods and steps. Those tables and calculation

structures can be modified to emphasize any concern a particular manufacturer has without hurting the overall structure and information required by the model.

- SLBPIM reduces the level of subjectivity in the decision process because of the standardization applied in the model.
- SLBPIM could probably be used for other production methods such as a machine intensive manufacturing at this moment.
- SLBPIM could probably be integrated with current manufacturing information system, such as MRP to identify waste, locate the cause and find the solution.
- SLBPIM could be used not only in manufacturing to improve its productivity, but also probably in other industries such as banking, health or government after more testing.

12.2 Recommendations

The procedure and models developed in the thesis are basically the prototypes and need to be further developed to make them useful in industry. Some recommendations are:

- More research should be done in terms of implementation of SLBPIM, including how to build and maintain the required database; how to collect, clean, integrate and analyze the data from different sources; how to collect and analyze the data at the least cost; and how to commercialize this model.
- The impact of data sensitivity to the SLBPIM should be tested further.
- The entire model system including tables can be further developed to be truly "Easy to use".
- More tests in a wide variety of situations need to be done, so that system usefulness can be extended well beyond skilled labor to other situations such as low or semi-skilled labor.

- Tests related to integrating the systems with a current manufacturing information system such as MRP need to be done to see whether a combined system can handle wastes in production. Ideally, a manufacturing information system should provide the worker with an ability to immediately report any issue found from the workstation. Once the report is received by management, the team can assess the problem, propose a solution and implement the solution quickly.

- Tests in areas other than manufacturing, such as health, banking and government should further extend the use of this model.

13 Appendix

13.1 References

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13.2 Glossary

The terms and concepts used in this thesis are mentioned as follow.

[1] 5S is the Japanese concept for "House Keeping" and stands for "Sort, Set in Order, Shine, Standardize and Sustain". Sort means "get rid of clutter"; Set in Order means "organize the work area"; Shine means "clean the work area"; Standardize means "establish schedules and methods of performing the cleaning and sorting, and maintain this status as long as possible". Sustain means "implement mechanisms to sustain the gains through involvement of people, integration into the performance measurement system, discipline, and recognition".

[2] Activity is the action in general or a task.

[3] Activity at micro-step level is the lowest level of activity in manufacturing such as a reaching and grasping.

[4] Activity at the company level is the activity that benefits the entire company such as determining which product should be produced or which company-wide used facility or machine should be maintained.

[5] Activity at the operation level is the activity that benefits an operation such as a lapping that is a part of surface correction process.

[6] Activity at the process level is the activity that benefits a process such as assembling a part.

[7] Activity at the product level is the activity that benefits a product such as creating "Bill of Material" for a specific product.

[8] Activity at step level is the activity that benefits a step such as a setup and cleaning.

[9] Activity based costing (ABC) is a tool to quantitatively measure the activity in terms of cost including overheads whenever appropriate.

[10] Baseline is the benchmark to reflect how well a production process can do.

[11] Capacity is the physical facilities, personnel and process available to meet the product or service needs of customers.

[12] Cause is any issue that can create a loss in any part of a production process.

[13] Control is the effort to plan, guide and adjust "Doing" through an open or closed control loop.

[14] Conventional costing (CC) is the most established accounting system to capture and distribute resource costs in terms of direct and indirect cost, and is based on the organizational element account or the budgetary account.

[15] Cost driver is any situation or event that causes a change in the consumption of a resource, or influences quality or cycle time.

[16] Cost element is the lowest level component of a resource, activity, or cost object.

[17] Cost statement is a complete cost picture for the issue of concern, which covers all cost information related to production and customer satisfaction in terms of "Quantity, Quality and Time", which is presented by: 1) Original value, 2) Value added, 3) Loss (Value lost + Solution cost (Short-term cost + Long-term cost)), 4) Seconds value, 5) Recovered value, and 6) Total cost.

- Original value is the value of "Inputs", which could be the cost of new material purchased or old product to be rebuilt.
- Value added is the value increased through performing the activity, which is a source of the profit.
- Loss is any value of "Output" decreased after performing the activity, which includes the value loss and the cost for solution.
  - Value loss is the value decreased during performing the activity.
  - Cost for solution is the cost of implementing the solution, which is the sum of "Short-term solution cost" and "Long-term solution cost".
    - Short-term solution cost is the cost to implement the short-term solution.
    - Long-term solution cost is the cost to implement the long-term solution.
- Seconds value is the market value of defects (As it is).
- Recovered value is the value restored through solution such as repair, which is the sum of "Seconds value" and "Solution cost".
- Total cost is the sum of "Original value", "Value added" and "Loss".

[18] Defect free is "No defect" in the item produced.

[19] Detailed measurement is the detailed information of how the activity is exactly performed.

[20] Disappearance is the lost output after Doing.

[21] Doing is the execution effort to actually transform the material to the output, which includes setup, run and wait.

- Setup is the effort to make the machine, and sometimes the operator, ready to do the job.
- Run is the effort to transform the material from one stage to another.
- Wait is doing nothing.

[22] Duration is how long the measure lasts, which could be snapshot measure and continuous measure.

- Snapshot measure is a one-time measure, which is used for understanding how the activity is performed at a specific moment such as the final step in the assembling line.
- Continuous measure is a non-stop measure, which is used for understanding how the activity is performed for a specific period such as a month, a quarter or a year.

[23] Excessive availability is the quantity more than planned.

[24] Excessive capability is the capability more than planned.

[25] Expert system is a knowledge based decision system that overcomes the problem of computational complexity by employing heuristic knowledge.

[26] Extra cost is the cost more than planned.

[27] Function is an assigned action, activity or duty.

[28] Function based costing (FBC) is a costing tool that has a standard activity structure, standard cost information and standard costing flow.

[29] Idle is a waiting without doing anything.

[30] Incentive is the money spent to obtain the required quality and timeliness of production.

[31] Input is any resource required to perform an activity, including the physical resource and information.

- Physical resource is a physical existing resource that is separated into material and actor.
  - Material is the consumable and modifiable resource that is transformed to the produced item.
  - Actor is the non-consumable resource that contributes the effort to transformation.
    - Labor is a person to do the job.
    - Machine is the equipment to transform the material from one form to another.
    - Fixture is the tool to assist the machine to function properly.
    - Space is the place to perform the job including shop floor (Area to transform the raw material to semi-finished or final product), inventory (Area to store raw, semi-finished or final products for balancing the production flow between supply and demand) and transportation area (Space to deliver the materials and items between sender and receiver).
    - Contract is the "Outsource" of work to increase the internal production capacity or reduce the cost.
- Information is the info required to perform an activity including BOM (Bill of material, a list of all parts contained in the product), specification (Detail required for defining the part or product, and determining the quality of the finished part or product), operation sheet (Detailed instruction of performing the job in terms of

part routing, job sequence and so on) and shop order (Form to provide shop floor an authorization to proceed with production in terms of quantity, quality and time).

[32] Loss is any reduction in a dollar value or extra cost increased.

[33] Machine manufacturing is the approach in which the machine contributes the major cost.

[34] Manufacturing is a collection of activities which transform raw materials into semi-finished or final products.

[35] Missing part is the part can not be found when required.

[36] Moment is the time to start or stop a job.

[37] Money Tied to Product is the interest paid (tied up) on material in stock.

[38] Multiple-skills worker possesses the knowledge and abilities to perform many complex job types independently.

[39] Neural network is a parallel processing and learning system, which improves an expert system.

[40] Non-skilled labor manufacturing is the approach in which non-skilled labor contributes the major cost.

[41] Obsolescence is the output no longer used as time elapses or the style changed and degrades the value.

[42] Off shift is the time, specified by the company, that the plant or the area of interest in the plant is closed. Sometimes, Maintenance & Repair is carried out during this period. Some days, the company may bring workers in for an overtime period to catch up if production problems occur through the last day or week. The machines continue to cost money even though they are not being used.

[43] On shift is the time for doing work defined by the company, which includes Work, No work, Wait and Maintenance & Repair.

- Work is the effort to produce items by using resources such as material, operator, machine, fixture, and space. The effort includes Prepare, and Setup, Run and Minor maintenance & repair.
  - Preparation is all efforts to gather materials, information, tools and fixtures to perform the next operation or set of operations.
  - Setup is specifically getting the Machine ready to perform the next operation. Efforts include removing the last used fixture and installing the next one, and changing cutting tools.
  - Run is the attempt to actually produce items, although the production may not actually occur if the parts move too slowly to or from the operation.
  - Minor Maintenance & Repair is minor maintenance and repair on the machine that is scheduled or random, and is expected during the normal operation of the machine. For example, changing the broken needle on a sewing machine, changing the dull cutter for a cutting machine.
- No work is done because of insufficient sales, late arriving material or something wrong in the plant. If this situation continues for some time, the workers are usually laid off or terminated. No work includes Rest break and Waiting periods.
  - Rest break can be seen as maintenance for the operator. The typical pattern is a 15 min break in the morning that the company pays for, a half hour lunch break that the company may or may not pay for, a 15 minute break in the afternoon that the company pays for, and a 5 minute end of shift cleanup period that the company pays for. In industrialized and many developing countries, this allowance for breaks is a legal requirement and cannot be removed.

- Waiting period means doing nothing for whatever reasons, for example, wait for the rest break or Maintenance & Repair.
    - Wait for rest break is the time that an operator waits for a rest break to start, without running an operation that takes a long time, to make sure that the operation does not run during the rest break, and causes him to miss some of it. The operator usually times the operations through the morning so that the time gap just before the break is a small one. This is not defined as a part of the process and therefore not an official time.
    - Wait for Maintenance & Repair is the time waiting for the maintenance or repair, which could range from several minutes to several days. If production were JIT, this wait would close down all related operations and supplier or customer operations as well, and cause a major problem.

- Maintenance & Repair means the maintenance or repair activity. Maintenance operations are usually done "Off Shift" at scheduled times so that the shift can still be run as normal; Repair usually must be done whenever a machine breaks.

[44] Operation based costing (OBC) is a costing tool to improve ABC by adding a work and resource content to an operation, through the use of eight cost elements.

[45] Operations research is mathematics and statistics based approach to analyze the data.

[46] Operator is a labor to do the job for changing the material.

[47] Over throughput is the quantity of output more than planned.

[48] Overall measurement is the rough measure, which is used to understand how the activity is performed in general.

[49] Output is the outcome after Doing is executed, which includes the physical item (e.g. part) and related information (e.g. identity, quantity, quality, time and next user).

- Identity provides the output identify such as a unique number or name.
- Quantity provides the throughput information such as 1000 parts/day.
- Quality provides the quality information such as acceptance rate and non-conformance rate.
- Next user is either an internal or external user.

[50] Penalty is the payment for customer's dissatisfaction related to timing, quality and quantity.

[51] Production flow chart includes information flow and material flow for all activities involved to produce the required item, including the administrative activity.

- Information flow includes the static information and dynamic information.
  - Static information is the descriptive information about the production such as the aim, task, capability, production level, material, penalty policy and unit cost.
  - Dynamic information is the interactive information between upstream and downstream to show how the involved activities interact with each other to produce the required item.
- Material flow shows where the material or part comes from and goes to.

[52] Productivity is a rate of how much input can be converted to output, which reflects the efficiency of a conversion system such as a production system. Productivity is the inverse of cost.

[53] Quantity is how many resources and how much effort are used to perform the activity.

[54] Quality is how good the resources are and how well the efforts are performed.

[55] Remanufacturing is a process in which a worn-out product or component is restored to like-new condition, which includes repair, overhaul and refurbish. Production scheduling for ordinary manufacturing operation requires the use of standards related to part routing and processing time. These standards are not available in remanufacturing operations due to the random nature of both the amount of work required and the routing required for rebuilding because the disposition of parts, routing, and amount of work required can only be determined after a unit is brought into the system. For example, until a unit or part is disassembled and inspected, there is no way to know what parts need repair or how extensive the needed repair will be.

[56] Reparable damage is the "Out of Specification" but repairable.

[57] Required amount is the quantity requested by the customers or inventory.

[58] Required customer lead-time is the time from customer order to customer receipt, which includes the production time and delivery time.

[59] Resource is the economic element applied or used in performing activities or direct supporting cost objects. The resource element includes people, materials, supplies, equipment, technologies and facilities.

[60] Rework is the part is out of specification and needs to be reworked.

[61] Right cost is the cost accepted by the market.

[62] Run is the effort to transform the material from one stage to another, such as drilling, cutting and welding.

[63] Scheduled continuous detailed measure is a detailed picture on whether the activity is performed as required during a scheduled time frame.

[64] Scheduled continuous overall measure is an overview picture on how the activity is performed during a scheduled period like a winter.

[65] Scheduled snapshot detailed measure is a detailed picture on whether the activity is done as required at a scheduled moment.

[66] Scheduled snapshot overall measure is an overview picture on how the activity is performed at a scheduled moment like the month end.

[67] Scheduling is to encompass all the decisions related to the allocation of resources to activities over the time domain. For example, sequencing the order of performing operations.

[68] Scrap is the part is defective and needs to be replaced.

[69] Semi-skilled worker possesses a certain level of a specific ability (obtained through training) to perform a specific skilled job with some supervision.

[70] Setup is the effort to make the machine, and sometimes operator, ready to do the job, which includes collecting, removing the last fixture used, installing the next fixture and changing tools.

[71] Shop order gap is the delay between shop orders

[72] Shop order overlap time is the time that the downstream shop order starts running before the upstream shop order stops.

[73] Skill is a proficiency, facility, or dexterity that is acquired or developed through training or experience.

[74] Skilled labor manufacturing is the approach, in which skilled labor contributes the major cost.

[75] Solution is any way to eliminate the causes of loss and reduce loss.

- Short-Term solution is the solution aimed at restoring the customer confidence as soon as possible by correcting the problems in terms of product quantity, quality and timeliness requested by a customer.

- Long-Term solution is the solution required to maintain the defined productivity for the long-term.

[76] Standardization means less variety and customization.

[77] Statistical process control (SPC) is a statistical based tool that monitors a long-term performance of an activity. One of its applications is to identify the causes of low quality performance.

[78] Support cost is the cost associated with doing the job indirectly, such as the cost of the information system, process engineering or purchasing.

[79] Tailcone is a component houses an auxiliary power unit that is used when the aircraft is on the ground.

[80] Time is the moment and duration to perform the job.

[81] Tooling is the activity of building a Jig, tool or the software necessary for performing the operation, which is normally a part of "Setup". It could be separated from Setup if tooling cost is the focus of analysis. Generally speaking, tooling is required if the production is to run for the first time.

[82] Total operation gap is the total gaps between operations.

[83] Un-reparable damage is the "Out of Specification" and un-repairable.

[84] Un-skilled worker possesses an ability (obtained through a basic education or general training) to perform a basic routine job that does not require any advanced knowledge.

[85] Unit cost is the cost associated with a single unit of measure underlying a resource, activity, product or service. It is calculated by dividing the total cost by the measured volume. Unit cost must be used with caution as it may not always be practical or relevant in all aspects of cost management.

[86] Unique-skill worker possesses a complete knowledge and ability (obtained through intensive training) to perform a specific, complex job independently.

[87] Unplanned busy is the time spent for unnecessary activities, such as duplicated inspections and un-required rework.

[88] Waste is any unplanned loss in terms of quantity, quality and time in manufacturing.