APPLICATION OF LEAN MANUFACTURING TECHNIQUES FOR THE DESIGN OF THE AIRCRAFT ASSEMBLY LINE

by

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B.S. Mechanical Engineering, CETYS Universidad, 1994

Submitted to the Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

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Application of Lean Manufacturing Techniques for the Design of the Aircraft Assembly Line

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ABSTRACT

The final assembly line for the Boeing Commercial Airplanes 717 Program is currently implementing "The 9 Tactics", a methodology based on the lean manufacturing principles to transform the current processes to continuous moving lines. The first two tactics, Value Stream Mapping and Balancing the Line define the manufacturing system configuration (the quantity of airplanes to load in the conveyor, headcount and workload per workstation) and the process to develop the production execution plans.

Understanding of the tradeoffs in the allocation of resources when selecting the most profitable manufacturing system configuration is a complex task for the Industrial Engineering department. The preparation of these plans is iterative and time-consuming, complicated by constraints such as assembly sequences and space limitations.

The problem solved during the internship was to propose a methodology or framework for the implementation of the Value Stream Mapping and Balancing the Line tactics, considering the economics involved and the frequent production fluctuations in the production rate.

The framework proposed is based on lean techniques and economic analysis, and is the main product delivered to the sponsor company. The economic analysis of the assembly line configuration alternatives is supported by the application of the Economic Profit financial metric (also known as Economic Value Added).

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EXECUTIVE SUMMARY

The final assembly line for the Boeing Commercial Airplanes 717 Program is currently implementing "The 9 Tactics", a methodology based on the lean manufacturing principles to transform the current processes to continuous moving lines. The first two tactics, Value Stream Mapping and Balancing the Line define the manufacturing system configuration (the quantity of airplanes to load in the conveyor, headcount and workload per workstation) and the process to develop the production execution plans.

Understanding of the tradeoffs in the allocation of resources when selecting the most profitable manufacturing system configuration is a complex task for the Industrial Engineering department. The department is also required to utilize Boeing's standard method to calculate the profitability of a project, the "Economic Profit" calculation (EP = net operating profit after taxes - opportunity costs of the assets used). Once the system configuration is selected, the next step for the Industrial Engineers (IE's) is to Balance the Line or evenly distribute the resources via production execution plans or "bar charts" to meet the production requirements. The preparation of these plans is iterative and time-consuming, complicated by constraints such as assembly sequences and space limitations. The process for balancing the line is not standardized and each IE prepares the plans based on his/her experience. For every production rate change, the IE department develops a new assembly line configuration and the corresponding production execution plans. The 717 Program has experienced several rate breaks (production rate changes) during its 2 years in operation and more fluctuations are expected for the future.

The problem solved during the internship was to propose a methodology for the implementation of the first two tactics, Value Stream Mapping and Balancing the Line, considering the economics involved and the frequent production rate breaks.

The following activities are the core elements of the proposed framework:

- A current VSM was constructed using a heuristic approach, analyzing the sequence of only the critical activities. The manufacturing lead time for the assembly line resulting from this analysis was immediately used by the 717 Program management to plan the next production rate slowdown.

- The selection of the optimal assembly line configuration was supported by a spreadsheet tool that calculates the operating costs and costs of capital charge (opportunity costs of the assets used) for different assembly line configurations and relates this information to Boeing's EP analysis. With this tool management now has a clear understanding of the tradeoffs in the allocation of the resources for the final assembly line. The tool showed that at low production rates, the resulting optimal configurations have long manufacturing lead times, counterintuitive to the lean manufacturing teachings.

- The future VSM was developed by multidisciplinary teams with employees from production, industrial engineering, quality assurance, lean manufacturing, etc. who re-sequenced the current VSM jobs to the allotted time from the new configuration. This methodology, called "Sequence Workshops" was practically applied to re-sequence the current VSM jobs performed in the airplane's flight deck.

- By design, the bar charts balance the use of the resources to the customer requirements. The sequence of steps to prepare the bar charts was optimized or de-coupled using Axiomatic Design. The optimized sequence was standardized in a procedure for further Industrial Engineer's training. This procedure also describes the practices to continuously improve the bar chart's effectiveness on balancing the resources.

The key lessons learned are:

- The application of lean manufacturing techniques in the design of manufacturing systems and production execution plans without an understanding of the economic tradeoffs in the allocation of the resources can result in designs and plans that will sub-optimize the profitability of the business.

- The EP analysis assists the Industrial Engineering activity in understanding the sensitivity of the operating costs and the capital charge to the bottom-line results when selecting from manufacturing system design alternatives.

- Heuristic approaches rather than sophisticated and costly software must be applied when the problems are complex and the planning resources scarce.

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I. BACKGROUND

The 717 Program

After the McDonnell Douglas - Boeing merger in 1997, the original McDonnell-Douglas MD-95 program was renamed to the 717 Program for the Boeing Commercial Airplanes Division.

The Boeing Commercial Airplanes' 717 Program serves the regional airlines market with a 106-passenger airplane, the 717-200. The 717 Program started customer deliveries in 1999, and since then the 717-200 has had the highest reviews in its class in performance (reliability, fuel efficiency, passenger comfort) by its customers.

The economic health of a commercial airplane program is very sensitive to the market demand, due to the high fixed operating costs. The forecasted customer orders for the 717 Program to date have not reflected the original market projections. Consequently, since the beginning of its operations, the 717 Program has struggled to survive Boeing Commercial Airplane Group (BCAG) financial assessments about the continuity of the program.

Given the financial pressures at the time this thesis was written (January to April, 2002), the 717 Program operates under a continuous cost reduction strategy. Part of this strategy is to be at the vanguard of the implementation of Lean Manufacturing initiatives for cost reduction.

Boeing Commercial Airplane Group Approach to the Lean Philosophies

The Lean principles at the Boeing Commercial Airplanes Group (BCAG) are explained in a clear, simple language that every employee can understand (Reference 1).

Lean is defined by Boeing as "a set of principles, concepts and techniques designed to eliminate waste and produce an efficient just-in-time production system that will deliver to customers exactly what they need, when they need it, in the quantity they need, in sequence, and without defects... applying Lean practices is one way to reduce costs, improve performance and create value for the company".

Two Concepts

The two principal pillars that support Boeing's Lean Production System are the concepts of just-in-time (JIT) and Jidoka (Japanese word for "error-free production"). They are explained below, in Boeing's terms:

JIT: simply means that you get what you need, where and when you need it. The power of JIT lies in what it can do for the bottom line. Having materials arrive at the factory in time to enter the production process allows a company to minimize the amount of inventory it must hold and store—a costly activity. By reducing the overall flow time of our product, we can reduce many of the associated costs of production, such as inventory holding costs.

Jidoka or error-free production: We can achieve high quality, error-free production by doing three things: stop production anytime a defect is detected, design reliable processes and machinery to prevent defects from occurring in the first place, and separate human work from machine work so that machines do the repetitive and dangerous tasks, while people perform the work that requires decision-making and problem-solving skills. By continuously driving out the waste of imperfection and improving the quality of our products, we can eliminate the amount of time and money spent on rework, scrap and lost production time.

Three Key Principles

Boeing also proposes that Lean is based in three key principles:

TAKT Paced Production: it describes the rate of assembly in a factory. Lean does not mean doing things faster; it means doing them at the right pace. Essentially, the customer's rate of demand establishes the pace or TAKT time (TAKT is a German word that means interval of time or rhythm). Rather than a race, Lean sets the pace in the factory, ensuring that the customer's needs are met on time.

One-Piece Flow: it is the opposite of batch production. Instead of building many products and then holding them in queue for the next step in the process, products go through each step in the process one at a time, without interruption. Producing a product one at a time continuously improves quality and lowers costs.

Pull Production: it is the opposite of push and means products are made only when the customer has requested them, and not before. Doing so prevents building products that are not needed.

The application of those principles will lead Boeing to faster customer response, higher product quality, more efficient use of space, and lower costs.

The Techniques and their Interaction with the Concepts and Principles:

The Boeing Lean Production System is an application of the existing Lean Manufacturing/ Lean Enterprise literature available: the Japanese concepts from Ohno (Toyota Production System, Reference 2), Hirano (JIT, visual workplace concepts, Reference 3), etc., the American studies in lean performed by Womack and Jones (Lean Thinking, Reference 4), Rother and Shook (Learning to see, Reference 5), Massachusetts Institute of Technology's Lean Enterprise Initiative (Reference 6), etcetera.

These concepts and principles are put into practice by applying a number of techniques such as standardizing work, using visual signals, defining standard work-in-process, etc. to the three principal resources: people, materials and machinery. Figure I-1 is one graphic representation of the interaction of the different elements of the Boeing Lean Production System. In Boeing's terms:

"In a Lean production system, the right resources and the right tools must be applied to achieve three key Lean principles. For instance, you need people using standard work to produce a product at a pace that matches the rate of customer demand—TAKT time. You also must know the standard quantity of materials you need to keep everyone in the process operating, and you need a signal which can tell you to "build one more" in order to achieve one-piece flow. And you must have machines available when you need them, and again, a signal to tell you when there's a problem".

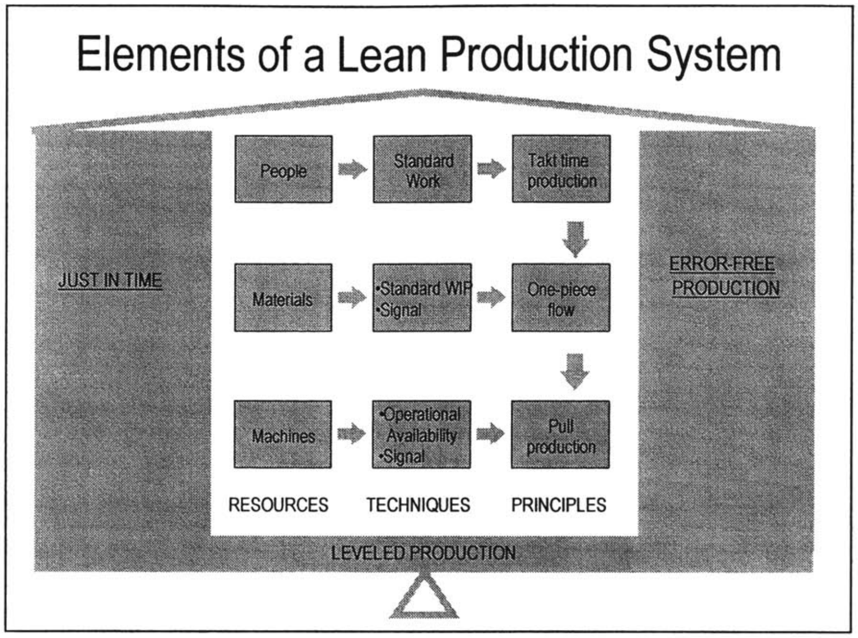


Figure I-1: Boeing Production System

Value Stream Map

BCAG uses the Value Stream Map methodology developed by Rother and Shook in their book "Learning to See" (Reference 5) to graphically represent the current state of the process analyzed and to determine the desired (future) state after the implementation of a project. From Boeing's literature:

"Developing a Lean enterprise means looking at the processes inside and outside our factory doors and applying the contributions of our employees at strategic points in what is known as the value stream. Airplane production can be seen as a steady stream of interconnecting processes. A value stream describes the entire set of activities necessary to create and produce a product from detail design through production, delivery and post-delivery support. Each part of our enterprise—marketing, sales, engineering, manufacturing, customer services, our suppliers and our suppliers' suppliers—must be lean for the entire enterprise to be lean."

Employee Empowerment and Communication

BCAG conveys a strong message of the benefits to the employees and the role they play in the implementation of the Lean enterprise (Reference 1):

"A Lean enterprise depends on all employees who are empowered to challenge and change existing processes. Boeing relies on you, the people who work with the processes and products every single day. Your ideas and expertise in identifying and removing the waste in our engineering, manufacturing and support processes are essential".

"A Lean enterprise benefits everyone in the value stream. Shareholders get increased profits and share value because of reduced waste. Customers and suppliers gain through partnership with lean companies by increasing their own value, reducing cost, and increasing profitability. Most importantly, you gain through empowerment, because those closest to the work make the improvements. The result is a stronger company, which means growth, and ultimately, better job security. And, through the Share Value program, you will also see gains associated with stock price increases."

Teamwork

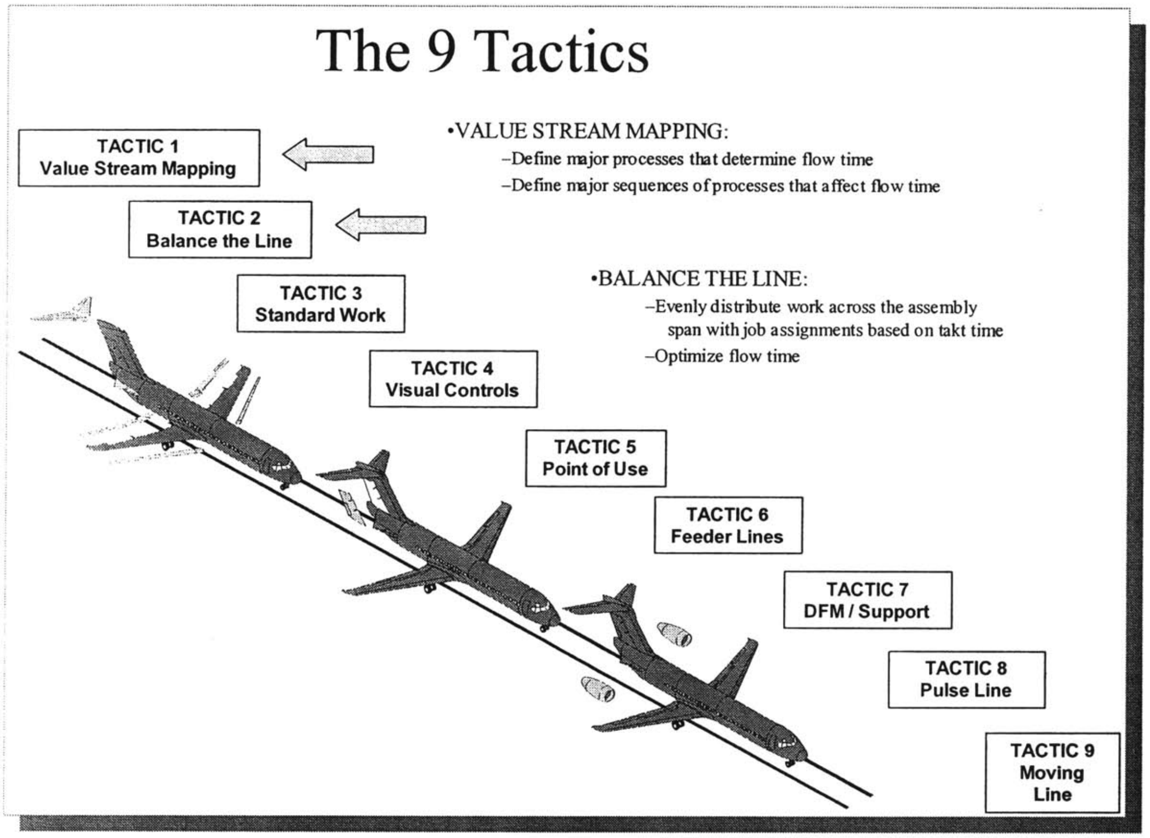
The Boeing Company has established several standardized approaches to teamwork, each designed to achieve the type of improvement desired (Reference 1).

For incremental continuous improvement, it is suggested to conduct accelerated improvement workshops (AIW's), which are Kaizen-like events (Reference 7) that combine training, planning, and implementation to make rapid improvements on the factory floor. During an AIW, managers have the responsibility to empower employees to make significant changes to work procedures, work rules, machines, and the flow of the work.

Other types of teamwork are: the autonomous maintenance workshops (AMW) focused on giving the responsibility to the operators and the maintenance personal for the daily care and critical component checks of their equipment; the distribution workshops, to improve the flow of material and information between the suppliers and the factory; the production preparation process workshops, to achieve major improvements in the design of parts, equipment, and process.

9 Tactics to Convert to a Moving Line and to Improve the Operational Efficiency

The 9 tactics represent a practical application of Boeing's lean manufacturing concepts, principles and techniques to meet the ultimate goal of implementing a continuous moving line for the aircraft's final assembly manufacturing system (Reference 1).



The 9 Tactics

TACTIC 1
Value Stream Mapping

TACTIC 2
Balance the Line

TACTIC 3
Standard Work

TACTIC 4
Visual Controls

TACTIC 5
Point of Use

TACTIC 6
Feeder Lines

TACTIC 7
DFM / Support

TACTIC 8
Pulse Line

TACTIC 9
Moving
Line

•VALUE STREAM MAPPING:
–Define major processes that determine flow time
–Define major sequences of processes that affect flow time

•BALANCE THE LINE:
–Evenly distribute work across the assembly span with job assignments based on takt time
–Optimize flow time

Figure I-2: The 9 Tactics to Convert to a Continuous Moving Line

9 Tactics programs are currently in the process of implementation for the 717, 737, 747, 757, 767, and 777 Programs (See Figure I-2). See also Appendix 1 for a description of each of the 9 Tactics.

From Boeing literature for the 9 Tactics: "The Boeing's 9 Tactics represent an approach that can be used in a manufacturing environment to increase efficiency and the ability to manage for value. Although each tactic can provide immediate benefits to an organization, it is the integration of these tactics with the quality system, business plans and supply chain that will provide the greatest benefit to the Boeing enterprise and its employees".

BCAG Managing for Value and Economic Profit

Managing for Value

Managing for value is the decision-making process BCAG wants its employees to follow to evaluate all business decisions: from big decisions as the reconfiguration of the assembly line, to small decisions as the rearrangement of tooling in the work area.

Boeing describes this process as follows (Reference 8):

"In its simplest sense, Managing for Value is a decision making process that can be applied to all business decisions- big or small. When faced with multiple options, employees should choose the one that generates the most value as measured by economic profit over the long term. By maximizing economic profit over time, Boeing will provide excellent returns to shareholders, new and innovative products and services for customers, and a secure future for employees.

This process will be used to determine what business opportunities to pursue, what new products and services to offer, and the long-range strategy of the company. It can also be used to make day-to-day decisions. Choices that help improve quality, speed up cycle time, or reduce cost and inventory all add value.

These choices can include rearranging the tools in the work area to streamline production processes, standardizing the computing and telephone equipment in your office, or eliminating variations in processes the work teams use every day.

The goal is to make Boeing one of the top-performing companies in terms of shareholder returns, customer satisfaction, and employee satisfaction" (see Figure I-3).

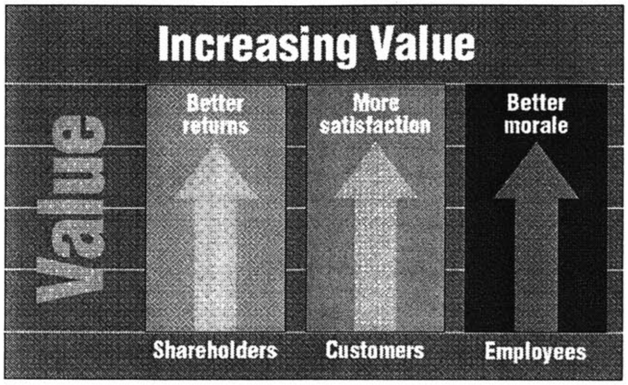


Figure I-3: Managing for Value Concept

Economic Profit

As stated above, Boeing employees should choose the project/decision that generates the most value as measured by economic profit over the long term (Reference 8). The Economic profit measurement is defined as the financial measure net operating profits after taxes (NOPAT, also known as net income) minus the Capital Charge (net assets times the cost of capital, see Figure I-4).

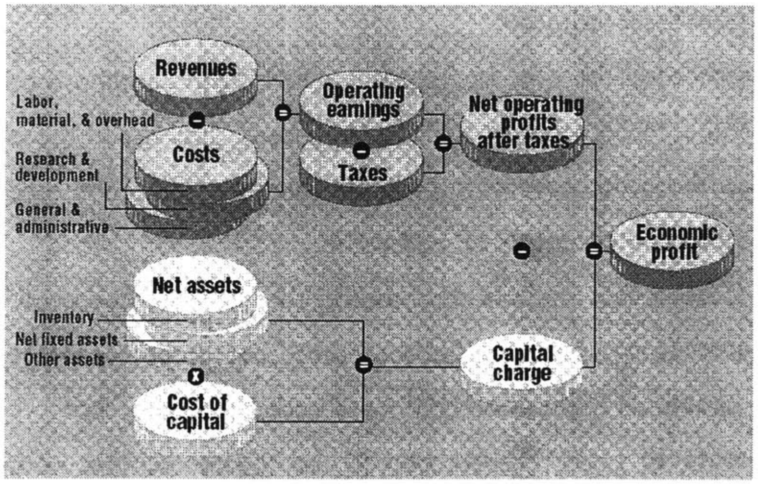


Figure I-4: Economic Profit Calculation

Boeing also argues that:

"Every organization within Boeing influences costs, the company's use of assets, or the company's revenues. The Economic Profit formula helps the employee to see how his or her organization contributes to the company's overall financial health.

Unlike traditional ways of measuring profit, this formula takes into account a capital charge-that is, how much money Boeing spends on assets (such as facilities, tooling, computers, and inventory) to build products, provide services, and generate sales. If the money generated exceeds the cost of assets, then the particular product or program creates value for the company. If not, then the product or program destroys value".

How the Managing for Value Concept Relates to Economic Profit:

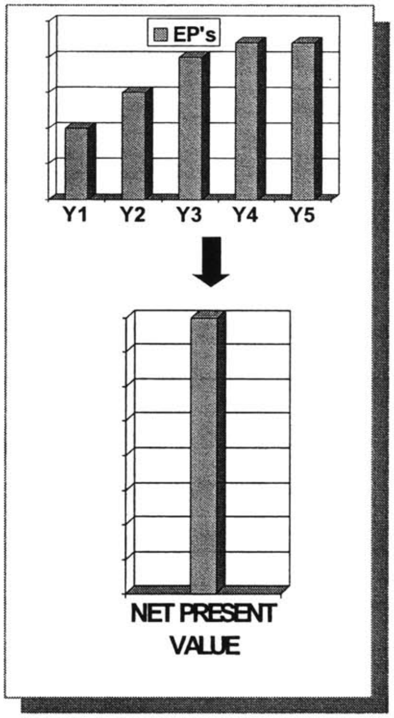


Figure I-5:Managing for Value

Boeing explains that economic profit is the best single-period financial measure, but relying on it alone can lead to short-term focus on decision-making. When evaluating long-term strategic decisions, Boeing proposes the "value creation" as the appropriate measure. Value creation is the sum of discounted economic profit over time, in a determined time horizon.

Economic profits for each year are discounted at the company's weighted average cost of capital to account for the time value of money (see Figure I-5).

As the sum of strategy's economic profits over time, value creation is the appropriate criterion for evaluating strategic decisions.

717 Current Challenges

These are the current challenges the 717 Program is facing:

Rate Fluctuations: The 717 Program has experienced several rate breaks (production rate changes) during its two years in operation and more fluctuations are expected for the future. The program historically has responded to those disruptions by assessing the economic performance of the current assembly system and deciding if a new manufacturing system configuration (defined principally by the quantity of airplanes to load in the conveyor or *positions*, the headcount, and the workload per workstation) is necessary.

Cost Reduction: as explained before, the program's strategy is centered in cost reduction. The understanding of the tradeoffs in the allocation of resources for the new assembly line configuration (positions, headcount and workload per workstation, number of operating shifts, etc.) given a rate break is a complex task for the 717 Program management, more specifically to the Industrial Engineering department. The department, as all the other organizations within the Boeing Company, is required to utilize Boeing's standard method to calculate the profitability of a project, the "Economic Profit" calculation (EP = net operating profit after taxes - opportunity costs of the assets used).

9 Tactics implementation: The final assembly line for the Boeing Commercial Airplanes 717 Program is currently implementing "The 9 Tactics", a methodology based on the lean manufacturing principles to transform the current process to a continuous moving line (see Appendix 1 for definition of the 9 Tactics). The 717-200 is currently assembled while traveling on a continuous moving line.

This Thesis

The original internship project statement proposed by the sponsor company was to "work on the implementation of the 9 tactics for the 717 Program in Long Beach, California". After a period of the intern's getting acquainted with the organization, participating in a Lean Manufacturing Assessment exercise and taking Boeing's lean manufacturing courses, the intern and the supervisor agreed to focus the internship on the implementation of the first two of the 9 Tactics.

Tactic 1, Value Stream Mapping (VSM) and Tactic 2, Balancing the Line (BL), were selected as the focus of the internship because they have the highest impact in the design of the assembly line. They define the manufacturing system configuration and the process to develop the production execution plans. VSM defines the major processes that determine flow time, and the major sequences of processes that affect flow time. BL evenly distributes the work across the assembly span with job assignments based on TAKT time; it also looks for an optimization on the span time or manufacturing flow time. See Appendix 1 for the methodology proposed by Boeing to implement Tactics 1 and 2.

Giving the magnitude of the economics involved in the design of a production system as large as the airplane final assembly, the implementation of these tactics must be necessarily supported by an economic analysis.

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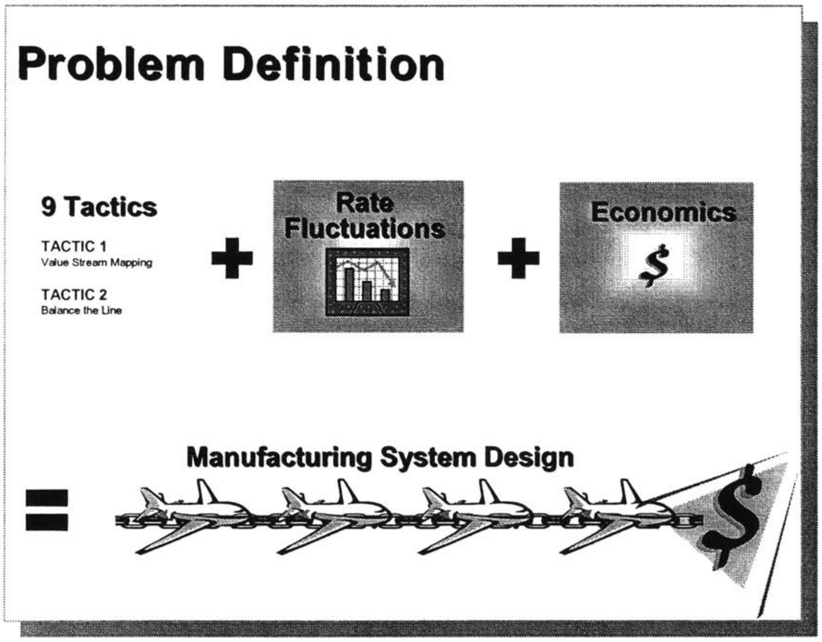
II. PROBLEM STATEMENT AND APPROACH

The LFM internship project must have the potential for developing new knowledge, be intellectually and technically challenging, generate generic and specific engineering and management results for the project and thesis, and support research activities that are critical to participating companies and to the LFM Program. At the same time the project must have a significant impact, meeting a need of the host company.

Problem Definition

The problem was defined as "Propose a methodology for the implementation of the first two tactics, Value Stream Mapping and Balancing the Line, to the final assembly line, considering the economics involved and the frequent production rate breaks."

The problem can be further described as the formula depicted in Figure II-1:



Problem Definition

9 Tactics

TACTIC 1
Value Stream Mapping

TACTIC 2
Balance the Line

\+

Rate Fluctuations

\+

Economics

=

Manufacturing System Design

Figure II-1: Problem Definition

The first component of the formula is the implementation of the first two tactics. As explained in the Background (Chapter 1), these first two tactics define the configuration of the manufacturing system. The second component, the production rate fluctuations, explains the fundamental need for the project: given a rate fluctuation, the first two tactics might be re-applied to reconfigure the line. The economics involved with the re-configuration constitute the third element.

These three elements are blended together in the project to define a methodology for the design of the Manufacturing System that will deliver the highest profitability to the 717 Program.

Approach to Solve the Problem

From the problem statement, it was decided that the main product of the internship was the proposal of a framework and specific guidelines for the design of the manufacturing system that contributes the most to the profitability of the 717 Program final assembly line. The framework will integrate the practical application of the first two tactics, an economic analysis, teamwork, and literature research of the lean concepts.

The methodology proposed will assist the different participants in the manufacturing design process –Operations Management, Finance, Supplier Management and the Leadership team– in understanding the role of the design of the manufacturing system in the bottom-line results.

The internship project was divided into two main components: the Assembly Line Configuration (or High Level Manufacturing System Design (MSD)), and the Resource Allocation (or Detail on the MSD). Figure II-2 depicts how these two components relate to Tactic 1 and Tactic 2. The figure also explains that an economic analysis is required for the Assembly line configuration part of the project, and that strong teamwork is required for the Resource Allocation part of the project.

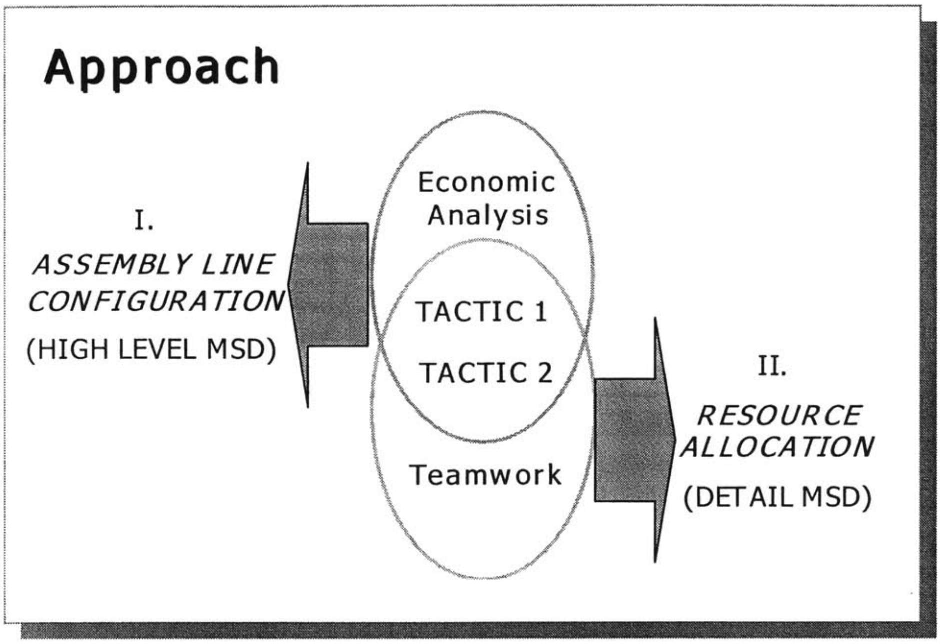


Figure II-2: Approach to the Internship Problem.

Figure II-3 shows the proposed framework to solve the problem, which translates the two main components of the project to specific activities or subprojects.

This framework evolved through the internship to this final state. The next chapters will explain in detail the methodologies, techniques, and lean concepts applied to these specific activities, and how this application supports or refutes the hypothesis statement.

Parallel with the development of the framework, the lean techniques applied will be analyzed to understand their applicability in defining the 717 final assembly manufacturing system, and to assess the potential dangers to the interpretation of the techniques in an economic/financial context.

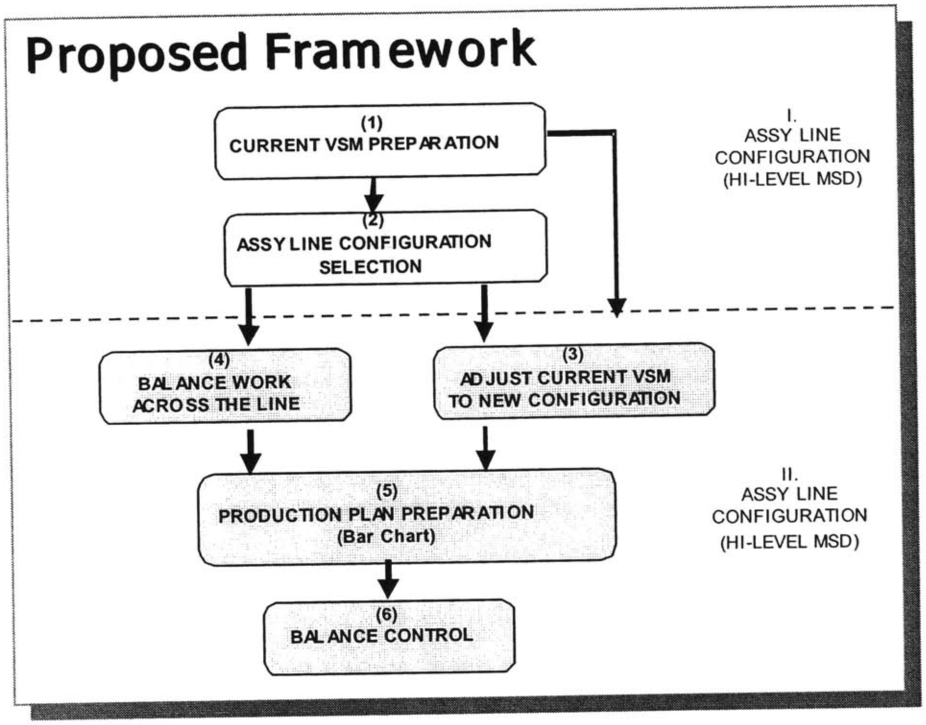


Figure II-3: Proposed Framework

Comparing Results and Benchmarking Exercise

During the internship the program experienced a production slowdown. The optimal solution for this rate break generated by the framework proposed was tested against the actual decisions taken by the program. Also, the methodology proposed was benchmarked to other Boeing commercial airplane program to validate the application of the proposed framework in a different manufacturing location.

Next Chapters

The next six chapters (from III to VIII) are structured following the flow from the top to the bottom of the framework of Figure II-3. Each chapter deals with one element of the framework: the current value stream map preparation part of the project ("1" in Figure II-3), the assembly line configuration selection process (2), the adjustment of the current value stream map to the new configuration (3), the process of balancing the resources across the assembly line (4), the production plan preparation activities (5) and finally the balance control part of the project (6).

Chapter IX describes a benchmark exercise performed on the 757 Program, and Chapters X and XI discuss the next steps and conclusions of the project respectively.

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III. CURRENT VALUE STREAM MAP PREPARATION

Value Stream Mapping

VSM Definition

The construction of a current Value Stream Map (VSM) is the first step in the definition of a Lean project. The current state VSM provides a graphic representation of the current state of the process to be analyzed, and the baseline to which the project improvements will be measured against (Reference 1).

Also the VSM methodology helps to identify:

- the opportunities for improvement, or the "waste" (complexity, labor, overproduction, space, energy, defects, idle materials, etc.) associated with the process,
- the major processes that determine flow time, and
- the major sequences of processes that affect flow time, and the main constraints on the process.

Depending on the project's objectives, different formats can be used to develop a current VSM with the same result: to provide a graphic representation of the current state of the process to be improved.

VSM Application to the Project

The first activity during the internship was to define a methodology to construct the current final assembly VSM utilizing a scarce resource for the 717 Program, Industrial Engineering labor time. The methodology proposed must be practical and flexible to support the frequent production rate fluctuations the Program has historically been experiencing.

At the beginning of the internship, the assembly line configuration for the next production slowdown to materialize four months later was already defined. This new configuration required the increase of the number of flow days of production, and the reduction of the number of operating shifts to one. The new configuration required a 46% reduction of the minimum flow time in consecutive hours.

Nevertheless, the complete precedence network for all the jobs or tasks required for assembling the 717 airplane was unknown, and consequently the critical path (or minimum flow time in consecutive hours) was also unknown. Previous attempts to develop the complete precedence network (of more than 3,000 tasks) were unsuccessful. This critical path was suspected to be substantially smaller than the current scheduled hrs, as slack between tasks was built in the current schedule.

As it was uncertain if the current critical path (with an unknown number of flow days) would support the new assembly line configuration, one of the most important outcomes of the VSM construction was to determine that minimum flow time, necessary for Industrial Engineering department and the Operations Management to assess the feasibility of the one-shift configuration.

Current Value Stream Map Construction

CPM versus Heuristics

The minimum flow time required to assemble an aircraft can be found by applying the Critical Path Method (CPM, or critical path analysis, see Reference 9). CPM searches the shortest path of all the possible paths in the network of *all* the sequenced jobs. The CPM was also an infeasible approach for the internship because the resources required would extend beyond the 6 months of the internship. Therefore it was decided to take a heuristic approach to build the VSM.

Heuristic Approach

A heuristic approach is used when the problem cannot be solved optimally, because we do not have all the required resources to apply mathematical or other complex models (as CPM). A heuristic is an alternative method to find a good solution to a complex problem. Heuristic methods are typically applied to solve complicated scheduling problems (Reference 10).

The different industrial engineering areas: Airframe, Systems, and Interiors had a good understanding of the critical sequences of jobs or "critical paths" under their responsibilities. But there was not an understanding of the sequence of all these critical jobs from the beginning to end of the final assembly process. The heuristic approach consisted of integrating the knowledge of the three IE areas in one single stream of critical jobs or "Critical Path". Figure III-1 represents the integration effort.

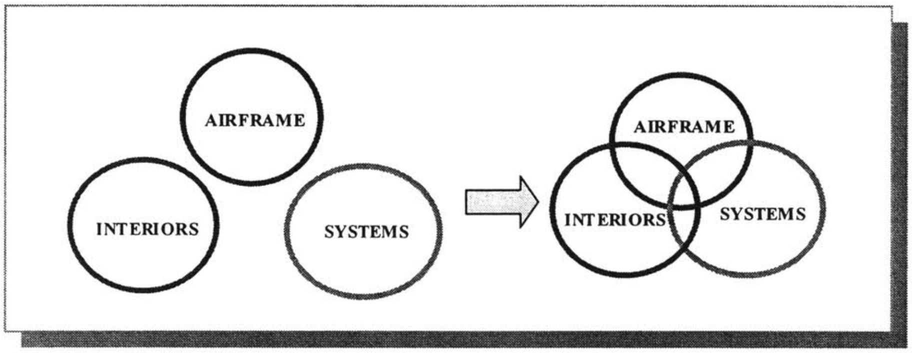

Figure III-1: Current Value Stream Map Integration

The flows of critical jobs for the different areas in the final assembly line were linked by working in teams with the Industrial Engineers to first, create and/or validate the individual Critical Path for their areas and second, to link the streams. This was a complex exercise as the sequencing nature of the jobs (or constraints) changes through the value stream map. For example, in some areas the systemic sequences (that are determined by the design of the aircraft) are critical, whereas in other areas the space constraints dominate.

To visualize the interrelationships between areas, the Industrial Engineers and the intern reviewed the job sequences printed in large paper scrolls posted in the walls (see Figure III-2).

All the critical job relationships collected in these meetings were fed into the Microsoft Project™ software and printed using a Pert Chart format. The construction of the VSM for a total of 429 jobs took approximately one and a half months. Finally, the software computed the minimum manufacturing time (in consecutive hours) required for the sequences under the current schedule.

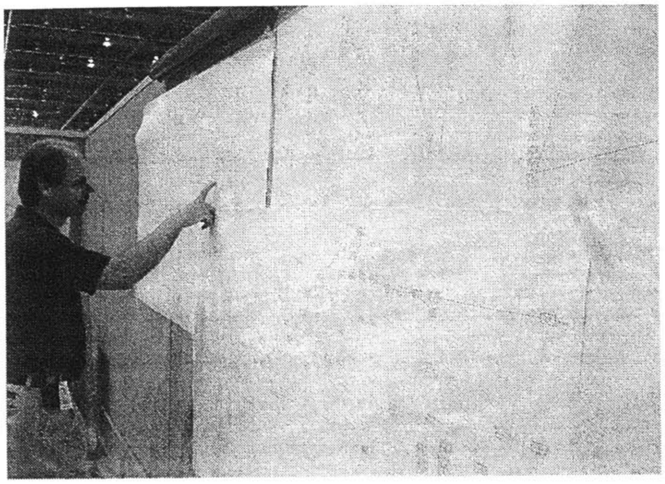

Figure III-2: Current VSM Construction and Analysis

VSM Groups

During the construction of the VSM the industrial engineers and the intern classified the jobs in 5 groups, based on the main constraint associated with each group. Figure III-3 is the condensed version of the current VSM using the "Learning to See" format (Reference 5) and shows the defined groups with their associated flow times. In Figure III-3, "C/T" means the cycle time (or contribution to the flow time, the actual values are no disclosed for proprietary reasons) and "DIB" means the days in building (or day numbers in which the tasks were performed) for every group.

One constraint is the location of the jobs regarding the final assembly line. The Major Body Join jobs (that integrate the different structure subassemblies of the aircraft to one single structure, "JOIN" group in Figure III-3), the Paint jobs (that paint the aircraft to the customer requirements, "PAINT" group in figure), and the Final Tests jobs (jobs performed after paint and before the plane is moved to the delivery center, "FINAL TEST AND MOVE" in figure) were grouped together as they are performed outside of the moving line and in different locations.

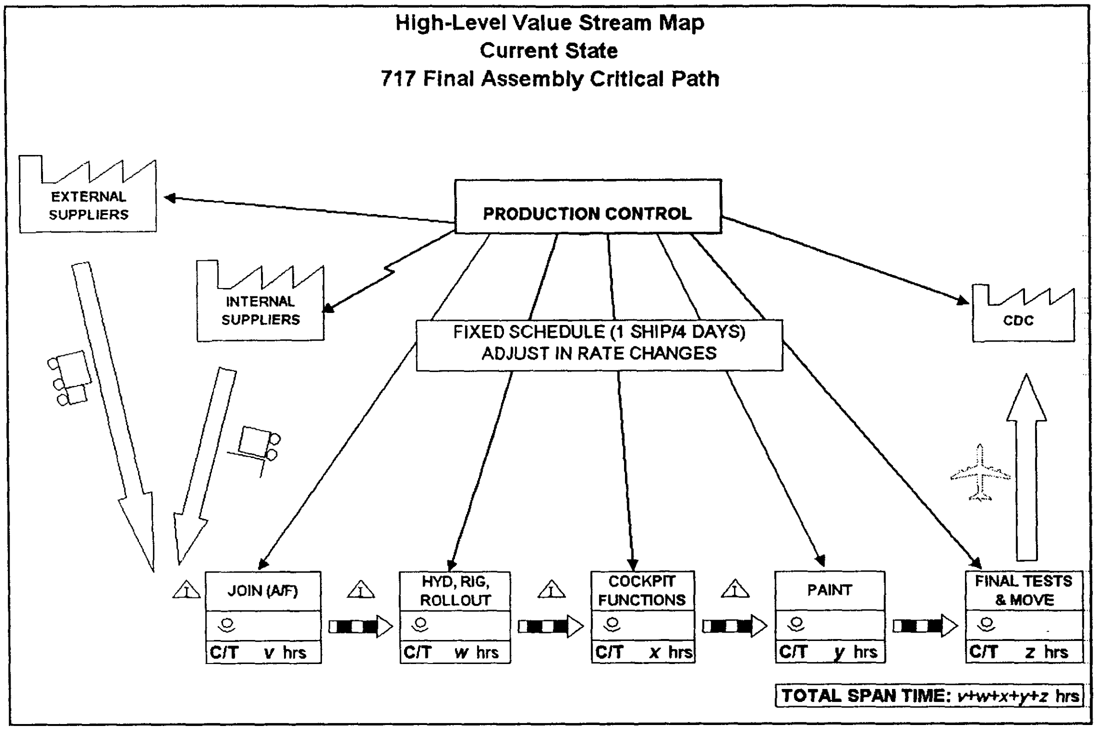

Figure III-3: Condensed Version of the Current VSM

The System Installations (jobs that integrate the mechanic, hydraulic, electric, and electronic systems on the plane, "HYD, RIG, ROLLOUT" in Figure III-3) are mainly constrained by the sequencing of the jobs, and for Cockpit Functions (system installations and interior installations performed in the airplane cockpit, "COCKPIT FUNCTIONS" in figure) the main constraint is the physical space inside the cockpit (also known in Boeing as flight deck).

This grouping gave the IE department a clearer understanding of the main drivers of the flow time. For example, they learned that the job sequence performed in the cockpit contributes the most to the total flow time. In Chapter V the cockpit job sequence will be analyzed thoroughly.

This classification was used as the base for planning the reduction of the current critical path to the new configuration requirements explained in Chapter V.

Results of the Current VSM Exercise

The use of heuristics to solve the problem proved to be successful: only one month and a half was required to construct the VSM. Even when the VSM exercise does not give one hundred percent accuracy on the flow time calculations, it provides a good estimate for management decision-making.

The VSM exercise also helped management have a better understanding of the main drivers of the flow time, and to apply this knowledge on the planning of the next rate break. It also guides the implementation of the subsequent 9 Tactics.

As will be explained in Chapter V, the current critical path's hours were not sufficient to support the new configuration. The same chapter explains the methodology followed to adjust the current VSM to the new requirements.

IV. ASSEMBLY LINE CONFIGURATION SELECTION

Introduction

The commercial airplane industry is a mature industry characterized by low profit margins as a result of the competition between the two industry contenders, the Boeing Company and Airbus. Therefore, cost reduction is one of the main elements of the aircraft manufacturer's strategy.

Based on this pressure of cost control, and in the event of a considerable change in the customer requirements, an economic assessment must be made to understand what is the optimal configuration of the assembly line that delivers the best profitability and aligns with the strategy of the program.

By performing an economic analysis, the Operations Management area (more specifically the Industrial Engineering department) will understand the tradeoffs between the resources utilized by the assembly line and their leverage in the program's economics. This understanding will lead to the selection of the best assembly line configuration for the program.

As mentioned before, the 717 Program experienced a drastic production slowdown and by the time the internship was started, decisions were already made for the future configuration of the line. The task for the intern was to evaluate the decisions already made with an economic analysis. This economic analysis must use Boeing's Economic Profit and Managing for Value concepts, described in Chapter I.

The lean concepts are incorporated in the economic analysis. This chapter will explain the economic analysis performed for the 717 Program final assembly line and the lean concepts utilized.

Lean and Economics

The literature that relates cost analysis to lean manufacturing concepts is very limited. Nevertheless, at the beginning of almost every book explaining the Toyota

Production System, or Just in Time, or lean concepts, etc. (Reference 3) there is an explanation about the "minus-cost" principle. This minus-cost principle is represented by the equation "Profit = Price – Cost". The main assumption of the practical application of this principle is that the market determines the product price, and the enterprise cannot alter (at least in the short run) price to increase profits. In consequence, the only means in which an organization can increase its profits is by reducing costs in all business activities.

Costs are reduced by eliminating what is commonly called "waste" in the lean literature. The four main forms of waste are: excessive production resources, overproduction, excessive inventory, and unnecessary capital investment (Reference 11).

The literature also warns the lean practitioner of the dangers of local optimizing costs, which could result in a sub-optimization of the total cost of the system as a whole. Therefore, the cost analysis must be focused on estimating the "total cost" of the system (an organization, program, or project), rather than on individual costs at stages or parts of that system.

Boeing, Lean and Economic Profit

As part of the strategy to reduce costs, the Boeing Company has adopted the financial measure called "Economic Profit", previously described in Chapter 1. This metric is equivalent to the Economic Value Added (EVA^{TM}) concept first introduced and highly publicized by Fortune Magazine in 1993 (Reference 12).

The EP concept states that a company or a business unit creates value for owners only when its operating income exceeds the cost of the capital employed. The EP concept is mathematically expressed as:

EP = Net Operating Profit After Taxes – Opportunity Costs of Assets Utilized

or

EP = (Revenues – Operating Costs) x (1- tax rate) – (Assets Utilized x Weighted Average Cost of Capital

The lean "minus-cost" is implicitly applied when calculating the Economic Profit to evaluate projects or investment alternatives. The minus-cost is a high level concept, oriented to maximize the profits per product by decreasing the costs, whatever the source of the costs are. The economic profit concept focuses on profitability also by managing costs, but it goes a step beyond the lean concepts by analyzing the effect of the opportunity costs of the assets utilized to the bottom line. This is particularly important for Boeing given the capital-intensive nature of its business.

As explained in Chapter 1, Boeing's Managing for Value approach requires the projects to be analyzed in a determined time horizon (see Figure I-5). Then the final value of the project is the net present value of the stream of economic profits discounted by Boeing's weighted average cost of capital (WACC, see Reference 13).

The use of EP is equivalent to evaluating the investment alternative (or project) comparing it to a project with the same discount rate, and with the same investment in assets. The net present value resulting from the comparison of those two projects must be positive to consider that the investment alternative is generating value. Otherwise, the investment alternative destroys value and must be rejected.

The EP metric also aligns to the "total cost" approach taught by the lean theory, as requires the calculation of the total costs using the information of the financial statements of the airplane program. One of the challenges of this metric is that it requires an "open-book management" approach, meaning that all financial information relevant to design, scheduling, and product tasks is shared by the employees of the firm, and even with the suppliers and distributors up and down the value stream.

Boeing's Economic Profit Calculator

The BCAG created an Excel tool to estimate value of a project using the Economic Profit calculations for five years. This tool is named "the EP calculator" (EPC).

EPC requires as input the information about the Income Statements and Balance Sheets and other financial and operations management parameters such as flow time, available manufacturing days, the weighted average corporate cost of capital, tax rates, labor hours and burden rates, R&D costs, Process Improvement costs, and other costs, etc. to calculate the Economic profit of the project based on the formulas of Figure I-3.

The EPC also allows performing what-if scenarios by changing the values of the different parameters (labor hours, R&D costs, work in process, etc., approximately 20 parameters in number) to understand their leverage in the economic profit calculation and managing for value results.

Due to proprietary reasons this thesis does not disclose the interface of the EPC.

Selection of Economic Profit as Project Metric

The Economic Profit calculation and managing for value concepts were used during the internship project for the selection of the assembly line configuration for two main reasons:

First, given the magnitude of the costs associated with the final assembly line configuration selected (work in process loaded in the continuous moving line, inventory buffers, etc., mechanics labor) it was mandatory to evaluate the alternatives using an economic analysis and in a long-term horizon, as managing for values suggests.

Second, EP was selected because it aligns with the estimating costs approach recommended by the lean literature. An EP analysis will define the assembly line configuration that will deliver the highest profitability to the 717 Program, given the customer requirements.

Project's Economic Analysis: Expanding the Capabilities of Boeing's EPC

Cost Analysis for Assembly Line Configuration Alternatives

As stated above, the objective of the economic analysis was to evaluate the different assembly line configuration alternatives, searching for the one that contributes the most to the economic profit of the program. The economic analysis was performed, expanding the capabilities of the existing EPC Excel tool by adding spreadsheets that estimate the operating costs and define the line configuration parameters such as flow days, number of shifts, and headcount, for the assembly line configuration alternatives.

The first intent of the economic analysis was to develop a non-linear optimization program to obtain the optimal assembly line configuration parameters for each of the five years, solving for the minimum cost. But given the small number of possible configurations that the 717 line can have (thirty, which equals ten possible airplane load configurations, from one to ten airplanes loaded in the assembly line, times three possible shifts), we decided to simply estimate the costs of the thirty possible options. Next we would select for each year the configurations with the lowest cost and capable of supporting the tactical plans for the five-year horizon of planning.

The Tool

The expanded tool comprises 13 spreadsheets, the six original EPC spreadsheets (one for inputting the financial statement information and five screens that estimate the economic profits for each of the five years) and another seven spreadsheets designed by the intern to calculate the operating costs of the assembly line.

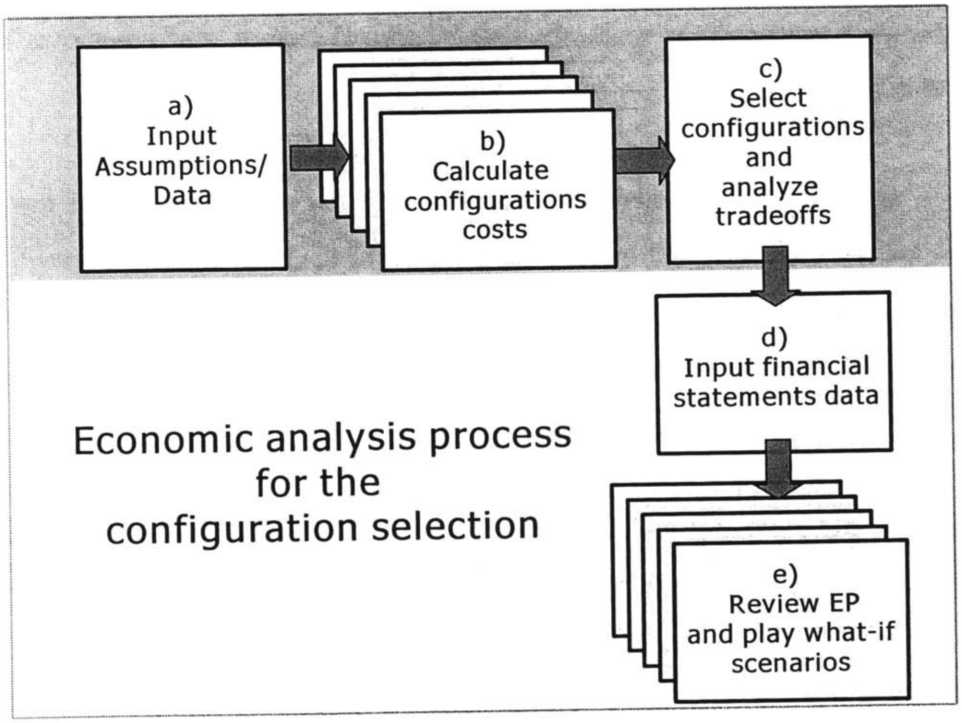

Figure IV-1: Configuration Selection Using the Tool

The following is a description of the tool's spreadsheets and the order in which the user interacts with them to complete an economic analysis (see Figure IV-1):

Input Assumptions/Data screen: assumptions and data specific to the 717 Program, as maximum and minimum number of positions allowed, percentage of support heads, critical path length, Paint and Delivery Center information, etc. are inputs. The user inputs in this screen the information necessary to perform the assembly line cost analysis that is not included in the original EP calculator input sheet. Appendix 2 shows the "Input Assumptions" screen and the other spreadsheets designed for the economic analysis.

Calculate configuration costs: 5 screens, one for each year of the planning horizon, calculate the operating costs of all possible layout configurations, and suggest as optimal the one with the lowest costs (see Appendix 2). Nevertheless, the user can override the proposed optimal solutions and pick any of the other possible configurations.

Select configurations and analyze tradeoffs: one screen summarizes the information of the selected configurations for the five years, and graphs (for each year) the incremental costs of the alternatives not selected, to help the user to understand the tradeoff magnitude between labor costs, the cost of capital charge, and other overhead costs (see Appendix 2).

Input financial statements data: the selected configurations of the line for the 5 years are automatically fed into the EPC Input sheet. Next the other financials such as the balance sheet and income statement figures, supplier costs changes, etc. must be input to the EPC Input sheet.

Review EP and play what-if scenarios: The tool calculates Economic Profit for the five years and computes their net present value. This is done in five identical spreadsheets, one for each year. These spreadsheets have the functionality to play what-if scenarios with the different parameters. The user can alter the final values of the parameters to understand how those changes impact the bottom line Economic Profit. Playing with the parameters management will develop a better understanding of the main drivers in the economics of the configuration of the line.

The tool assists Operations Management, specifically the Industrial Engineering department, in understanding the tradeoffs in the distribution of the resources for the assembly line configuration alternatives. It applies the Economic Profit concept twice: first to select the assembly line configuration and second to analyze the other financial aspects of the 717 Program related to the configuration selected.

Moreover, the tool considers all the economic aspects of the program. It considers not only the operating costs of the best assembly line configuration, but also considers the rest of the working capital required to operate the program and therefore supports the Lean concept of "Total Cost".

Economic Analysis and Application of Tactics 1 and 2

The economic analysis performed by the tool involves the application of Tactics 1 and 2 concurrently. It relates to Tactic 1 as it defines the "backbones" for the future VSM: flow days, number of positions or planes loaded in the moving line, number of shifts, headcount for engineering, support and mechanic groups.

The economic analysis also involves Tactic 2 in a two-fold way: first, it defines the constraints to be considered in the distribution of the resources: optimal flow time, number of shifts, and the TAKT time, being those; second, it defines the rough cut in the distribution of the most valuable resource, the mechanic time, across the optimal flow time, number of shifts and TAKT time.

Understanding the Tradeoffs

The tool was constructed and applied to the 717 assembly line. The Industrial Engineering and Finance departments provided the data required to execute the analysis.

Figure IV-2 plots the optimal results (results for the configurations with the lowest costs) from the tool's operating cost analysis for different production rates (in aircraft per year). The four graphs for the optimal number of shifts, flow days, number of positions, and total costs against the production rates unveil interesting insights.

The top-right graph in Figure IV-2 shows that in the event of a drastic reduction of the production rates the 717 Program is better off increasing the flow time and reducing operations to one shift. For example, if the production rate falls from 35 aircraft per year to 10 (marked with an "x" in Figure IV-2) the optimal solution suggests increasing the number of flow days by 142%.. The optimal solution also suggests operating in a single shift.

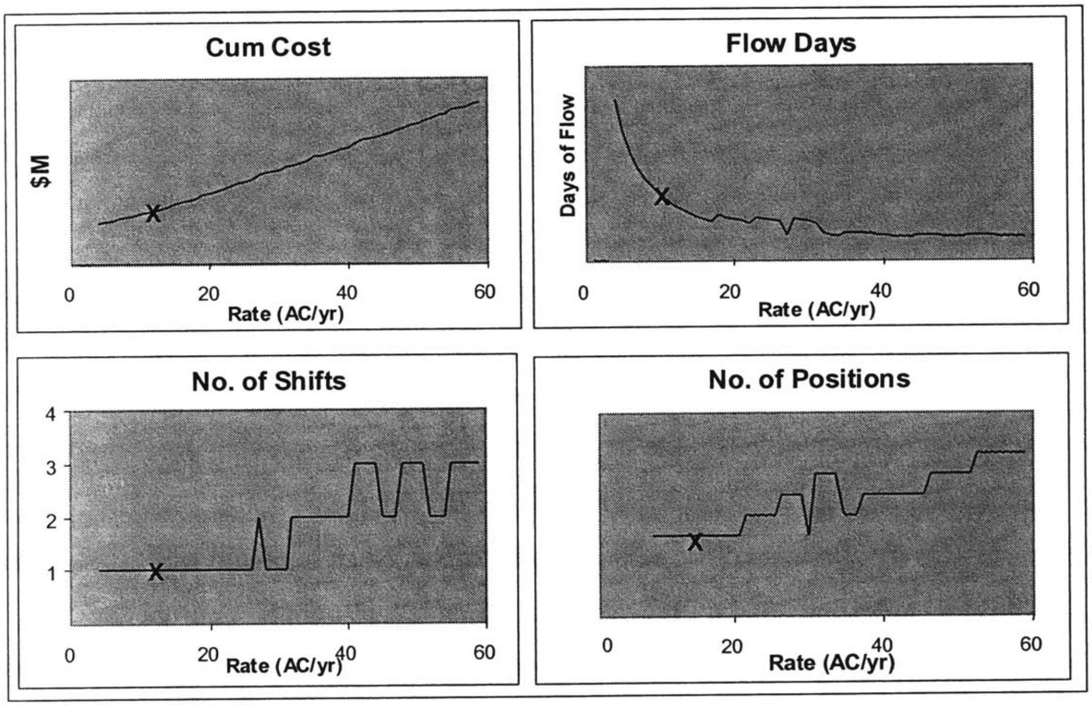

Figure IV-2: 717 Operating Costs Analysis Results

By analyzing the components of the cost equations in the tool, we understood the dynamics of the economics that drove the one shift and longer flow time selection. Figure IV-3 shows the different components in the calculation of the operating costs or "Total Cost", using a System Dynamics format. This format is very useful for understanding the interrelation of the variables in complex systems (Reference 14).

The main components of the Total Cost are represented as five "branches" of calculations. The elements of the diagram in italic font are inputs to the calculations and the rest are computed parameters. For proprietary reasons this thesis does not disclose the actual formulas applied. Nevertheless, this framework gives the reader an understanding of the logic followed in the cost analysis.

The tool proposes as the optimal solution the configuration of the final assembly line with the lowest operating costs, from all the possible alternatives. For low production

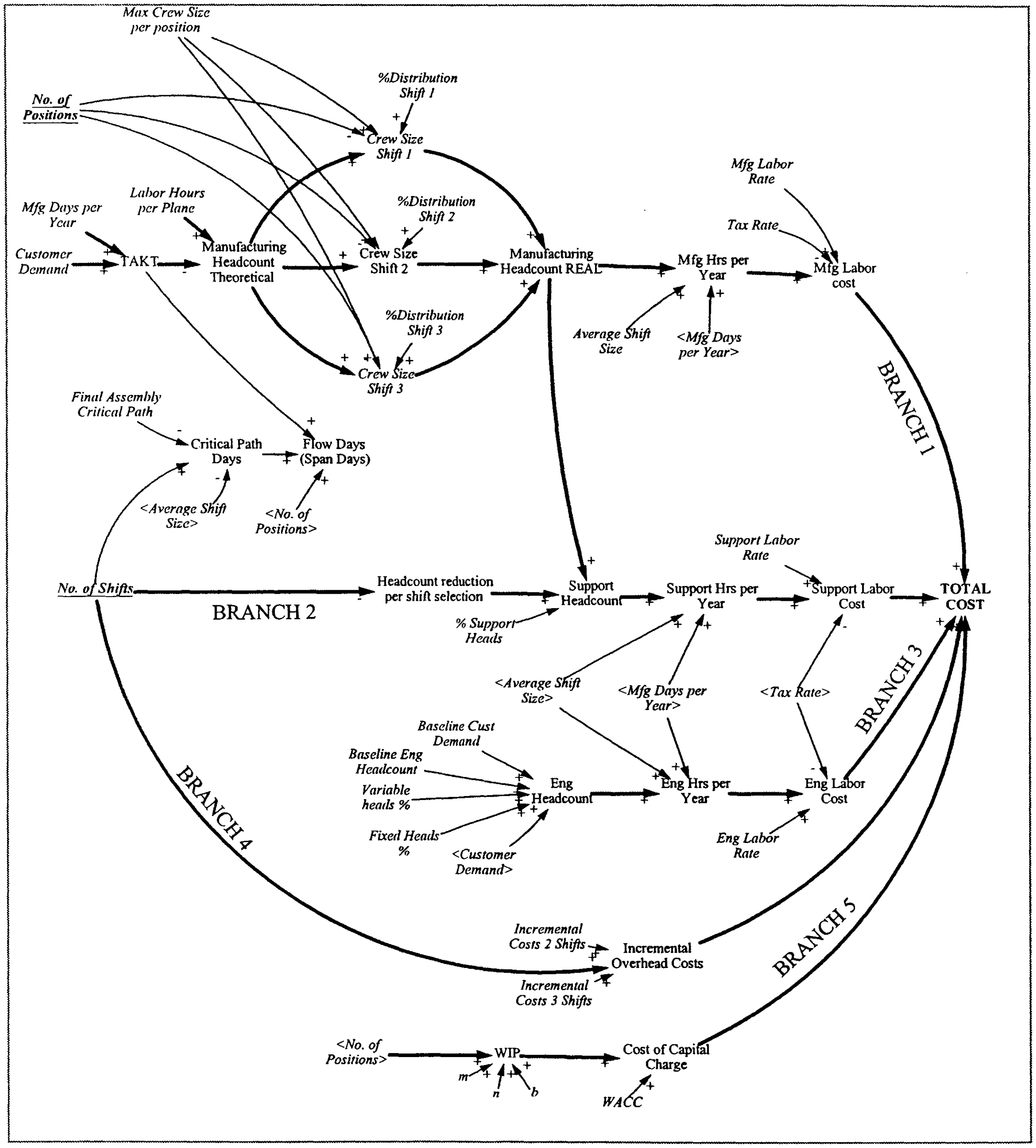

Figure IV-3: Calculation of Total Cost for the 717 Assembly Line

rates, configurations operating in only one shift appeared to be more economical. This is explained by the fact that the savings related to consolidations on the responsibilities of the support and engineering functions (working on just one shift) surpassed the costs of capital charge to be incurred by the increased flow time of the one-shift configuration.

"Branch 2" and "Branch 3" in Figure IV-3 represent the calculations performed by the tool to determine the support and engineering labor costs respectively. The support headcount is calculated as a percentage of the manufacturing headcount, and next this number is adjusted reducing heads accordingly with the number of shifts selected. As the number of operating shifts is reduced, fewer support heads are required due to consolidations on the responsibilities of the functions. Similar reductions are accounted for the computation of the required Engineering workforce.

"Branch 5" in Figure IV-3 represents the calculation of the capital charge cost for the assembly line configuration. It is determined as the total work in process (WIP) multiplied by the weighted average cost of capital (WACC) for the company. WIP is determined as a function of the number of positions and the coefficients m, n and b resulting from a quadratic regression (least squares method) for expected WIP against the number of positions.

Branches 1 and 4 (computation of manufacturing labor costs and extra overhead costs) did not change significantly with different configurations hence are not an important influence for the observed tradeoff.

For different customer rates and assembly line configurations, branches 2 and 3 (support and labor costs) "team" to compete against branch 5 (cost of capital charged) on contribution to the Total Cost. For low rates, the support and labor costs are the absolute winner with the highest contribution to the cost, driving the number of positions, shift and the other configuration parameters.

Another insight derived from the plots in Figure IV-2 is the understanding of the frontiers to which the parameters (shifts, positions) increase. This is very important for medium-term planning. For example, if the production rate for the next year is 20 aircraft per year (see the top left graph in Figure IV-2) and the forecast for the years after are larger than the next year's requirements, the airplane program might be better off selecting a 2-

shift configuration in the beginning and avoiding the switching costs for later years. Similar insights can be obtained for the number of positions graph in Figure IV-2.

The switching costs required to reconfigure the assembly line are not directly considered in the operating costs analysis part of the tool. For the internship exercise these costs were considered in the Input Sheet of Boeing's Economic Profit Calculator (EPC), which is not disclosed in this thesis due to proprietary reasons. A possible next step to improve the tool is to model and incorporate the switching costs.

Understanding the "Paradox"

In the Background section of this thesis (Chapter I) the Boeing's approach to the Lean concepts was explained. Boeing has been successful embedding those lean concepts in the organization.

The importance of reducing the flow time in the production processes is well understood by the employees. Because of that, it was difficult for the 717 Program to explain to the BCAG the need for increasing the number of flow days for the next rate break's new configuration. This increase seemed counterintuitive to the lean doctrine of "the fewer flow days, the better".

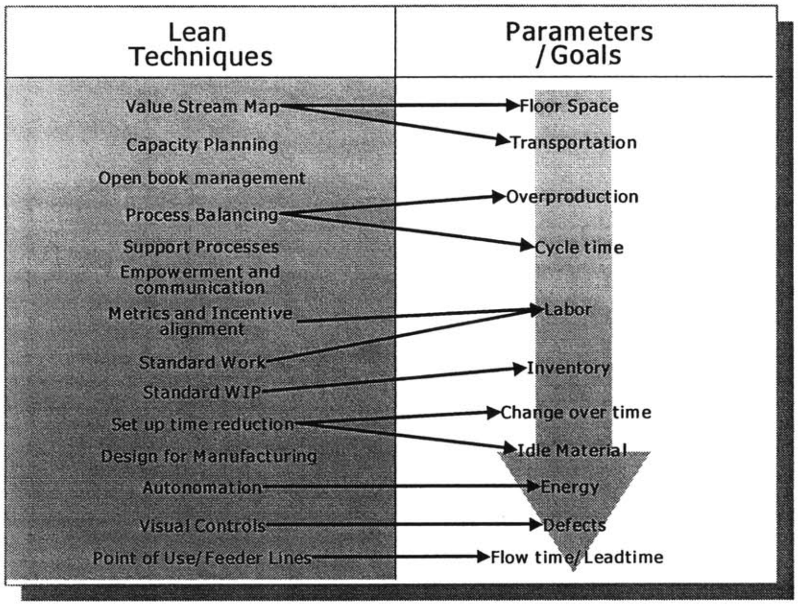

Figure IV-4: Linear Conceptualization of Lean Techniques

This apparent confusion can be explained as follows: the traditional way lean is taught explains the application of techniques to reduce waste, such as floor space, inventory, unnecessary labor, etc. assuming that the application of the technique will always result in savings to the program.

The Boeing Production System model (see Figure I-1) proposes in a very linear fashion the cause-effect relationship of the lean techniques to improve the use of the resources. The application of lean seems simple: by using a technique waste is removed from operations parameters, and total cost is reduced (Reference 1, see Figure IV-4 for this traditional view of lean).

Nevertheless, it must be acknowledged that the interactions between the lean techniques, and even between the parameters listed in Figure IV-4, could be more complex than they seem at first glance. Figure IV-5 shows a more realistic scheme of those interactions. There are potential tradeoffs. For example, perhaps in a project the set-up time will be reduced, but the amount of labor will increase.

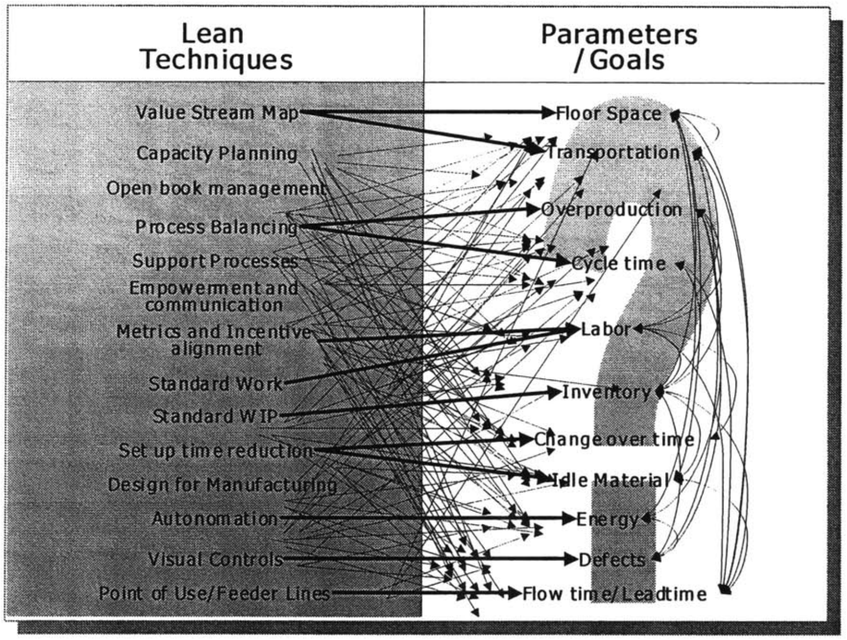

Figure IV-5: Potential Interactions Between the Lean Techniques and Parameters

Depending on the size of the economics of a project, the organization may or may not be interested in understanding those tradeoffs and how they affect the bottom line. For continuous improvement projects of small economic scale, the understanding of the economics involved could be cumbersome, and the resources spent on calculating the economics might be larger than those required to execute the improvement project. This explains why the hands-on projects executed on the shop floor to improve the day-by-day operations, are evaluated by the reduction in the waste parameters rather than in economic figures. This argument is heavily supported by the Japanese "just do it" approach to continuous improvement (Reference 3). Moreover, even if the small project does not result in an economic improvement, the potential negative impact in the economics of the whole program is small. What matters to this methodology is the combined effect of many small projects, delivering at the end a considerable impact to the total cost of the organization.

On the other hand, the understanding of the tradeoffs of the parameters for a project involving substantial economics is mandatory. Failure to understand the tradeoffs can result in a significant loss to the bottom line. This is the case of the assembly line configuration selection for the 717 Program.

Figure IV-6 explains the differences between different types of projects in the organization and the right metrics to use for evaluating their performance.

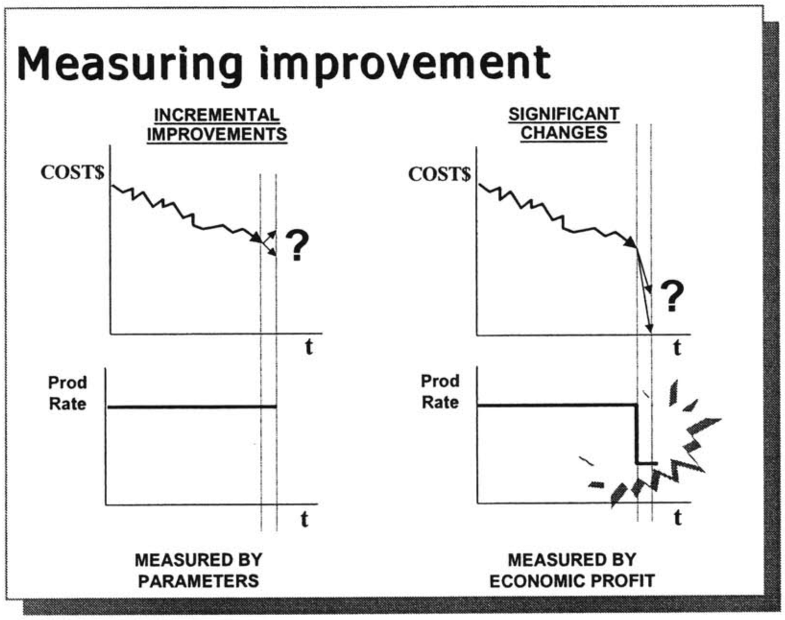

Figure IV-6: Measuring Improvement for Different Types of Projects

After performing the economic analysis with the tool, it was learned that the main trade-off for the 717 assembly line configuration was between the parameters support group labor costs for the second and third shifts, and the inventory holding costs (cost of capital charged) related to the aircrafts loaded in the line.

The meticulous economic analysis performed by the proposed tool solves the apparent "lean paradox" confirming the need for increasing the number of flow days and helping management to explain the tradeoffs in the use of resources. The analysis also validated the original configuration proposed by the 717 Program before the internship work, which required a reduction of operations to one shift and an increase in the number of flow days.

V. ADJUST THE CURRENT VSM TO THE NEW CONFIGURATION

Introduction

The previous chapter dealt with the design of the manufacturing system at the highest level; it defined the methodology to select the structural parameters in the configuration of the assembly line.

This and Chapters VI, VII, and VIII will explore the detailed level in the design of the manufacturing system. They will explain the activities required to distribute the resources in preparation for production execution.

At this point of the project the current VSM had been already developed and the new configuration for the assembly line had been validated by the economic analysis. The next step was to define a methodology to adjust the current VSM to the new configuration required. This Chapter develops that step.

As mentioned before, during the time of the internship the 717 Program experienced a production slowdown. Even though the new configuration required an increase in the number of flow days, the fact that the number of shifts was reduced implied that the critical path in hours needed to be reduced by 30%.

Approach

Another heuristic approach was followed to adjust the current VSM to the new requirements, or in other words to reduce the current critical path. The groups defined during the current VSM in Chapter III (see Figure III-3) were the basis for this exercise. Different teams of industrial engineers and other knowledgeable and empowered employees worked together reducing the critical path of each of the groups: Major Body Join, Systems, Cockpit functions, Paint and Final tests.

The intern worked in the reduction of the cockpit functions section because this portion contributed the most to the critical path.

Cockpit AIW (Accelerated Improvement Workshop)

From chapter III it was known that the main constraint in the critical path of the jobs performed in the cockpit is the cockpit space. Only two to three mechanics can be working simultaneously in the cockpit. During the preparation of the production execution plans for the cockpit, the jobs have to line up waiting for space in the cockpit to be scheduled.

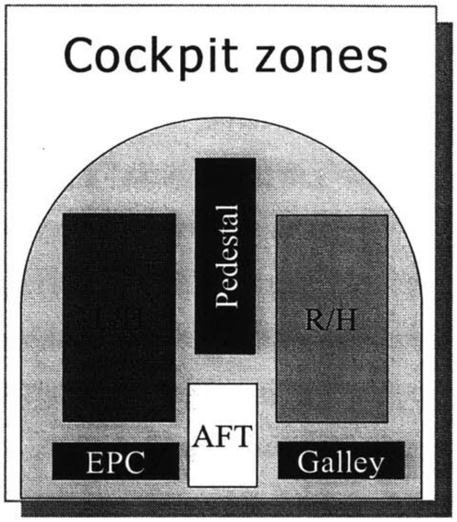

Figure V-1: Cockpit Zones

Consequently, a graph showing the use of the cockpit space during through time was constructed from the information already gathered in the current VSM exercise, and by collecting the zone of the cockpit each of the jobs is executed (left hand or pilot seat zone, right hand or copilot seat zone and aft zone, see Figure V-1).

The horizontal axis in the graph in Figure V-2 represents consecutive eight-hour time slots for the current VSM for the jobs performed in the cockpit. The vertical axis represents the number of hours scheduled for those time slots. Therefore, each bar represents the number of hours scheduled for each time slot and for the left hand (bottom blue portion), right hand (middle orange portion) and aft (top yellow portion) zones. The imbalance in the cockpit zones usage for the current VSM is quite noticeable, with a standard deviation for the number of hours scheduled per shift of 18 hours. It is also

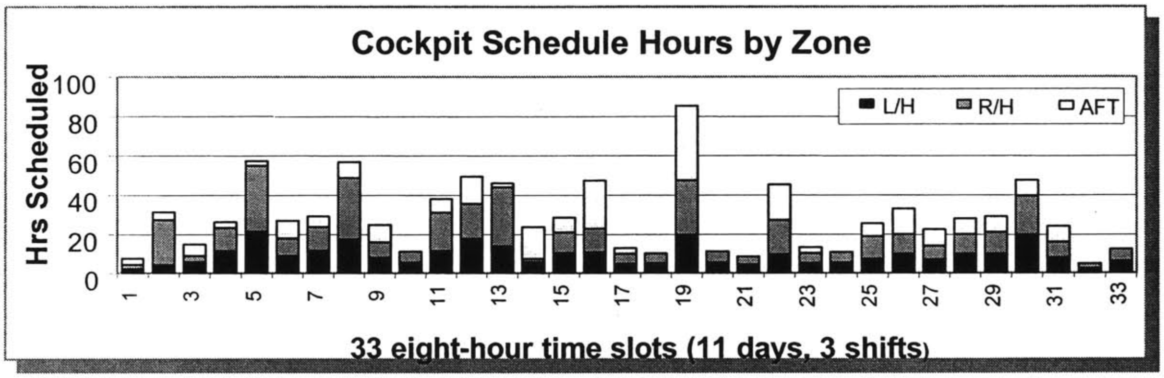

Figure V-2: Cockpit Space Usage for the Current VSM noticeable that for some days more work is scheduled than can be done, as in the time slot 19 in Figure V-2.

This imbalance in the use of the cockpit space usage can be explained by the fact that different engineers scheduled the jobs to be performed in the cockpit. Although the industrial engineers try to coordinate their schedules for a smooth production execution the efforts have not been focused on an efficient use of the cockpit space.

A multidisciplinary team was formed with people from Production, Quality Assurance, Industrial Engineering, and the Lean office to attack this problem. The goals were first, to reduce the number of flow days (from 11 days in 3 shifts to 24 days in one shift) on the cockpit and second, to balance the use of the space.

The team worked in an AIW (Accelerated Improvement Workshop, Boeing's approach to Kaizen events, see Chapter I for an explanation) for a week distributing evenly the jobs in the three zones of the cockpit and in the flow time allotted. The media utilized was sticky notes posted on big scrolls of paper (see Figure V-3).

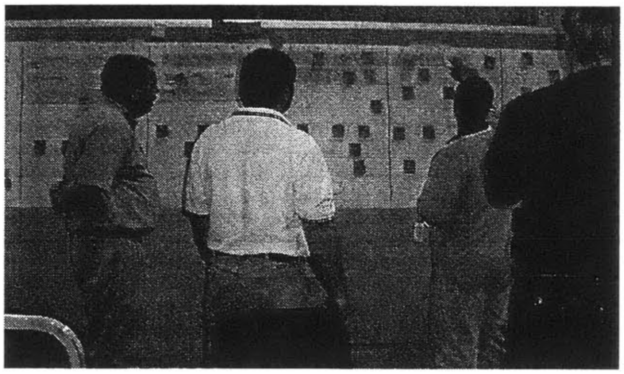

Figure V-3: Cockpit AIW Teamwork

Team Dynamics

The team members were (alphabetical order) Duane DeBolt (production, Systems area), Paul Dejeu (industrial engineering, systems area), Michael Dilts (production, systems area), Victoria Gastelum (MIT intern), Audrey Gory (production, systems area), Bryan Metzger (lean office), Rick Midland (industrial engineering, interiors area), Dave Morgan (production, systems area), and Alan Oaks (production, interiors area).

The team performed the following steps:

a) The MIT intern and coordinator of the team showed the data and graphs available, and explained the goals.

b) The team discussed the expectations and concerns related to the exercise and the proposed goals. These main expectations and concerns were:
   - To set realistic goals.
   - Not to focus only on "having three people in the cockpit all the time" but also on the real cockpit utilization
   - To use realistic times of job execution
   - To be able to push some jobs upstream, before the cockpit jobs begin
   - The sequence to be developed will help to develop the bar charts (or production plan schedules)
   - Concerns about the people skills after the rate break / Learning curve issues
   - What is the right scenario to work on – to pick a customer with complex interior jobs, or a customer with complex system job packages.
   - Safety concerns at the end of the line, as some potentially dangerous jobs are executed (to test moving components of the airplane).

c) The team defined the new sequence by rearranging the jobs required using sticky notes and large pieces of paper posted in the walls.

d) The intern and the lean group representative acted as bridges to communicate the concerns of the team to the external constituencies (as the managers of the different areas affected by the workshop) and help breaking barriers for the team.

When developing the new sequence in what the team described as a very tight flow time requirement the following actions were performed:

- Prioritized jobs that can be worked together
- Bundled functions that can be performed together
- Transferred jobs upstream

The main requirements / assumptions for the execution of the sequence proposed were:

- Inspection headcount will support concurrent functions – Zero wait time
- First Time Quality on Electrical Installations from prior departments to eliminate quality non-conformance findings.
- For the "in-and-out" jobs (jobs that require work to be performed inside and outside the cockpit), the mechanic or the person inside the cockpit will accommodate and support moving flight surfaces/switches, etc. for other mechanics.

In the exercise the team also identified opportunities for DFM (design for manufacturing) and continuous improvement projects.

The leadership role on the team switched during the development of the AIW: originally the MIT intern exerted the leadership on communicating the problem and helping the team on setting realistic expectations for the completion of the goals. Once the team was up and running the leadership naturally switched to Michael Dilts (the production manager for the systems area) as he had the knowledge and technical expertise to direct the team to the desired results.

Results of the Adjusting Exercise

The team successfully fit the jobs in the allotted time and for one single shift, though the team had to consider assumptions as zero wait for inspection and strong cooperation and coordination between the mechanics working simultaneously in the cockpit. Figure V-4 shows the final results. The number of hours scheduled per shift was balanced to a standard deviation of 3.5 hours. Again a heuristic procedure (teams reducing the critical path of their assigned portion of the current VSM) was applied.

The careful selection of participants was key for the success of the AIW. The drafting criteria were knowledgeable, empowered, and motivated employees, with a can-do attitude that resulted in achieving the goal in a timely fashion.

As the industrial engineers were involved in the AIW, they developed the sense of ownership in the outcome, the resulting sequence, and used it to develop the new bar charts.

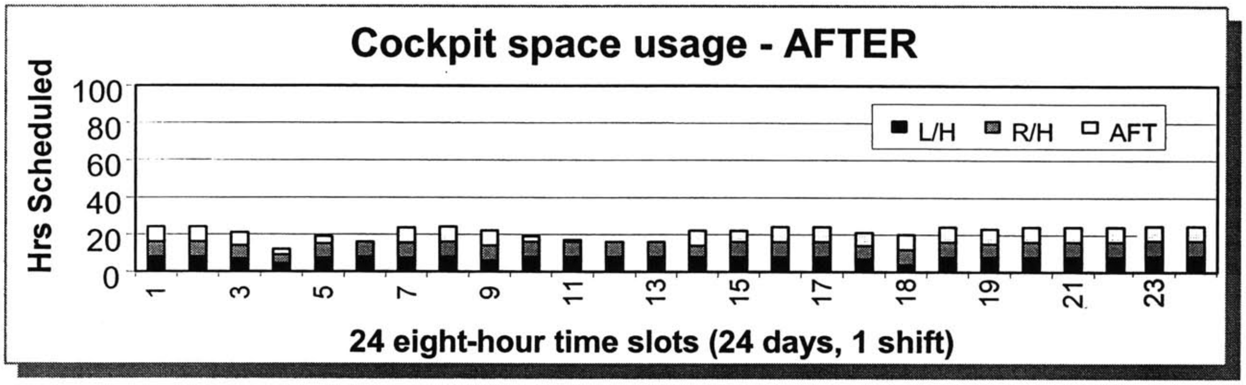

Figure V-4: Cockpit Space Usage After the AIW

As a next step we recommend to the Industrial Engineering department to develop bar charts dedicated solely to the cockpit jobs, in order to avoid the complexity of coordinating the different areas for the use of the cockpit space when preparing the bar charts.

VI. BALANCE RESOURCES ACROSS THE LINE

Introduction

Balancing the Line Definition

A typical definition for balancing the line from the Operations Management literature is (Reference 1):

"The problem of balancing an assembly line is characterized by a set of n distinct tasks that must be completed on each item. The time required to complete a task is a known constant. The goal is to organize the tasks into groups, with each group of tasks being performed at a single workstation. In most cases, the amount of time allotted to each workstation is determined in advance, based on the desired rate of production of the assembly line. This is known as cycle time".

In contrast, BCAG's 9 Tactics definition for balancing the line is (Appendix 1):

"Balance the line essentially means distributing both the quantity and variety of work across available work time, avoiding overburden and under use of resources. Work that is evenly distributed provides predictability to standardize work processes with ease. This eliminates bottlenecks and down time, which translates into shorter flow time."

Both definitions suggest the arrangement of tasks to deliver products at the desired cycle time or TAKT. The first definition is quite general and accepts whatever manufacturing system design as long as it produces to the required cycle time. In contrast, the Boeing definition is colored by the particularities of the airplane manufacturing business and presumably by the lean concepts as it emphasizes the need for an even distribution of resources, work process standardization, elimination of bottlenecks and down time, and flow time reduction.

This thesis divides the implementation of Tactic 2 "Balance the line" into two main activities: balancing the assembly line across positions, and balancing a single position. This Chapter deals with the first portion, and the next (Chapter VII) with the second.

Balancing the Line: Prime Owner

The literature also appoints the Industrial Engineering department as the owner of Tactic two: they are responsible to lead development and execution of the Tactic. This is correct, as the deliverables of this tactic (bar charts, job packages definition, precedence diagrams, etc.) are associated with the traditional Industrial Engineering activity.

Balancing the Assembly Line Across Positions

Chapter IV dealt with the selection of the configuration of the line. The analysis defined the appropriate values for the parameters flow days and workforce size that minimized the operating costs of a process running at a determined TAKT (see Chapter 1 for a definition of TAKT). Part of the Balancing the Line definition has been already achieved, as the work content required to assemble an airplane was even distributed (theoretically) through the process flow time. The workforce size (number of mechanics working at any time) was also calculated, as a function of the work content, the number of flow days and TAKT.

If no more constraints existed in the manufacturing process, the load chart of workforce requirements per manufacturing day will look like the example in Figure VI-I. The mechanic workforce would be evenly distributed across the chosen flow time to meet TAKT, and teams of equal size would be assigned to each position. A position is analogous to a workstation for an airplane assembly line (see the first definition for balancing the line at the beginning of this chapter).

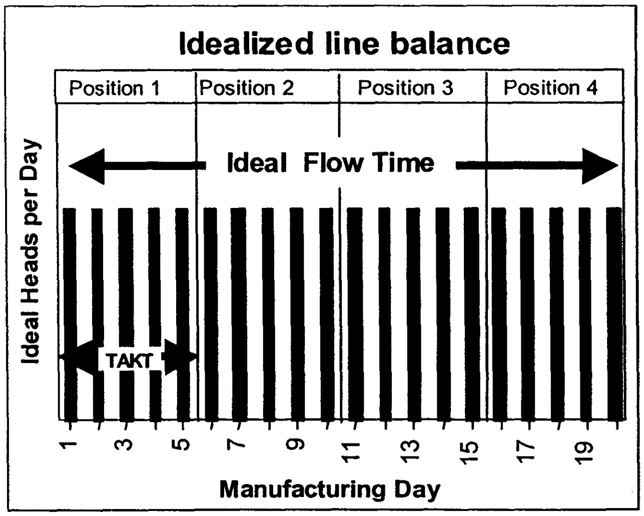

Figure VI-1: Idealized Man Load Distribution

But when other constraints such as job precedences, congestion in the aircraft zones, cost of the components, mechanic job skills classifications, building constraints, etc. are considered in the preparation of the production execution plans (called "bar charts"), the resulting workforce distribution across the line is uneven. In particular, the 717 program schedule follows a "bell shaped" man load distribution (see Figure VI-2 for a conceptual example).

The integral design of the 717 prevents performing systems installations upstream in the process; the basic airframe (fuselage, wings, landing gear, empennage) must be completed before the systems can be installed and integrated. This is the main driver of the characteristic bell shape of the graph for the final assembly process. In the first stages of the 717 assembly process the man load requirements are limited to the airframe construction, requiring a relatively moderate crew size. In the intermediate stages, the man load requirements increase as mechanics work simultaneously to complete the airframe installations and to integrate the different systems (mechanical, hydraulic and electric). In the last stages, the installation of physical components is almost completed, and the man load requirements are limited just to the installation of the interiors and the test of the aircraft systems.

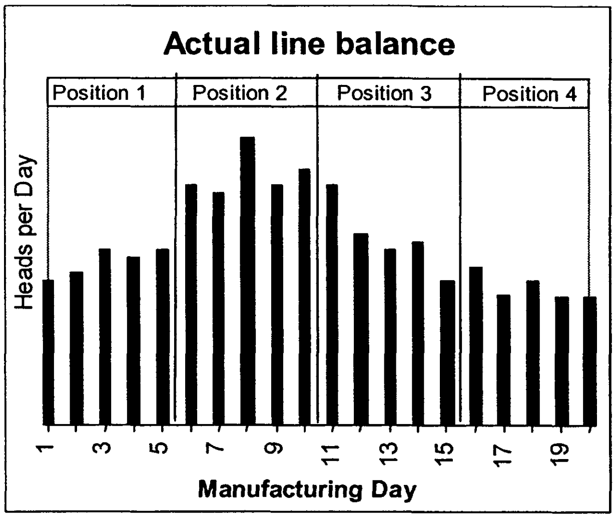

Figure VI-2: Bell Shaped Man Load Distribution

Once the configuration is defined, the bar charts are prepared for each position by a number of industrial engineers. Even with the best efforts in coordination, the final schedules typically do not balance the use of mechanic time evenly, for the reasons just explained above.

This difficulty of achieving the balance becomes the balancing activity (or Tactic 2) a continuous improvement activity with two primary goals, first, to avoid the overuse and under use of the resources, and second, to reduce the flow time.

One aspect of Boeing's balancing the line definition must be interpreted with caution: the "available work time" in which the resources must be distributed. A mechanic has different tasks assigned for each of the days the airplane is in his or her position. To avoid overuse and under use of work time, each member of the team must have a balanced, even amount of work every day. This explains the need for even distributing resources (mechanic time) through the available work time (TAKT).

Nevertheless, an even distribution of work across positions, (or in other words, across the line) is not indispensable. As long as the jobs are completed at TAKT and everyone is reasonably busy, there is no need to strive for equalizing the workforce for every production day. Moreover, and given the many constraints to consider in the scheduling process, it may be impossible and impractical to achieve an even distribution of mechanics across the line (or in other words, across positions).

There are some practices that help to achieve the objectives of eliminating the overuse and underuse of resources and reducing flow times that actually require the redistribution of jobs across the assembly line. Practices of this nature were collected by interviewing Industrial Engineers and by process observation, and are described next.

Practical Solutions for Balancing Across the Line

The following are best practices collected by interviewing industrial engineers and by process observation during the internship.

Move Jobs Upstream in the Process

As a rule, it is more convenient to relocate jobs upstream rather than downstream in the production process for two main reasons. First, the sooner the jobs are performed (upstream), the more time available to react to process failure modes such as materials not arriving on time, quality rework, etc. Second, the tests are performed and high-dollar components are installed at the end of the line. The tests require completion of systems installations and are less labor intensive. The high dollar components require fewer interruptions and more space for installations (engines, seats, lavatories, avionics, etc.), they are also less labor dense. Therefore, the less interference of other jobs with the tests and interior installations, the better.

Identify Candidates for Feeder Lines (Tactic 6)

From the BCAG's 9 tactics literature, Tactic 6 (Feeder Lines, see Appendix 1) is explained as follows: "Feeder lines allow an assembly area to take the pre-assembly tasks and perform them off the main production line. These tasks can then be done before or at the same time major assembly tasks are performed on the main line (...) Performing certain processes off the main production line means fewer parts in the main assembly area, the availability of service-ready components and assemblies in the main production area, and, most important, improved quality and less lead time to build a product".

Creating feeder lines, or in other words moving subassemblies out of the final assembly line, means reducing flow time by working in parallel rather than sequentially. The balance across positions can be improved by constructing feeder lines to reduce congestion and complexity.

Identify Candidates for Process Breakthrough Redesign (Tactic 7)

The 9 Tactics literature explains Tactic 7, "Radically redesign products and business processes" as follows: "Breakthrough process redesign uses innovative ideas and concepts to reduce *flow time*, work-in-process inventory, and defects. With an understanding of the relationship among materials, processes, and machines, employees can radically rethink the entire transformation process".

By applying Design for Manufacturing (DFM), a form of process breakthrough redesign oriented to improve the manufacturability of the airplane, the final assembly process can attain significant line balancing improvements.

The design of the aircraft plays an important role in the program's ability to balance the resources. For example: the 737 design allows the installation of electric systems (wiring) into the separate sections of the fuselage (barrels), in contrast with the 717 design that requires the fuselage to be completed (all barrels joined) to start the installation of the electric systems. The result of the 737's more modular design is a more balanced process with less congestion in the middle stages of the production process and a less "bell shaped" curve.

DFM projects typically result in important reductions in the number of jobs required or in the jobs' work content. Substantial improvements on the balance of the line can be obtained by targeting DFM projects to the most congested days of the production process.

Co-share Mechanics with High RTS

We recommend to co-share mechanics in different positions (assign mechanics to work in more than one position) when the Report to Supervisor time (RTS, time programmed in the schedule in which no work is assigned to the mechanic) is large. This practice requires coordination between IE's and supervisors from different production teams in the preparation of the schedules.

Methodology to Balance the Line Across Positions

A procedure explaining the practices to balance the line across positions was constructed by process observation and interviews (see Appendix 3). The objective of this procedure is to standardize (Tactic 3, see Appendix 1) the methodology followed by the Industrial Engineers. The procedure was documented in BCAG's standard format for operations' procedures.

The procedure also states that some projects for balancing the line across positions requiring substantial change in the manufacturing process might involve significant investment. The lean practitioner and the industrial engineer must be aware that some improvement initiatives will need to be supported by a business case.

Results

The analysis explained the rationale behind dividing the line balancing activity in two categories: balancing the line across positions (addressed in this chapter) and balancing within the position (addressed in the next chapter).

The different factors affecting the line balance were analyzed (airplane design, zone congestions, etc.) with the ultimate result of a procedure that standardizes the practices to balance the work force across the assembly line.

The BCAG's 9 Tactics literature defines as deliverables of Tactic 2 the precedence diagram, the bar charts, and the jobs broken into even work packages. In this thesis the precedence diagram is considered part of the application of tactic one, not two (this apparent contradiction strengthens the argument of the impossibility of a sequential implementation of the 9 Tactics).

This section warned the practitioner of a potential misinterpretation of the balancing the line concept. The efforts to achieve an "even distribution of resources across the available time" (from the Tactic 2 definition) must be focused on redistributing the workforce in the position, but not necessarily to even distribute resources across the line.

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VII. PRODUCTION PLAN PREPARATION

Introduction

This chapter explores the application of Tactic 2 (Balance the Line), to balance the resources within an assembly line position.

Once the system configuration is selected, the next step for the Industrial Engineers (IE's) is to Balance the Line or evenly distribute the resources via production execution plans or "bar charts" to meet the production requirements. The preparation of these plans is iterative and time-consuming, complicated by constraints such as assembly sequences and space limitations. The process for balancing the line is not standardized and each IE prepares the plans based on his/her experience. For every production rate change, the IE department develops a new assembly line configuration and the corresponding production execution plans. The 717 Program has experienced several rate breaks (production rate changes) during its 2 years in operation and more fluctuations are expected for the future.

The bars in Figure VII-1 show an example of the distribution of the mechanic assignment across the manufacturing flow time, with fictitious data. The bold line shows the ideal situation of having balanced the mechanic's use per position. In this chapter the focus is on optimizing the use of the mechanic workforce, in contrast with the cockpit balance analysis that optimized the space usage.

Bar Charts

The bar charts or production execution plans are Gantt-chart-like visual tools that show each mechanic what jobs to execute, and at what time with half-hour of detail in a determined position. The bar chart distributes the use of the most valuable resource, the mechanic time, through the position. Therefore, the balance of the mechanic workforce per position is as balanced as the bar charts associated to that position. This is the reason why this chapter focuses on improving the bar chart preparation processes.

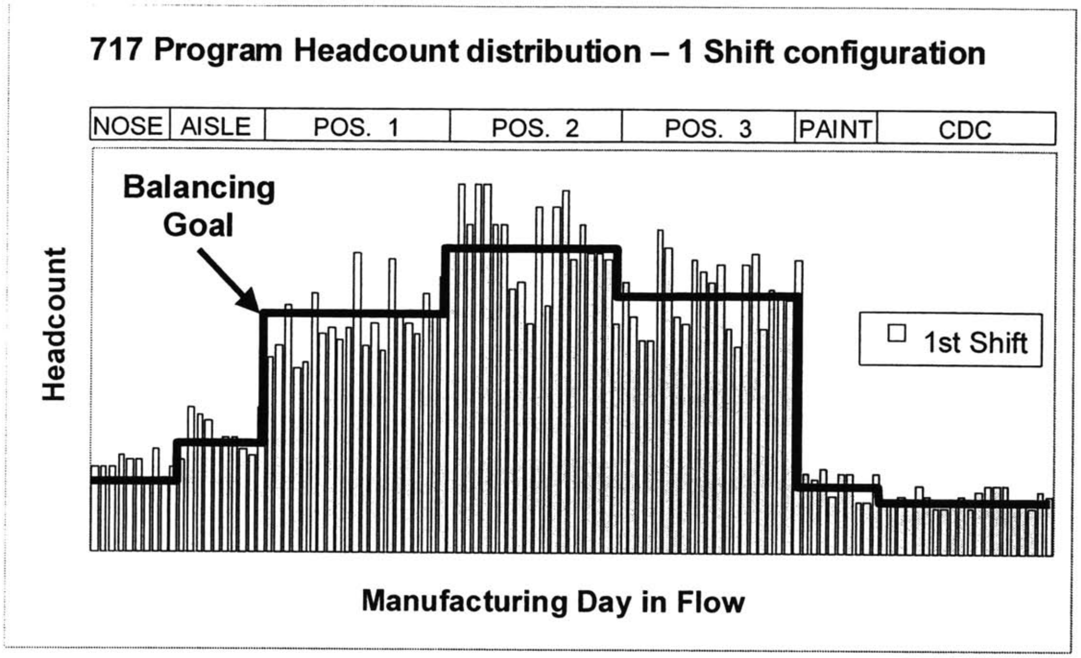


Figure VII-1: Balancing the Resources within the Position (fictitious data)

Approach

The goals associated with improving the bar chart preparation process are not only to improve the balancing of the position, but also to reduce the costs associated with the construction of the bar charts. The approach followed was to optimize the procedure to prepare the bar charts using Axiomatic Design and to Standardize/Document this procedure for further training and improvement.

Axiomatic Design Application

The Axiomatic Design theory was applied to optimize the sequence of steps of the Bar Chart preparation process. Simply explained, the axiomatic design approach uses a design matrix to analyze the interrelationships between what the bar chart must accomplish (or functional requirements) and the process steps (design parameters) to build the bar chart. The process sequence is re-arranged to perform first the steps with the most complex interrelationships in the design matrix and the jobs with the simplest relationships at the end. See Appendix 4 for a more detailed explanation of the Axiomatic Design theory.

When analyzing a sequential process using axiomatic design, the Design Parameters or DP's are identified as the process steps, and the Functional Requirements or FR's the desired results of the process. For the bar chart preparation process (the sequential process), the FR's are the requirements that the bar chart must meet, such as the department budget, avoiding area congestion, etc. The DP's are the steps the IE execute to construct the bar chart.

The interrelations between the process steps and the functional requirements for an administrative process can be complicated to the point that the design matrix is almost full (coupled design, see Appendix 4), without the opportunity to arrange it as a decoupled design. Even in that situation, if the coupled design matrix resulting from analyzing a sequential process has been arranged as close as possible to a decoupled design (triangular matrix), it delivers an optimized sequence of DP's. This DP sequence minimizes the iterations in the execution of the process steps.

Methodology to Rearrange the Interrelationships Matrix:

The following is a proposed methodology to rearrange a design matrix and obtain an optimized sequence of process steps:

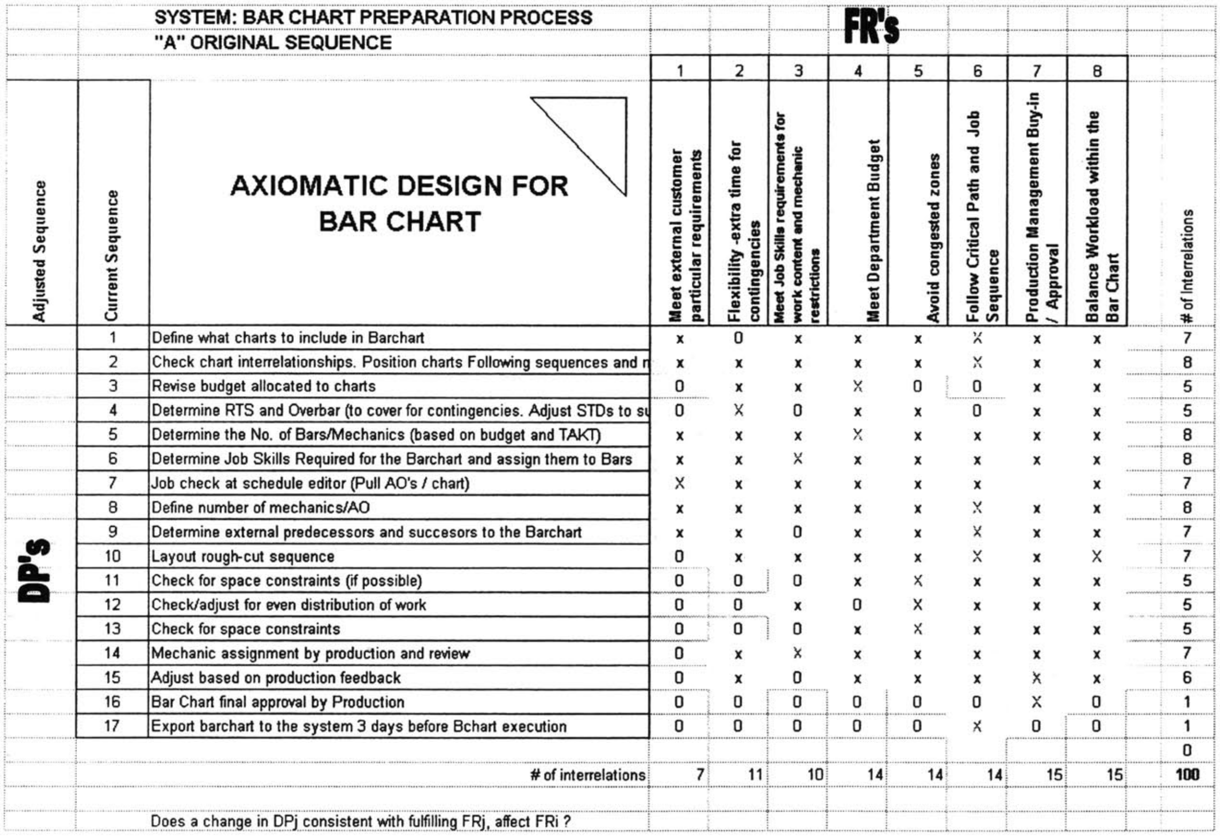
a) Map the administrative process or identify the DP's.
The process steps followed by four IE's from different areas (airframe, systems, and interiors) were mapped and consolidated in one generic process.

b) FR's of the process. Understand the requirements of the customer for this process.
The customer of the Bar Chart preparation process is the final assembly line-the operations group. These are their requirements for the Bar Chart: "Meet external customer particular requirements", Flexibility -extra time for contingencies", "Meet Job Skills requirements for work content and mechanic restrictions", "Meet Department Budget", "Avoid congested zones", "Follow Critical Path and Job

Sequence", "Production Management Buy-in / Approval" and "Balance Workload within the Bar Chart"

c) Construct the design matrix identifying the interrelationships between the FR's and DP's.

The graph in Figure VII-2 shows the format used for the design matrix. DP's are listed vertically and FR's horizontally. The IE's defined the interrelationships by asking the question: "Does a change in DPj consistent with fulfilling FRj, affect FRi?" Strong relationships were depicted with a capital "X" and medium relationships are small caps "x". Weak or null relationships were marked as zero. Given the arrangement of the matrix, the decoupled matrix must follow a triangular shape as is depicted in the shaded triangle. Also counts of the number of interrelationships (or "X's) by row and column in the matrix were added to help in the arrangement of the matrix to a triangular shape.



SYSTEM: BAR CHART PREPARATION PROCESS
"A" ORIGINAL SEQUENCE

FR's

DP's

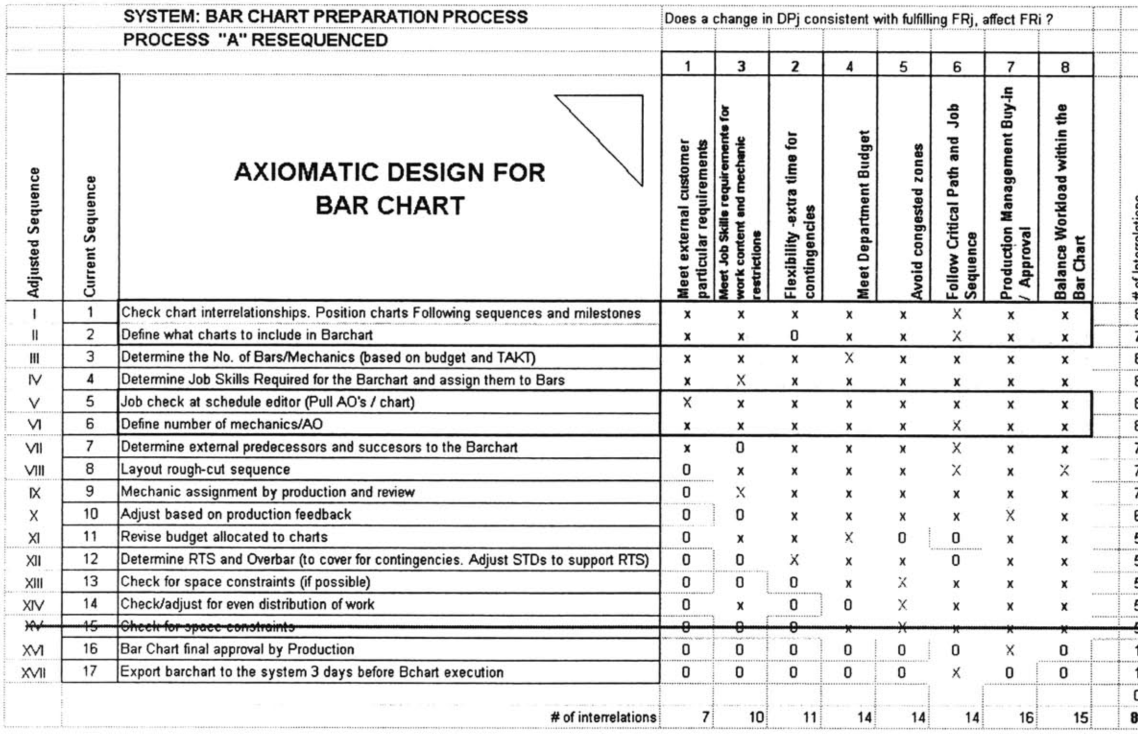
Adjusted Sequence	Current Sequence	AXIOMATIC DESIGN FOR BAR CHART	1 Meet external customer particular requirements	2 Flexibility -extra time for contingencies	3 Meet Job Skills requirements for work content and mechanic restrictions	4 Meet Department Budget	5 Avoid congested zones	6 Follow Critical Path and Job Sequence	7 Production Management Buy-in / Approval	8 Balance Workload within the Bar Chart	# of Interrelations
	1	Define what charts to include in Barchart	x	0	x	x	x	X	x	x	7
	2	Check chart interrelationships. Position charts Following sequences and r	x	x	x	x	x	X	x	x	8
	3	Revise budget allocated to charts	0	x	x	X	0	0	x	x	5
	4	Determine RTS and Overbar (to cover for contingencies. Adjust STDs to s	0	X	0	x	x	0	x	x	5
	5	Determine the No. of Bars/Mechanics (based on budget and TAKT)	x	x	x	X	x	x	x	x	8
	6	Determine Job Skills Required for the Barchart and assign them to Bars	x	x	X	x	x	x	x	x	8
	7	Job check at schedule editor (Pull AO's / chart)	X	x	x	x	x	x		x	7
	8	Define number of mechanics/AO	x	x	x	x	x	X	x	x	8
	9	Determine external predecessors and succesors to the Barchart	x	x	0	x	x	X	x	x	7
	10	Layout rough-cut sequence	0	x	x	x	x	X	x	X	7
	11	Check for space constraints (if possible)	0	0	0	x	X	x	x	x	5
	12	Check/adjust for even distribution of work	0	0	x	0	X	x	x	x	5
	13	Check for space constraints	0	0	0	x	X	x	x	x	5
	14	Mechanic assignment by production and review	0	x	X	x	x	x	x	x	7
	15	Adjust based on production feedback	0	x	0	x	x	x	X	x	6
	16	Bar Chart final approval by Production	0	0	0	0	0	0	X	0	1
	17	Export barchart to the system 3 days before Bchart execution	0	0	0	0	0	X	0	0	1
											0
		# of interrelations	7	11	10	14	14	14	15	15	100

Does a change in DPj consistent with fulfilling FRj, affect FRi ?

Figure VII-2: Design Matrix for Original Sequence

d) Arrange the matrix as close as possible to a decoupled design matrix. Re-arrange the order of DP's and FR's.

DP's or Process steps were arranged in a descending order of "# of interrelations" per row (or X's, see Figure VII-3). FR's were arranged in an ascending order from left to right of "# or interrelations" per column. The final triangular shape of the design matrix resembled as much as possible a decoupled design. Figure VII-3 shows the original matrix re-arranged.



SYSTEM: BAR CHART PREPARATION PROCESS
PROCESS "A" RESEQUENCED

AXIOMATIC DESIGN FOR BAR CHART

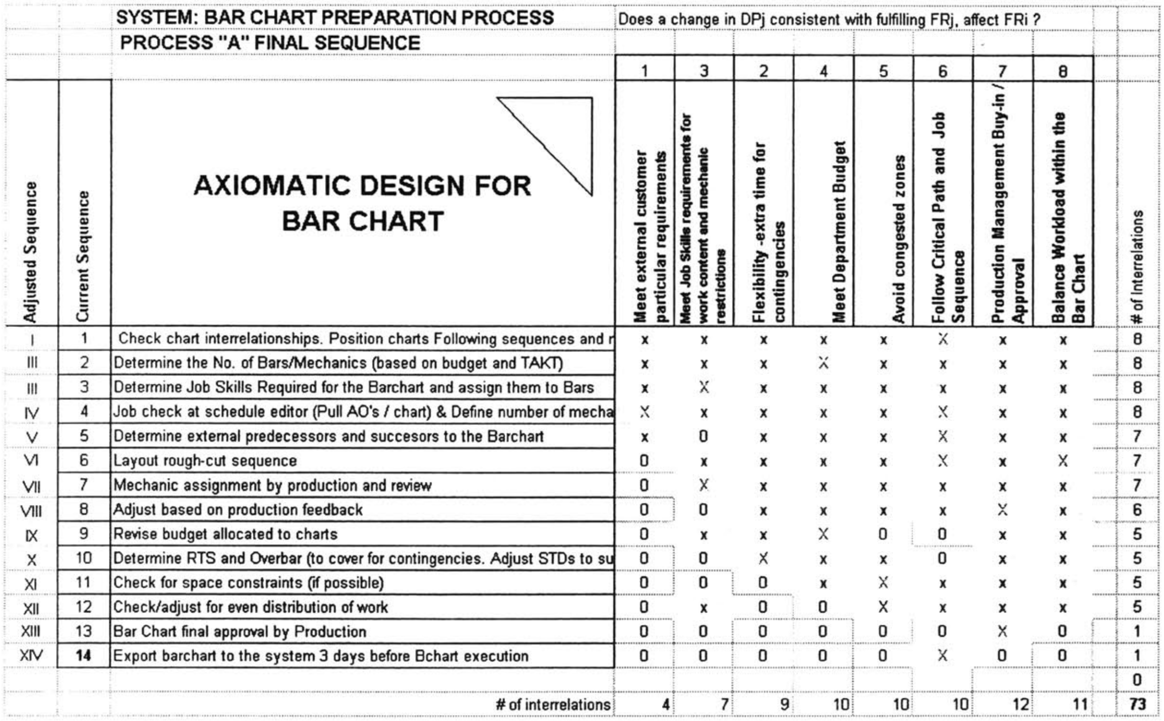
Does a change in DPj consistent with fulfilling FRj, affect FRi ?

Adjusted Sequence	Current Sequence		1 Meet external customer particular requirements	3 Meet Job Skills requirements for work content and mechanic restrictions	2 Flexibility -extra time for contingencies	4 Meet Department Budget	5 Avoid congested zones	6 Follow Critical Path and Job Sequence	7 Production Management Buy-in / Approval	8 Balance Workload within the Bar Chart	# of Interrelations
I	1	Check chart interrelationships. Position charts Following sequences and milestones	x	x	x	x	x	X	x	x	8
II	2	Define what charts to include in Barchart	x	x	0	x	x	X	x	x	7
III	3	Determine the No. of Bars/Mechanics (based on budget and TAKT)	x	x	x	X	x	x	x	x	8
IV	4	Determine Job Skills Required for the Barchart and assign them to Bars	x	X	x	x	x	x	x	x	8
V	5	Job check at schedule editor (Pull AO's / chart)	X	x	x	x	x	x	x	x	8
VI	6	Define number of mechanics/AO	x	x	x	x	x	X	x	x	8
VII	7	Determine external predecessors and succesors to the Barchart	x	0	x	x	x	X	x	x	7
VIII	8	Layout rough-cut sequence	0	x	x	x	x	X	x	X	7
IX	9	Mechanic assignment by production and review	0	X	x	x	x	x	x	x	7
X	10	Adjust based on production feedback	0	0	x	x	x	x	X	x	6
XI	11	Revise budget allocated to charts	0	x	x	X	0	0	x	x	5
XII	12	Determine RTS and Overbar (to cover for contingencies. Adjust STDs to support RTS)	0	0	X	x	x	0	x	x	5
XIII	13	Check for space constraints (if possible)	0	0	0	x	X	x	x	x	5
XIV	14	Check/adjust for even distribution of work	0	x	0	0	X	x	x	x	5
~~XV~~	~~15~~	~~Check for space constraints~~	~~0~~	~~0~~	~~0~~	~~x~~	~~X~~	~~x~~	~~x~~	~~x~~	~~5~~
XVI	16	Bar Chart final approval by Production	0	0	0	0	0	0	X	0	1
XVII	17	Export barchart to the system 3 days before Bchart execution	0	0	0	0	0	X	0	0	1
											0
		# of interrelations	7	10	11	14	14	14	16	15	86

Figure VII-3: Process Re-sequenced

e) Assess the feasibility of the new sequence from the re-arrangement. Check for impossible precedences and adjust, trying to maintain the triangular shape of the matrix. Consolidate redundant DP's or FR's.

The new sequence suggested executing the step "Define what charts to include in bar chart" at the middle of the process. By logic, this step must be done at the beginning of the process and was moved as the second step. Also the step "Check for space constraints" was eliminated, as it was redundant (see Figure VII-3). The rest of the precedences were feasible. Process steps "Check chart interrelationships", "Position charts Following sequences and milestones" and "Define what charts to include in bar chart" were consolidated as a single step as they covered fairly the same FR's and were logically executed at the same point of time. The same for "Job check at schedule editor (Pull AO's / chart)" and "Define number of mechanics/AO". See the process steps marked with boxes in the Figure VII-3.



SYSTEM: BAR CHART PREPARATION PROCESS

PROCESS "A" FINAL SEQUENCE

Does a change in DPj consistent with fulfilling FRj, affect FRi ?

Adjusted Sequence	Current Sequence	AXIOMATIC DESIGN FOR BAR CHART	1 Meet external customer particular requirements	3 Meet Job Skills requirements for work content and mechanic restrictions	2 Flexibility -extra time for contingencies	4 Meet Department Budget	5 Avoid congested zones	6 Follow Critical Path and Job Sequence	7 Production Management Buy-in / Approval	8 Balance Workload within the Bar Chart	# of Interrelations
I	1	Check chart interrelationships. Position charts Following sequences and r	x	x	x	x	x	X	x	x	8
III	2	Determine the No. of Bars/Mechanics (based on budget and TAKT)	x	x	x	X	x	x	x	x	8
III	3	Determine Job Skills Required for the Barchart and assign them to Bars	x	X	x	x	x	x	x	x	8
IV	4	Job check at schedule editor (Pull AO's / chart) & Define number of mecha	X	x	x	x	x	X	x	x	8
V	5	Determine external predecessors and succesors to the Barchart	x	0	x	x	x	X	x	x	7
VI	6	Layout rough-cut sequence	0	x	x	x	x	X	x	X	7
VII	7	Mechanic assignment by production and review	0	X	x	x	x	x	x	x	7
VIII	8	Adjust based on production feedback	0	0	x	x	x	x	X	x	6
IX	9	Revise budget allocated to charts	0	x	x	X	0	0	x	x	5
X	10	Determine RTS and Overbar (to cover for contingencies. Adjust STDs to su	0	0	X	x	x	0	x	x	5
XI	11	Check for space constraints (if possible)	0	0	0	x	X	x	x	x	5
XII	12	Check/adjust for even distribution of work	0	x	0	0	X	x	x	x	5
XIII	13	Bar Chart final approval by Production	0	0	0	0	0	0	X	0	1
XIV	**14**	Export barchart to the system 3 days before Bchart execution	0	0	0	0	0	X	0	0	1
											0
		# of interrelations	4	7	9	10	10	10	12	11	**73**

Figure VII-4: Final Sequence

f) Document the new process sequence in the proper format.
The new 14 steps (see Figure VII-4) were documented using the Boeing standard format. The Industrial Engineering department was identified as the owner of this procedure for further maintenance.

Results

Application of Lean and Axiomatic Design to Administrative Processes

As explained in Reference 15, to significantly improve performance, management has to look at the company as a whole. Improving the capabilities only in the factory floor, while useful, is not enough. Management has to extend its focus to the engineering and support "factories" (also known as "white-collar" processes) to see truly striking results. These results encourage the companies to improve capabilities throughout its system –the sales force, the distributors, and even the suppliers.

In this chapter lean concepts (balance the line, teamwork, employee involvement) were utilized to improve administrative process. As a result of this analysis a process to improve and standardize administrative process using lean and other continuous improvement techniques was prepared and delivered to the sponsor, the 717 Program (see Appendix 5).

A new application of axiomatic design for re-sequencing complex processes was explored in this chapter. The new sequence developed, though endorsed by the industrial engineering department, needs to be validated numerically to test its effectiveness.

Standardization: Weaving Tactic 3 into the Framework

This chapter required the application of Tactic 3, standard work, to document the sequence developed. This proves again that the implementation of the 9 Tactics must be done in a parallel rather than sequential fashion.

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VIII. BALANCE CONTROL

Introduction

The last chapter dealt with the preparation of the production execution schedules, or bar charts. Once the plan is completed, it is handed over to production for execution. Even though bar charts are prepared with some built-in slack to prevent variation in the system, management must monitor the timely execution of the plan by performance measures. This chapter proposes a performance metric to monitor the performance of the bar charts execution.

The relative importance of performance measures depends on the specific system and its business strategy (Reference 16). It has been mentioned before that Boeing's strategy is focused on cost reduction; therefore it is not surprising that the existing measures for the 717 final assembly line are cost-control oriented. Two of those measures are the "Jobs Behind the Schedule" (JBS) and "Jobs Ahead the Schedule" (JAS).

JBS and JAS assist management in monitoring the throughput performance for the assembly line. JBS represents the quantity of jobs that weren't finished (and still pending) on the day scheduled for completion for a given position. JAS describes the quantity of jobs that were completed ahead of the scheduled completion date.

There are two main drawbacks for the use of JBS and JAS as throughput measures. First, they do not give visibility to management to understand the variation or spread between the job's scheduled dates and the actual completion dates. The target values for JBS and JAS are obviously zero, but given the complexity in the execution and the number of jobs assigned to a position (typically hundreds) it should be expected that an acceptable execution of the bar chart would include some slack, or in other words some tolerance limits should be considered when evaluating the performance. This is not the case, and the JBS and JAS numbers only give management intuition about how behind the crew is relative to the plan, in the form of some mental percentage.

Secondly, JBS and JAS metrics do not establish a base to evaluate performance across mechanic crews (one position has one crew assigned). If tolerances were to be included in the use of the JBS/JAS metric, they have to be calculated for each position, as every position has a different quantity of jobs assigned. JBS and JAS require the calculation and maintenance of those limits for each position, and do not permit numerical comparisons between crews' (or positions') performances.

This chapter proposes a different metric to complement JBS/JAS, the Crew performance to goal index (CPGI), which will give management, with a single number, more information about the variability on the execution process, and will allow comparisons between positions.

Crew Performance to Goal Index

CPGI is based on the statistical quality control (SQC) measure called process capability index, or C_{pk}.

Process Capability Index

Process Control is defined under the umbrella of SQC as the continuous monitoring of processes with respect to both mean and variability of performance to determine when special problems occur or when the process has gone out of control. A process is capable if it is able to meet process specifications with regularity. A measure of capability is the Process Capability Index, which is defined as

$$C_{pk} = \min \begin{cases} (\mu - LSL) / 3\sigma \\ (USL - \mu) / 3\sigma \end{cases}$$

The minimum acceptable value of C_{pk} is generally considered to be one, but it varies depending on the application. Note that C_{pk} is sensitive to both variability (σ) and asymmetry (μ, a process mean that is not centered between the upper specification limit (USL) and the lower specification limit (LSL)). Hence, C_{pk} gives us a simple quantitative measure of how capable a process is of meeting its performance specifications (Reference 10).

CPGI Variable

The first step in determining the CPGI is to select the appropriate variable. This variable, called "execution gap" (EG) is defined as the actual completion date of a job (ACD) minus the scheduled completion date (SCD).

$$\mathrm{EG} = \mathrm{ACD} - \mathrm{SCD}$$

EG represents the number of days a single job is ahead or behind the schedule, and its target value is zero. EG will be positive if the job is delayed and negative if the job was completed ahead the planned date. Both ACD and SCD for a given position can be obtained from the 717 Program's electronic data collection systems.

The traditional C_{pk} calculations are performed on a key quality measurement associated with only one process (for example, a hole diameter measurement for parts produced with the same specific machine and tooling). The data points to estimate the mean and standard deviation are successively collected across a period of time. In contrast, CPGI requires the analysis of the distribution of EG not for a single job being completed by one mechanic across time, but of several jobs executed by several mechanics at one point in time. All the data points required for calculations (the EG's for each job associated with one position) are collected for an instant of time, or date for which the calculation of CPGI is made. Therefore another important assumption is that the behavior of the variable EG is the same for all the jobs related to one position. This is a broad generalization but acceptable, as the objective of the CPGI is managerial control rather than scrupulous control of a key quality measurement (such as a hole diameter).

CPGI Tolerance Limits

The second step is to calculate the acceptable limits for EG. Typically the 717 Program has considered as acceptable a tolerance range for JAS/JBS one day ahead and one day behind the schedule. This translates to tolerance limits for EG of (-1, 1) days.

Target Value for CPGI

The third step is to determine the acceptable value for CPGI, related to C_{pk}. Current literature and industry practices recommend a C_{pk} in the range of 1 (3 Sigma Level) to 1.33 (4 Sigma Level). These C_{pk} goals are historically targeted to evaluate key quality end product measures as size, weight, strength, speed, etc. variables or parameters. Therefore, as the application of C_{pk} is different than the current industry practices, in this analysis the target CPGI value will be calculated rather than benchmarked to an established standard.

It has been mentioned before that the 717 Program operations management is willing to tolerate a job execution gap (EG) between –0.5 and 0.5 days. Another important assumption to determine the right CPGI-C_{pk} is the maximum percentage of jobs out of the EG limits management will tolerate for a given position/crew at a given time. For this exercise let's assume that management accepts a maximum of 5% to 10% of the jobs out of these limits.

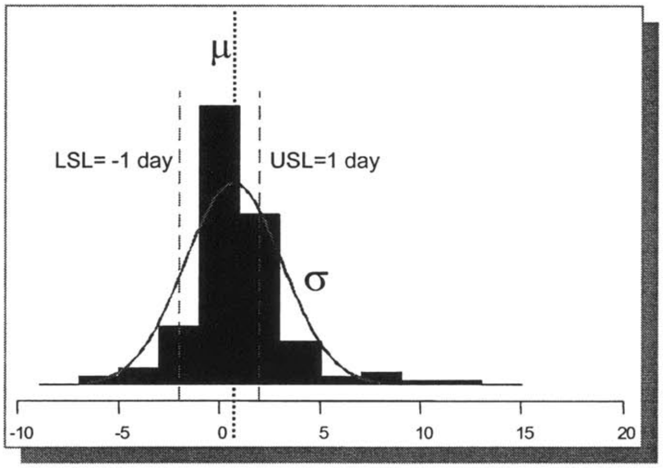

Figure VIII-1: Example of EG Distribution for a Position

Let's assume also that the distribution of EG is normal. During the internship normality tests for EG's for different jobs were conducted with successful results, so it is appropriate to assume normality for EG for practical purposes. See Figure VIII-1 for a one example of distribution of EG's for one position (fictitious data).

Another assumption is that EG has a symmetric distribution, meaning that the same percentage of jobs are delayed more than one day and performed more than one day ahead (see normal distributions in Figure VIII-2).

Two scenarios will be calculated (see Figure VIII-2):

a) 5% of the jobs are delay/ahead the EG limits (-0.5, 0.5) days

b) 10% of the jobs are delay/ahead the EG limits (-0.5, 0.5) days

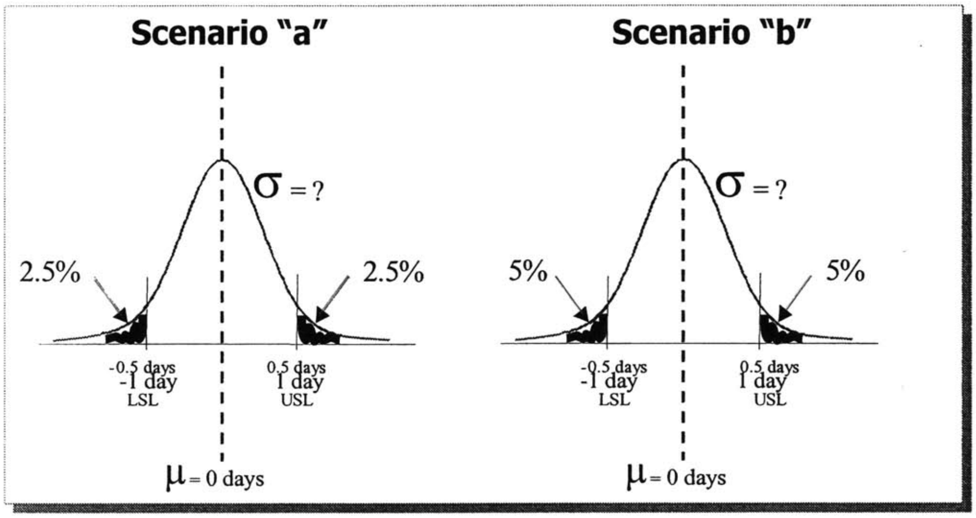

Figure VIII-2: Scenarios for CPGI Calculations

By using the central limit theorem we estimate the standard deviation of the process for both scenarios.

The standard values or "Z's" for 2.5% and 97.5% are $Z_{2.5\%}= -1.96$ and $Z_{97.5\%}= 1.96$ respectively in the normal distribution table. For 5% and 95% they are $Z_{5\%}= -1.64$ and $Z_{95\%}=1.64$. With these values it is possible to estimate the standard deviations of the process for both scenarios from the formula:

$$Z = \frac{LSL - \mu}{\sigma}$$

where LSL is the lower specification limit of 1 day (see Figure VIII-2). Then for scenario "a":

$$Z_{2.5\%} = \frac{LSL - \mu}{\sigma} = \frac{-0.5 - 0}{\sigma} = -1.96$$

Then $\sigma_{2.5\%} = \sigma_{97.5\%} = 0.255$. The same result can be obtained by analyzing $Z_{97..5\%}$, as we are assuming a symmetrical normal distribution.

For scenario "b":

$$Z_{2.5\%} = \frac{LSL - \mu}{\sigma} = \frac{-0.5 - 0}{\sigma} = -1.64$$

Then $\sigma_{5\%} = \sigma_{95\%} = 0.304$

With these values for standard deviations, the C_{pk} number for CPGI can finally be calculated. For scenario "a" (using formula for C_{pk} at the beginning of this chapter):

$$C_{pk} = \min \begin{cases} (0 - (-1)) / (3 \times 0.255) = 1.31 \\ (1 - 0) / (3 \times 0.255) = 1.31 \end{cases}$$

For scenario "b":

$$C_{pk} = \min \begin{cases} (0 - (-1)) / (3 \times 0.304) = 1.10 \\ (1 - 0) / (3 \times 0.304) = 1.10 \end{cases}$$

The goal for production, given the assumptions, is to achieve a CPGI of 1.31 or 1.10, accordingly to management's choice.

Therefore, it is recommended not to name the new performance metric as "C_{pk}", but as "crew performance to goal index" (CPGI). The reason is that C_{pk} is typically used in the industry to measure the quality of the end product. This is not the intention of the proposed metric and using the C_{pk} name could create confusion.

The process CPGI evaluates is highly complex, involving the execution of thousands of jobs. Another argument to support an acceptable value of Cpk that is smaller than other industry/process standards is that the variable CPGI does not directly define the quality of the end product of the process (the Aircraft). Most of the other industrial applications of C_{pk} define the quality of the end product.

Practical Use of CPGI

For a given position at a given time, a report is run from the electronic data collection system to obtain the ACD's and SCD's of every job. Then EG's are computed for every job, followed by the calculation of EG's mean and standard deviation. Then CPGI is calculated by

$$\text{CPGI} = \min \begin{cases} (\mu_{EG} - \text{LSL}) / 3\sigma_{EG} \\ (\text{USL} - \mu_{EG}) / 3\sigma_{EG} \end{cases}$$

LSL = -0.5 day
USL = 0.5 day

CPGI must be between 1.10 and 1.31, depending on management choice.

Plotting the distribution for EG (as in Figure VIII-1) also will help management to understand the spread. Statistical Packages as Minitab (available within the Boeing Company) can be used to prepare these graphs.

Plotting the distribution for EG (as in Figure VIII-1) also will help management to understand the spread. Statistical Packages as Minitab (available within the Boeing Company) can be used to prepare these graphs.

The analysis must be complemented with the JAS/JBS metrics, to understand the scale of the number of jobs ahead or behind.

Results

The use of CPGI supports the continuous improvement activity. As the process learning curve goes down, the CPGI target can be increased by means of tightening the percentage of jobs to be tolerated out of the EG limits, or by stretching the acceptable limits of one day behind or ahead. Nevertheless, the ideal or "vision" target for CPGI must be 2, which translates to a Six Sigma level of process performance widely accepted as the benchmark in the manufacturing industry.

CPGI is a statistical measure that focuses on variation reduction as well as the completion of the plan goals. Even though CPGI calculation holds assumptions (such as EG normality), it can be considered valid for providing management direction, rather than exact calculations.

Operations management at the 717 Program showed interest in the metric, and they plan to gradually implement it. It will be used as a high level metric only by area managers in the first stages. As the production processes stabilize (meaning that a small percentage of the jobs are being executed in a different position than scheduled) the metric will be utilized in the shop floor.

IX. BENCHMARK TO THE 757 PROGRAM

Introduction

The 757 Program located in Renton, WA has many similarities with the 717 Program as both have similar production rates. Moreover, after the tragic developments of September 11th, all of the Boeing's commercial programs had to cut production rates considerably, a situation that the 717 Program had been experiencing even before 9/11.

The benchmark exercise consisted of visiting the 757 Program in January 2002 to compare the methodology proposed in this thesis to the procedures followed by the 757 to reconfigure the assembly line, given the production slowdown.

This chapter will describe the similarities and differences of the two programs by analyzing each of the sections of the proposed framework to solve the internship problem in Figure II-3.

1-Current Value Stream Map Preparation

The value stream map (VSM) preparation proposed in this thesis focuses on analyzing the historically known critical jobs, linking them by using the CPM (critical path methodology) to estimate the total days of flow. The data collection is a team-oriented exercise that allows the participants to understand the main constraints driving the flow (for example, the understanding of the leverage of the cockpit space in the flow, see Chapters III and V).

The 757 Program uses two electronic resources to manage their job scheduling processes and to understand the drivers of the flow: the Job Requirements Database (JRD) and TimePiece© software.

The BCAG's I. E. Methods Process Council, initiated May 2000, is responsible for setting and implementing an integrated direction for Industrial Engineering Methods processes and practices with the goal of using technology as one platform towards driving process commonality. The first priority for this council has been to implement common job scheduling systems and processes. JRD and TimePiece© are important elements of this strategy.

JRD

The I.E. Methods process council describes the job data library or JRD as the foundation on which the rest of the scheduling tools are built. The purpose of this database is to act as a single source of data, capturing basic IE knowledge about a job. JRD holds for each job its generic information (not scheduling data) and the job history. This information, combined with capacity plans, schedule parameters, etc., is necessary to do scheduling, flow analysis, recovery planning and other IE processes implementation status.

The database has been released for production use and is in the early implementation stages across all Everett and Renton programs.

TimePiece©

TimePiece© is an Advanced Planning and Scheduling (APS) software tool developed by the Planning and Scheduling Technology team based on Houston, Texas. TimePiece© is a Finite Capacity Scheduling (FCS) tool to manage large, complex, discrete processes.

In its brochure (Reference 16), TimePiece© promises to generate feasible schedules fast enough to be of value in managing the process, to provide tools for controlling how schedules are generated, and to help identify critical elements in the schedule. TimePiece© uses the concept of "Critical Chains" to take into account all of the constraints in the process, such as product constraints (jobs, precedences, etc), process constraints (labor skills, tooling, etc.), cultural constraints (real breaks durations, people's preferences for jobs, etc.), and business constraints (aspects of the business that constraint the process). TimePiece© provides several configurable built-in reports that can be used to assign work. The most commonly used are the Daily Work Plan and the Bar Chart reports.

The JRD database inputs the job information required for TimePiece$^{\copyright}$ to formulate feasible schedules.

How the 757 Deploys the Use of this Tools

The JRD for the 757 Program is completed and used in conjunction with TimePiece$^{\copyright}$ to generate feasible schedules almost immediately. The feasible schedules are then analyzed to understand the main drivers of the flow, construct the critical path and determine the flow time for the process.

In contrast, the methodology used during the internship for constructing the critical path in the 717 required one month and a half. The 717 current situation (production slowdowns, frequent organization restructures due to the downsizing), has prevented the I.E. department from setting up the JRD, as the implementation requires a substantial amount of work to collect and input the information in the new database.

Another benefit of using JRD and TimePiece$^{\copyright}$ is easier identification of shifts in the critical path, meaning that as the individuals in the process improve execution, continuous improvements are implemented, or other constraints associated to the process change, the critical path can shift from the original stream of jobs to another. By using JRD and TimePiece$^{\copyright}$ at almost no time cost (and therefore in a frequent fashion), more accurate estimations of the critical path and the total flow time of the process can be obtained.

In conclusion, the main benefits on the use of the JRD and TimePiece$^{\copyright}$ are the cost savings and the accuracy in the preparation of critical paths and calculation of the flow time.

2-Assembly Line Configuration Selection

In chapter IV we proposed preparing business cases for the new configuration of the assembly line decision, by performing an Economic Profit analysis. The practical application of this approach to the 717 Program resulted in an assembly line process with longer flows, fewer shifts (one shift) and higher inventory holding costs.

The economic analysis performed by the 757 Industrial Engineering department focused also in the estimation of labor and inventory holding costs. The resulting configuration had similar characteristics to the 717 configuration: flow days increase, increase in the inventory holding costs, and the reduction to a two-shift operation.

In conclusion, the use of Economic Profit analysis (as proposed in this thesis) is a more complete analysis and considers all the elements of the business, in contrast with a business case analysis for the main cost elements of the assembly line (labor and inventory holding costs) performed by the 757 IE department. By using EP, the airplane program benefits from Industrial Engineering's understanding of the leverage points in the economics of the business (not only the assembly line), with the final result being more optimal final assembly line configurations.

3-Adjust the Current Value Stream Map to the New Configuration

The existence of the JRD and TimePiece© again establishes significant differences between the proposed framework and the 757 current practices.

In the 757 the future VSM construction starts by conducting "Tier 0 Management team workshops". In these workshops, the management team defines the future vision of the assembly line, creating a macro "to be process" and identifying the issues associated with the new configuration. At this level the process flow is analyzed by job packages, not by individual jobs. The methodology applied is similar to the proposal in Chapter III: a team re-arranges the job packages, represented as sticky notes, in large Gantt-chart-like scrolls of paper with the new time requirements (days of flow, number of operating shifts, etc).

There is no significant difference between the methods used by both airplane programs in constructing the future VSM. It is a team approach. For both the main goal is to maximize the critical path work.

4-Balance Work Across the Line

During the benchmark no significant information was collected to assess the differences in this activity between the two programs.

5-Production Plan Preparation

The information collected from the Tier 0 workshops is entered into TimePiece©, to create what is called TimePiece©-driven bar charts, or TimePiece© models. With that information the IE's prepare the bar charts using the schedule editor (same software tool used by the 717 Program).

Then supervisors and leads analyze the bar charts in "Tier 1 supervisors and leads workshops", reviewing and validating the macro process, analyzing the sequences of jobs, prioritizing issues, and assigning owners and implementation schedules for those issues.

The IE's finalize the bar charts as the issues revealed in the workshop are solved.

Because of the 757's use of TimePiece©, the bar chart preparation process are fundamentally different. The 757 process for preparing the first draft of the bar chart is automated by TimePiece©, with considerable savings on IE labor. But it is uncertain that the labor costs for maintaining the JRD and operating TimePiece are justified.

6-Balance Control

The metrics to assess the throughput performance per position used for both the 717 and the 757 Programs are similar.

The 757 Program uses charts to graph the number of jobs behind schedule (JBS, see Chapter VIII) across time. JBS are classified as "in-position" (jobs are delayed but still in the right position), "out-position" (jobs delayed so much that they have to be performed out of the assigned position) or "traveled". These performance metrics, as described in Chapter VIII, do not give visibility to management to understand the variation or spread between the job's scheduled dates and the real completion dates. They also fail to establish a base to evaluate performance across mechanic crews.

The CPGI metric proposed in Chapter VIII will also help the 757 Program to understand the variance and capability of the crews to meet the plan.

Results

The same tradeoffs in the allocation of resources (labor cost and inventory holding costs) were found in the new configuration results for both programs. Even though the 757 Program business case analysis approach seems to be equivalent to the EP approach, it does not consider all the other economic aspects of the project in the decision. The 757 Program will benefit from the use of the economic analysis tool proposed in Chapter IV, and developing a thorough understanding of all aspects of the business and their impact on the configuration decision.

JRD and TimePiece© bring speed to the production schedules preparation process, though is recommended to the 717 program to understand the tradeoffs between the costs of setting up and maintaining these electronic resources and the costs incurred in the current bar chart preparation process.

As in the 717, we recommend to the 757 team to explore the use CPGI as a measurement.

X. NEXT STEPS

Current Value Stream Map Maintenance

With every reconfiguration of the line it is necessary to maintain the current VSM (or Critical Path). As a next step, the 717 Program must allocate resources to review and adjust the current VSM, documented in the MS Project format, in order to accommodate the changes resulting from reconfiguration of the line or a major change in the production schedule structure.

Nevertheless, if the JRD and TimePiece© are implemented, it would not be required to maintain the current VSM in the MS Project format proposed in this thesis; the critical path analysis will be supported by the TimePiece© software.

Better Integration of the Lean-Finance

The realization of the cash flows product from the implementation of lean projects can be a matter of years. For example, if the reduction on the requirements of some supplier's material is achieved by one of the accelerated improvement workshops (AIW, see Chapter I), given the dynamics of the relationship with the suppliers, it could take from six months to a year to get the supplier to implement the reduction on the quantity supplied. Only then the finance department will realize the cash flows, and recognize the project savings. Even though this practice aligns with standard accounting principles, it can generate frustration for the lean teams, as they are not promptly recognized for the goals achieved.

The Boeing Company is continuously working to improve performance measures and financial metrics; an example is the previously mentioned upgrade to the EPC. We recommend closer cooperation between the finance and lean groups at Boeing to look for alternatives to simplify and expedite the recognition of improvements achieved during the workshops.

The Tool Developed and EPC Upgrades

An updated version of the economic profit calculator (EPC) has been already released by this time, and it is expected that other versions will be developed in the future. The next step for the continuous use of the tool proposed in Chapter VI at the 717 Program is either to update the Excel tool, linking it to the new program, or to simply use the assembly line cost configuration and input that information manually in the new EPC version.

JRD and TimePiece© Implementation

Chapter IX explained the benefits from implementing the electronic tools job requirements database (JRD) and the TimePiece© software. The main potential benefit for the use of these technologies is the reduction of the time required to produce the rough-cut bar charts. It is recommended that the 717 Program assess the possibility of utilizing those tools. As a pre-requisite, it is necessary to understand the economic tradeoff between the costs and the availability of resources for the implementation and maintenance of JRD and TimePiece© against the current costs of preparing the production execution plans (bar charts) manually.

Test the Effectiveness of the Procedure

Another next step is to validate numerically the savings in industrial engineering labor time for the new sequence proposed in the bar chart preparation discussed in Chapter VII. Even though the procedure was formulated in conjunction with the Industrial Engineering department, the different Industrial Engineering areas have different constraints, making this difficult to establish as a standard procedure. This is the reason why the procedure is defined in the standardized document as guidelines for bar chart construction, rather than a rigorous process to be followed. Further refinement may be required to further optimize the bar chart construction process.

If the JRD and TimePiece© tools are implemented, the standardized procedure will require major maintenance to describe the new and automated process.

Deploy the Metric

The crew performance to goal index (CPGI) proposed in section VIII requires certain stability in the process. Otherwise, the resulting CPGI calculated will be useless. For example, if 50% of the jobs are out of the position (50% of the jobs are delayed and being performed in the next position from what they originally planned) the CPGI measure will result in a very small or negative value. This situation of jobs being out of position is typical from the production crews adapting to a production re-schedule. This is the current situation of the 717 Program at the beginning of the year 2002.

As it was stated in Chapter VIII, we recommend starting the use of this metric first to evaluate performance at the higher level of production management (at an area manager level), and then to roll it down to the rest of the organization when the execution of the process stabilizes and the CPGI value is no less than 0.1.

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XI. CONCLUSIONS

The original problem was defined in chapter two as proposing a methodology for the implementation of the first two tactics, Value Stream Mapping and Balancing the Line. It was also stated that the problem solution required an economic analysis and the consideration of the frequent production rate breaks.

The internship solved this problem by proposing, and practically applying, a framework for the implementation of the first two tactics. The final framework was depicted in chapter II, in order to give the reader a better understanding of the structure of this document (see Figure II-3).

Chapters III through VIII described the different components of the proposed framework and explained their practical application. Chapter IX described a benchmark exercise performed on the 757 to compare both programs' Industrial Engineering practices to balance the line. This chapter summarizes the results and important insights found about the appliance of lean concepts, economic analysis and heuristics during the internship process.

The Proposed Framework

The development of the framework was an iterative process. An initial framework was developed at the beginning of the internship, and it evolved as new insights and information were discovered through the development of the internship.

The activities performed during the internship were planned and selected (from many possible courses of action proposed by members of the organization), by assessing their alignment with the implementation of the first two tactics. Usually after the completion of the activities their role or position in the final framework became evident.

The final framework (Figure II-3) proposes a methodology based on six main steps to implement the first two tactics, and is the main product delivered to the sponsor of the internship, the 717 Program at the Boeing Company. Other products delivered to the Program were the current VSM, the tool to analyze the costs of the assembly line, the bar chart preparation procedure, the balancing the line procedure, and the metric to measure production team execution to the bar chart. All of these products are necessary to re-apply the framework.

The Economic Analysis Tool and Lean

The decision-making activity in business organizations is performed at three levels: strategic, tactical and operational. The strategic decisions define the long-term plans for market positioning and profitability. The tactical decisions define how to implement the strategy, and the operational decisions define the day-by-day execution of the tactic decisions. The economic analysis performed for this thesis evaluated the profitability of possible scenarios of assembly line configurations (at a tactical level), and selected the one that delivers the highest profitability and aligns to the long-term strategy of the airplane program.

The results of the economic analysis confirmed that the one-shift configuration with longer flow times is the most profitable for the new production rate requirements. The analysis also explained that the tradeoff between the labor costs for second and third shifts and the increase in inventory holding days (for the increase of flow days) led to the resulting configuration. The configuration proposed aligned with the 717 Program strategy for future low production rates defined before the internship work.

In the development of the Excel tool for economic analysis, the lean concepts future Value Stream Map, one-piece flow, producing to TAKT, and open-book management were utilized.

First, the economic analysis determined the main parameters for the definition of the future Value Stream Map. Second, the analysis used the one-piece flow concept: in the definition of the new configuration, the economic analysis assumed the production of one aircraft in each position, only one aircraft flows through the assembly process at a time. Third, the "producing to TAKT" lean concept was covered by the economic analysis as the labor and other important resources were distributed to balance the production rate requirements.

Finally, an open-book management approach was necessary, as it was required to input to the Excel tool financial information of the program traditionally confidential to most parts of the organization.

Nevertheless, the economic analysis did not focus on reducing parameters as the traditional lean literature and lean Boeing applications suggest. The economic analysis focused on understanding the leverage and tradeoffs between the different assembly line configuration parameters, but did not help to reduce them per se. The typical applications of lean do not require economic analysis; they are centered in continuous improvement. As explained in Chapter IV, it is important that the organization understands where to draw the boundary between the projects requiring an economic analysis and the projects for continuous improvement that, as bundle, are assumed to deliver value in the long run (see Figure IV-5).

The decision making process was accelerated by the Excel tool proposed. Once the tool was configured and the required information was fed, a number of scenarios could be evaluated in a very short period of time. This tool can be applied to other airplane programs with minor adjustments in the operating costs modeling.

Assembly Line Configuration Tradeoffs and Lean

The literature analyzed and the Boeing approach to lean, explain the use of some techniques as balancing the line, reducing set up time, and reducing unnecessary labor to "eliminate waste". Waste is defined in parameters like floor space, inventory, unnecessary labor, etc. Following this logic, in the event of a re-configuration of the assembly line one might think it is against lean to consider alternatives that increase the number of flow days, as that seems counterintuitive to lean.

Notwithstanding, the economic analysis performed to define the configuration of the assembly line (in response to the production slowdown) in Chapter IV suggested that an increase in the number of flow days from the current configuration would deliver more value. The economic analysis explained this apparently anti-lean result by the fact that there is a tradeoff between the support group labor for the second and third shifts and the inventory holding costs of the aircrafts loaded in the line.

Insights in the Application of Lean Concepts to the Project

During the development of the framework a number of other lean techniques were applied and analyzed. The following are insights discovered during the internship work.

The 9 Tactics

An important insight from the application of the first two tactics is that the 9 Tactics cannot be implemented sequentially, as might be suggested by the order in which they are presented in Boeing's literature (see Figure I-2). In the project tactics one and two were implemented simultaneously in the different steps of the framework. To strengthen this argument, Tactic 3 (Standardize Work, see Appendix 1) was also utilized to document the processes improved in the framework, even though it was not the intent of the internship to implement Tactic 3.

It was also explained how Tactics 6 and 7 (feeder lines and design for manufacturing respectively, see Appendix 1) play a crucial role on improving the line balance (Tactic 2) in Chapter VI.

Value Stream Mapping

During the internship the importance of the Value Stream Mapping concept was repeatedly proved. VSM is the base for every continuous improvement activity or economic analysis project. First, it promotes the understanding of the current process and sets the baseline against which the improvements will be measured. Second, its construction promotes teamwork as people engage in conversations, generate new ideas and understand the main constraints or the root causes for the main problems of the system. Value stream map is also the foundation for implementation of further tactics.

The Value Stream Map concept was utilized constantly in all the stages of the internship. Value stream maps of different forms were used to determine the critical path, to define the new configuration, to understand the bar chart preparation processes, and to understand the current balancing of the line processes.

Balancing the Line

During the part of the project devoted to balancing the line, the importance of understanding of the critical constraints in the process flow in order to distribute the resources adequately was acknowledged. For most of the balancing activity, the main resource to balance in the assembly line is mechanic labor, but during the internship there was an instance in which the constraint to balance was the space of the cockpit, not the workforce. Only through the VSM exercise was it possible to identify the right constraints to balance.

Another important insight is the following: in the Boeing literature, the lean concepts point out that the use of the resources must be balanced across the entire process, with no emphasis on applying economic analysis. Nevertheless, during the balancing activity in the internship, tradeoffs between the benefits of moving jobs from one position to other, and the cost of changing the supplier schedules to accommodate to the new work schedules were identified. For this situation, a business case (or economic analysis) was recommended (see Chapter VI) to assess the benefit of balancing the line against supplier penalties, or other potential tradeoffs.

The lean theory suggests (Reference 3) the automation of repetitive, labor - intensive processes. Typically, this automation is applied to processes that do not require mental analysis such as some steps in the operation of equipment. Even though this could not be the case of the bar chart preparation process, in the 757 Program benchmark it was learned that the bar chart preparation process lead-time is reduced by applying TimePiece© software, automating that process. The software tries to capture the standard mental processes followed by the industrial engineer, considering all the constraints involved on defining the job sequences. As explained in next steps, it is recommended that the 717 Program explore the possibility of using Timepiece©.

Total Cost and Open Book Management

Economic analysis requires a culture in which financial information is shared by the different parts of the organization. Efforts must be taken to assure the safe flow of this information to the different areas requiring it.

Teamwork

The implementation of lean concepts and manufacturing system design are never a single person effort, and this was constantly proved during the internship. All the activities were supported either by a team or the coordinated input from different members of the organization. Another important aspect of the success of teamwork in time-constrained lean-related projects, as the internship, is the selection of employees with the highest knowledge or the highest organizational leverage for the problem to be solved.

Other success factors for the teamwork in this internship were to assign empowered, motivated people to the teams, and the definition of clear goals, background information, and expectations before the teamwork exercises start.

It was also learned from the teamwork exercise described in Chapter 5 that the leadership position can rotate during the execution of the project.

Lean for Administrative Processes

The lean concepts, so commonly applied to manufacturing processes, can be also applied to the white-collar activities (Chapter 6). Administrative processes are usually difficult to quantify, and the lean parameters can give us a direction for improvements.

Nevertheless, some creativity may be necessary to invent a practical approach to the lean concept. This was the case for the improvement of the bar chart preparation process, using axiomatic design.

Use of Heuristic Techniques

A combination of the internship's time constraints and the complexity of the 717 Program final assembly line fostered the application of heuristic techniques rather than complete, mathematical approaches to solve the problem. The heuristic techniques provide guidance to the managerial decision making, rather than exact calculations or forecasts. The following are the heuristics applied in the internship:

- The methodology to construct the future Value Stream Map, which used a simplified data collection procedure to apply the Critical Path Method (see Chapter III).
- The optimal configuration of the final assembly in the economic analysis was obtained by a simple spreadsheet cost analysis rather than more complex integer optimization programs (see Chapter IV).
- A simplified application of the Axiomatic Design theory was used to analyze process sequences (see Chapter (see Chapter VII) for the bar chart preparation process

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Appendix 1: The 9 Tactics to Improve Operational Efficiency

Tactic 1—Understand how value flows

Understanding how value should flow through the business is the first tactic in value creation. Aligning to the vision and direction set by leadership, employees and managers must define a future state of business and the associated goals and metrics. Once the future state is defined and understood, employees and managers must then understand the current state—how the business operates, how different functions and processes link together, and how process improvements can affect each segment of the company. Using value stream analysis, employees and managers can understand how best to apply resources and focus Lean tools in the places that will provide the most benefit. During this analysis, the improvement team understands and documents the current state of the business such as flow time, queue time, and the amount of work-in-process inventory. Understanding how value is created and flows through the business ensures that changes are made systemically rather than randomly and independently of other organizations.

Tactic 2—Balance the line

Balancing the line essentially means evenly distributing both the quantity and variety of work across available work time, avoiding overburden and under-use of resources. Work that is evenly distributed provides predictability and the ability to standardize work processes more easily. This eliminates bottlenecks and down time, which translates into shorter flow time.

Tactic 3—Standardize work procedures

Standard work procedures are the foundation of a Lean production system. A standard operation is a known, repeatable process that results in high-quality output. A standard operation ensures that everyone does the same job in the same way, in the best way possible. Having reliable, consistent processes in place can help employees eliminate the non-value-added activities. Standard work procedures also provide the ability to detect abnormalities or defects quickly. From a people perspective, this tactic allows easier cross-training and provides greater opportunities for all employees as they increase their abilities to perform more than one task.

Tactic 4—Put visual controls in place

Visual controls in the workplace can help people quickly and accurately gauge production status at a glance. These visual systems fall into two basic categories: progress indicators and problem indicators. A production-scheduling scoreboard is an example of a progress indicator. It can help people easily see when production is ahead, behind, or on schedule. Another visual control system, like a red-yellow-green light signal, can indicate the status of a machine or process. This visual system can help employees rapidly detect and fix problems. Visual controls allow everyone to instantly see the group's performance and increase the sense of ownership in the area. Having these types of visual cues can help save time and improve work quality.

Tactic 5—Put everything at point of use

Point-of-use is a technique that ensures people have exactly what they need to do their jobs—the right information, parts, tools, and equipment—where and when they need them. Using this technique requires close partnerships with the entire supply chain. Having parts, tools, equipment, and work instructions delivered to the point of use saves time, eliminates wasted movement and wasted space, and ensures that the time spent on products and processes adds value to the final product.

It is at this point that the focus of the tactical approach changes from cleaning up a work environment to radically improving quality and increasing the velocity of work. While the preceding tactics pave the way for increased efficiency, the remaining tactics dramatically cut flow time in leveraged areas and ensure that improvements are maintained.

Tactic 6—Establish feeder lines

Feeder lines allow an assembly area to take the pre-assembly tasks and perform them off the main production line. These tasks can then be done before or at the same time major assembly tasks are performed on the main line. For instance, when commercial airplane wings come into a final assembly area, inboard and outboard flaps are installed onto the wing after the wing is attached to the fuselage. A wing feeder line would allow flaps to be installed on a wing before arriving to the final assembly area. The wings would then arrive when employees are ready to attach the wings to the fuselage. Performing certain processes off the main production line means fewer parts in the main assembly area, the availability of service-ready components and assemblies in the main production area, and, most important, improved quality and less lead time to build a product.

Tactic 7—Radically redesign products and business processes

Breakthrough process redesign uses innovative ideas and concepts to reduce flow time, work-in-process inventory, and defects. With an understanding of the relationship among materials, processes, and machines, employees can radically rethink the entire transformation process. Redesigning a process, a part, a tool, or a piece of equipment provides an enormous opportunity to mistake-proof or design things in a way that prevents defects, waste, and inefficiencies.

Tactic 8—Convert to a pulse line

During this tactic, products are positioned into a straight-line configuration on the factory floor and stay at a production station for a period of time before advancing to another station. Standard processes, visual control systems, point-of-use staging, and feeder systems are in place, allowing work to flow continuously and quickly. During this tactic, work does not continue or move to the next assembly position until detected problems are corrected and all work assigned to that position is complete. It is during this tactic that reliable processes are put in place to respond to potential problems or immediate problems to keep work moving or to quickly resume after work has stopped.

Tactic 9—Convert to a moving line

A moving line moves products from one assembly team to the next. This line stops only when a problem is detected. The pace of the line is determined by the rate of customer demand. Parts, tools, and equipment are staged along the moving line so employees have everything they need, where and when they need it, to complete their work. Moving production lines ensure that value is added as long as the product moves continuously through production, eliminating enormous costs. Critical during this tactic is the ability of all employees to stop the production line when an error is detected. This ability prevents defects from being passed on to the next step in the process. Equally critical is the ability to get the production line moving again once a defect has been detected and corrected. Although a moving production line reduces flow time, defects, and work-in-process inventory, the biggest benefit may be the sense of urgency a moving line conveys throughout the production process. Employees can truly see and feel the pace of production. And a moving line further ensures discipline and commitment to sustaining improvements, because to keep the line moving, the improvements made in the previous eight tactics must be maintained.

The human element cannot be overemphasized, however. The tactics to achieve a Lean production system rely on empowered and high-performance work teams who have the responsibility and authority to make day-to-day decisions relating to their work. Achieving this kind of paradigm shift requires changing the work culture, and that change starts with leadership. Leaders must create a new infrastructure, change the reward system, and provide all employees with the appropriate training, tools, and information. Each leader must model new work behaviors and take an active role in directing and communicating these changes. The bottom line: the implementation of Lean principles and practices requires a different mindset. People closest to the work need and deserve the authority to improve the work. It requires faith and trust in one another and suppliers. Every part of the extended business must work together to achieve the business goals of The Boeing Company.

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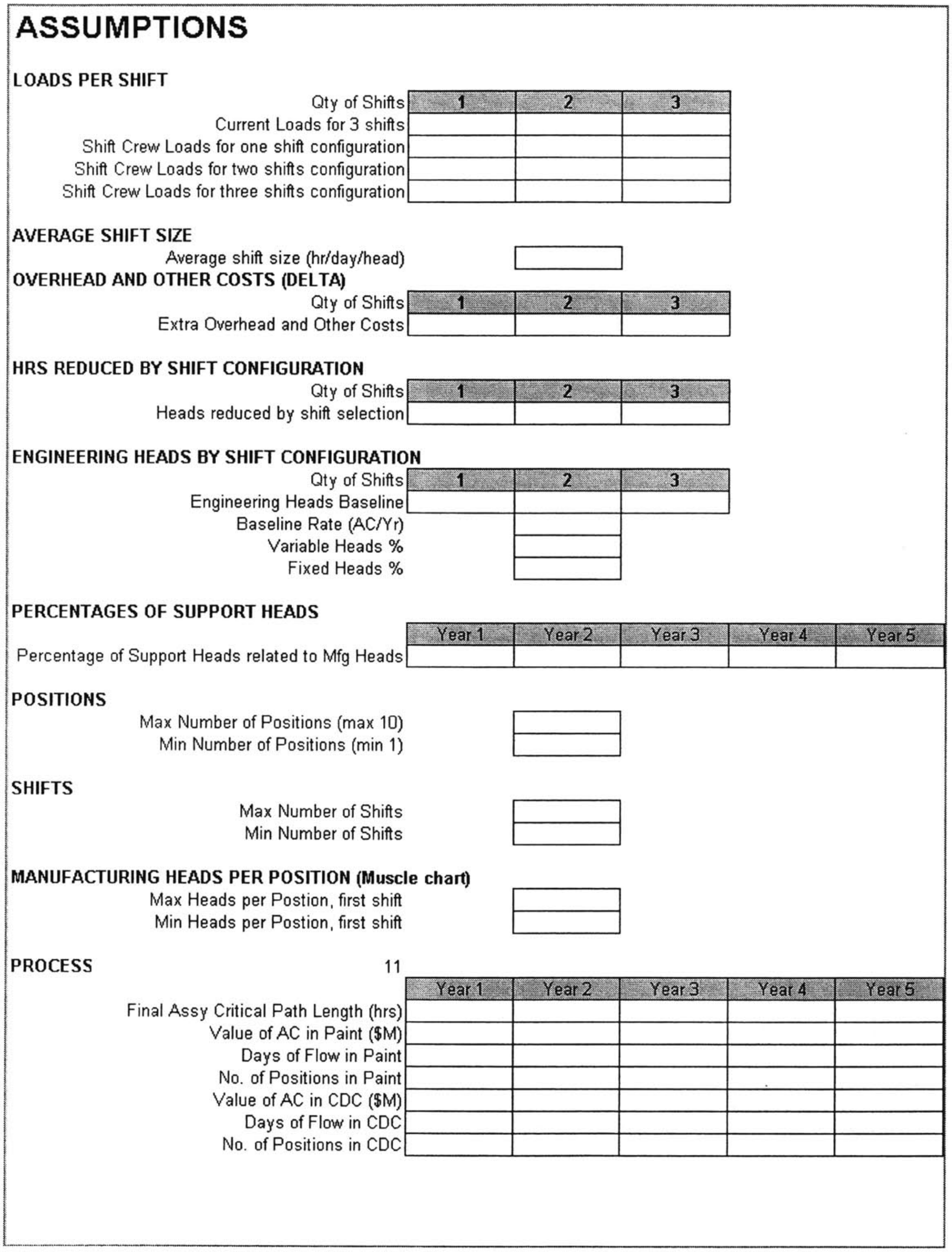
Appendix 2: Economic Analysis Tool Screens

1. Input Assumptions/Data Screen:



ASSUMPTIONS

LOADS PER SHIFT

Qty of Shifts	1	2	3
Current Loads for 3 shifts			
Shift Crew Loads for one shift configuration			
Shift Crew Loads for two shifts configuration			
Shift Crew Loads for three shifts configuration			

AVERAGE SHIFT SIZE

Average shift size (hr/day/head)

OVERHEAD AND OTHER COSTS (DELTA)

Qty of Shifts	1	2	3
Extra Overhead and Other Costs			

HRS REDUCED BY SHIFT CONFIGURATION

Qty of Shifts	1	2	3
Heads reduced by shift selection			

ENGINEERING HEADS BY SHIFT CONFIGURATION

Qty of Shifts	1	2	3
Engineering Heads Baseline			
Baseline Rate (AC/Yr)			
Variable Heads %			
Fixed Heads %			

PERCENTAGES OF SUPPORT HEADS

	Year 1	Year 2	Year 3	Year 4	Year 5
Percentage of Support Heads related to Mfg Heads					

POSITIONS

Max Number of Positions (max 10)

Min Number of Positions (min 1)

SHIFTS

Max Number of Shifts

Min Number of Shifts

MANUFACTURING HEADS PER POSITION (Muscle chart)

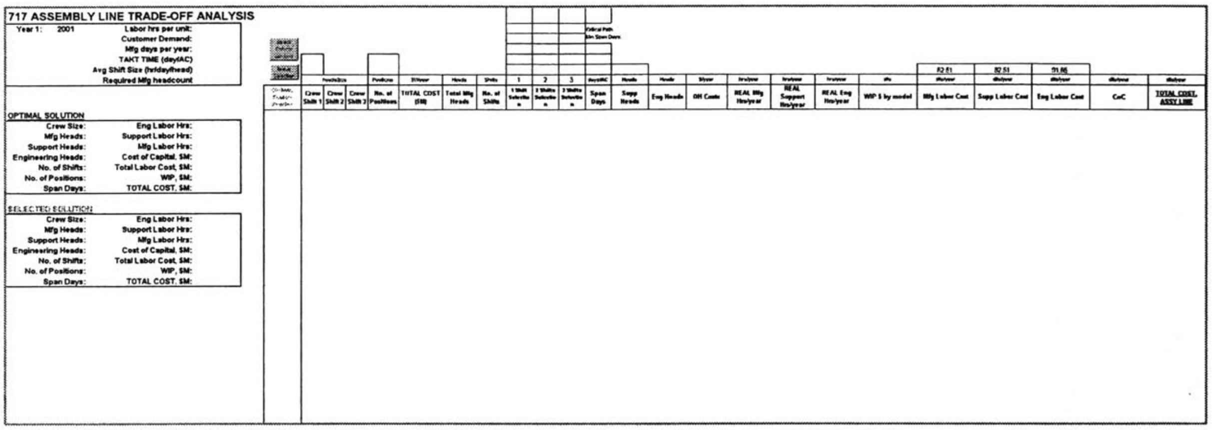
Max Heads per Postion, first shift

Min Heads per Postion, first shift

PROCESS 11

	Year 1	Year 2	Year 3	Year 4	Year 5
Final Assy Critical Path Length (hrs)					
Value of AC in Paint ($M)					
Days of Flow in Paint					
No. of Positions in Paint					
Value of AC in CDC ($M)					
Days of Flow in CDC					
No. of Positions in CDC					

2. Operating Costs Calculation screens:



717 ASSEMBLY LINE TRADE-OFF ANALYSIS

Year 1: 2001

Labor hrs per unit:
Customer Demand:
Mfg days per year:
TAKT TIME (day/AC)
Avg Shift Size (hr/day/head)
Required Mfg headcount

OPTIMAL SOLUTION

Crew Size:
Mfg Heads:
Support Heads:
Engineering Heads:
No. of Shifts:
No. of Positions:
Span Days:
Eng Labor Hrs:
Support Labor Hrs:
Mfg Labor Hrs:
Cost of Capital, $M:
Total Labor Cost, $M:
WIP, $M:
TOTAL COST, $M:

SELECTED SOLUTION

Crew Size:
Mfg Heads:
Support Heads:
Engineering Heads:
No. of Shifts:
No. of Positions:
Span Days:
Eng Labor Hrs:
Support Labor Hrs:
Mfg Labor Hrs:
Cost of Capital, $M:
Total Labor Cost, $M:
WIP, $M:
TOTAL COST, $M:

Critical Path
Min Span Days

																			82.51	82.51	91.86		
								1	2	3													
	Crew Shift 1	Crew Shift 2	Crew Shift 3	No. of Positions	TOTAL COST ($M)	Total Mfg Heads	No. of Shifts	1 Shift Selection	2 Shifts Selection	3 Shifts Selection	Span Days	Supp Heads	Eng Heads	OH Costs	REAL Mfg Hrs/year	REAL Support Hrs/year	REAL Eng Hrs/year	WIP $ by model	Mfg Labor Cost	Supp Labor Cost	Eng Labor Cost	CoC	TOTAL COST, ASSY LINE

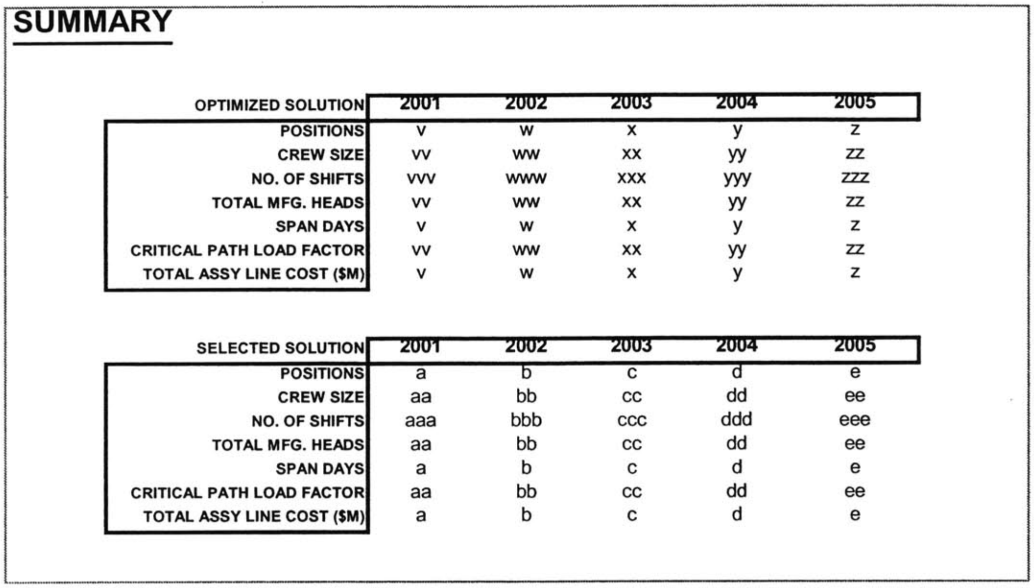
Each of the five spreadsheets calculates the operating costs for the 30 possible configurations for the assembly line (10 positions times 3 possible shifts). Each of the rows (one for each possible configuration) calculates the following parameters: crew size for Shifts 1, 2 and 3, total manufacturing heads, span days (flow time), support groups heads, engineering group heads, incremental overhead costs (maintenance, utilities, etc), number of required manufacturing, support and engineering labor hours per year, estimated work in process (WIP) required, manufacturing, support and engineering labor costs, capital charge (assets opportunity costs), and finally the total cost.

The total cost is the sum of the labor costs (for manufacturing, engineering and support groups), the costs of capital charge and the incremental overhead costs.

The spreadsheet automatically selects the configuration with the lowest total cost; nevertheless the user can override this selection to choose a different configuration.

3. Results and trade off analysis screen

This screen summarizes the parameters for the configurations selected for each year, helping to consider the variations in the parameters through the years on the long-term decisions

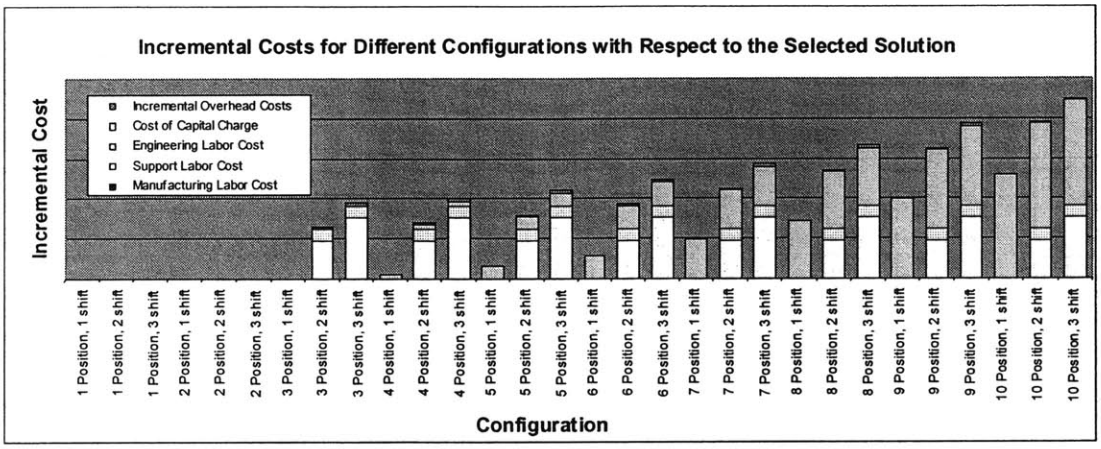


SUMMARY

OPTIMIZED SOLUTION	2001	2002	2003	2004	2005
POSITIONS	v	w	x	y	z
CREW SIZE	vv	ww	xx	yy	zz
NO. OF SHIFTS	vvv	www	xxx	yyy	zzz
TOTAL MFG. HEADS	vv	ww	xx	yy	zz
SPAN DAYS	v	w	x	y	z
CRITICAL PATH LOAD FACTOR	vv	ww	xx	yy	zz
TOTAL ASSY LINE COST ($M)	v	w	x	y	z

SELECTED SOLUTION	2001	2002	2003	2004	2005
POSITIONS	a	b	c	d	e
CREW SIZE	aa	bb	cc	dd	ee
NO. OF SHIFTS	aaa	bbb	ccc	ddd	eee
TOTAL MFG. HEADS	aa	bb	cc	dd	ee
SPAN DAYS	a	b	c	d	e
CRITICAL PATH LOAD FACTOR	aa	bb	cc	dd	ee
TOTAL ASSY LINE COST ($M)	a	b	c	d	e

The graph below helps management to visualize the incremental costs of the alternatives not selected, to help the user to identify the tradeoff magnitude between labor costs, the cost of capital charge, and other overhead costs. The tool presents five of these graphs, one for each year analyzed.



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Appendix 3: Balancing Across the Line Procedure.

1. **Identify opportunities or jobs to move, from different sources:**
    - From production requests: based in production employees' observations and suggestions
    - From observation: identify, by observing the production execution, congestions in aircraft zones, jobs constantly "out of position" (out of position means that jobs are performed in a different position than originally planned), etc.
    - Example: the positions with the highest man load (see Figure VI-1, top chart) typically have congested areas, and jobs "out of position" constantly. These disruptions caused variation in production execution performance and in quality. A project to move 160 Jobs (consisting on installing brackets and pulleys) upstream helped to free up some of this congestion.
    - Work to be potentially outsourced: some jobs can be moved outside the boundaries of the final assembly line to the suppliers, depending first whether that job must be kept inside by strategic reasons and second in the economics involved.

2. **Evaluate opportunities:**
    - Ask the "Five W's" (What, Why, When, Where, HoW) to collect the information available related to the problem.
    - Create a solution: define the new location or position for the jobs (one or more positions earlier), define a feeder line, or propose a process/product breakthrough re-design.
    - Develop a business case or economic analysis as required (for low dollar components an economic analysis it is not required).
    - Quantify the economic impact of:

        Supplier economics· For example, an economic analysis performed to determine the feasibility to move upstream the jobs for installing flap and slats showed that the supplier penalties for the change on the schedule overcome the benefits of moving jobs upstream.

        Reducing work content. Historically the best business cases are related to mechanic work time reduction by moving the jobs. Example: the installation of an electric harness required the mechanic to constantly wait for other peers to clear the congested area where the harness should be located. By moving this harness installation upstream, the work content (mostly waiting time) was reduced from four to two days.

Inventory reduction: Generally the savings by reducing the opportunity costs of inventory are difficult to quantify to the finance department. The main reason for this is the big lapse of time from the implementation of the improvement to the realization of the savings upstream (for example, the supplier sending lots of reduced size). This lapse of time could be several months to years. In other words, the realization of the cash flows required by the financial analysis is not completed until one or two years typically. Consider an economic analysis for the inventory reduction for a) high-dollar reductions or b) short lapses of time for the realization of the cash flows.

3. **Explain the benefits for the departments involved in the change.**
   - In order to obtain the buy-in of all the parties involved in the change (and in consequence a successful implementation of the change proposed), explain first the benefits to all the parties involved. Explain not only the benefits and changes for the party but also for the program in general.

4. **Approval or rejection by management.**
   - Based on the business plan and/or the explanation of the benefits, the management involved in the change will approve or reject it.

5. **Implementation.**
   - Create an implementation plan. In the case of moving jobs, generate a PCR (Planning Change Request) form to outline the jobs to move. Get the PCR approval from the other support functions: planning, engineering and supplier management. The approval determines the cut-in ship (serial number of aircraft in which the change will be effective) and date of implementation.
   - Monitor the change to verify its effectiveness.
   - Modify bar charts to reflect the change.
   - Negotiate the transfer of mechanics to the new areas, considering the union job classifications or job skill codes.
   - Obtain the bar chart modifications approval by production.

Appendix 4: Axiomatic Design theory

AXIOMATIC DESIGN - Definition

From the book "The Principles of Design" of Nam Suh (Reference 17):

Design is defined as the mapping process between the Functional Requirements (FR's) in the functional domain and the Design Parameters (DP's) in the physical domain. This relation may be characterized mathematically. Since the characteristics of the required design are represented by a set of independent FR's, these may be treated as a vector **FR** with *m* components. Similarly, the DP's in the physical domain also constitute a vector **DP** with *n* components. The design process then involves choosing the right set of DP's to satisfy the given FR's, which may be expressed as:

$$\{ FR \} = [A] \{ DP \}$$

Where **FR** is the functional requirement vector, **DP** is the design parameter vector and **A** is the design matrix. Each line of the vector equation above may be written as:

$$FR_i = \sum_j A_{ij} \; DP_j$$

The design matrix **[A]** is of the form:

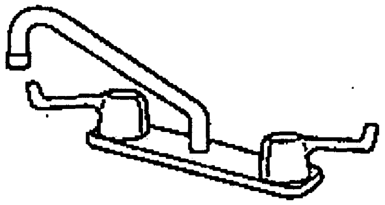
$$[A] = \begin{pmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ A_{1n} & A2_{n} & \dots & A_{nn} \end{pmatrix}$$

Each element $\mathbf{A_{ij}}$ of the matrix relates to a component of the **FR** vector to a component of the **DP** vector. In general, the element $\mathbf{A_{ij}}$ may be expressed:

$A_{ij} = \delta \; FR_i / \; \delta DP_j$

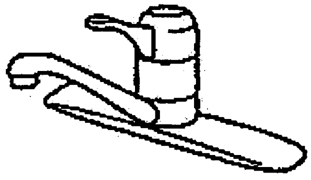
Depending on the shape of the design matrix, the designs can be classified as:

COUPLED DESIGN



$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{pmatrix} X & X \\ X & X \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

UNCOUPLED DESIGN



$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{pmatrix} X & 0 \\ 0 & X \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

DECOUPLED DESIGN

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

In an UNCOUPLED design, the FR's can be independently satisfied by means of the corresponding DP's [Theorem 6, pgs. 66-67]. A simple example of this is a faucet with a single handle: the FR's are temperature and flow, and the DPs are the up-and-down and left-to-right movements of the faucet handle. The first DP, up-and-down movement affects only the flow, not altering the temperature. Similarly, the left to right movement changes temperature only.

In a COUPLED design, there is no particular sequence of varying the DPs that is guaranteed to produce a satisfactory result. Although in a coupled design, it may be possible to achieve the desired values of the FRs by either varying the DPs in an iterative manner or by creating a sufficiently detailed mathematical model. [Theorem 7, pgs. 66-67]. This is the case of the faucet with two handles that both control the temperature and flow of the water.

In a DECOUPLED design, the FRs can be satisfied if the DPs are varied in the right sequence. In the graph, DP1 is set first, then DP2 and DP3, in that sequence.

Appendix 5: Methodology Proposed to Improve and Standardize Administrative Processes:

The Bar Chart Preparation white-collar process is used as an example to explain this methodology.

1. **Define the current Value Stream Map (VSM) of the process**
    a. **Document the current VSM**
    b. **Identify constraints**

The current state of the Bar Chart preparation process was defined by mapping the activities of 6 Industrial Engineers (IE's) of the different areas.

The VSM was graphically represented as a flowchart.

Constraints identified:

- Iteration in the execution of the Bar Chart preparation steps
- Long Bar Chart preparation lead times
- Variation in the execution order of the process steps and lead times by IE.

2. **Utilize an optimization method to prepare the future VSM, either:**
    - AIW's, Sequence Workshops, etc
    - Mathematical, Statistical or Heuristic techniques
    - The goal is to reduce the constraints previously identified.

In this case the Axiomatic Design theory was used to optimize the process steps sequencing. For more information about the Axiomatic Design application refer to Appendix 4.

3. **Test the effectiveness of the methodology proposed, and improve as necessary.**

The sequence proposed by the Axiomatic Design was validated by the IE's and refined.
A further step not completed yet is to measure the new lead times resulting of the new methodology. At the end of the internship the procedure was at the step of proposal.

4. **Document the methodology using Boeing's policy and procedures standard format. This must be a live document and must be maintained for further corrections/improvements by the department owner of the process.**

The Boeing's standard format was used. The Industrial Engineering department was identified as the owner of this procedure for further maintenance.