

Simulation Tool for the Improvement of the Coating Development Process
by

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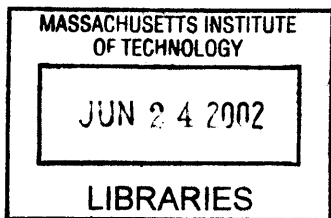
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ABSTRACT

Historically, the development of new coating processes at Alstom's Birr, Switzerland factory was iterative, time-consuming and expensive. In the coating shop, each order for a new coated component requires identification of a statistically acceptable production process in order to conform to engineering requirements. In an effort to streamline coating process development, Alstom began working on a computer-based coating simulation tool to allow for offline programming and coating process simulation. This research effort focused on continued development, calibration and analysis of an offline coating simulation tool.

The Alstom offline coating simulation tool merges the prediction capabilities of an internally developed plasma coating analysis program with the environment and simulation capabilities of an off-the-shelf CAD package. A programming firm was contracted to integrate the two systems and provide customizing macros to tailor the program for specific use with Alstom's low-pressure and atmospheric plasma spraying processes. An analysis of the offline tool simulation results for low-pressure plasma spraying was accomplished through a systematic comparison of the theoretical results from the offline tool with actual results for production parts. Results from an experiment were used to calibrate Alstom's coating analysis program. The offline tool was first developed for use with low-pressure plasma spraying processes. This development served as a platform for subsequent expansion of the tool for use with atmospheric plasma spraying processes. This thesis outlines the results of the development, analysis and calibration efforts along with recommendations for future development.

The final chapter of the thesis analyzes Alstom's improvement efforts at a system-wide level specifically looking at the role that the offline tool plays in helping Alstom overcome production challenges in their Birr, Switzerland coating shop.

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1.0 INTRODUCTION

Historically, the development of new coating processes at Alstom's Birr factory was iterative, time-consuming and expensive. Each order for a new coated component requires identification of a statistically acceptable production process in order to conform to engineering requirements. In an effort to streamline coating process development, Alstom began working on a computer-based coating simulation tool to allow for offline programming and coating process simulation.

This chapter provides an introduction to Alstom, the hot gas path business unit and their products. Chapter two provides an overview of the coating development process and chapter three outlines the technical challenges and requirements for Alstom's coating processes. The project details and results are presented in chapters four through six. Finally, chapter seven analyzes Alstom's improvement effort at a system-wide level.

1.1 Company Overview

This thesis outlines research and project work completed within the Power Sector of Alstom. Alstom is a large, multi-national company based in France with sales of over 22 billion euros¹. It employs more than 120,000 people in 70 countries. Primary Alstom businesses include Power, Transmission and Distribution, Transport, Power Conversion, and Marine.

In March 1999, Alstom entered a joint venture with ABB creating ABB-Alstom Power. ABB-Alstom Power merged the power generation businesses, excluding nuclear, of both companies. In May 2000, Alstom purchased ABB's 50 percent ownership in ABB-Alstom Power making Alstom the sole owner of the renamed Power sector. Today, Alstom's Power Sector represents the combined power generation businesses of ABB (Sweden) and Alstom (France).

The Power sector is the largest of Alstom's businesses with sales of € 12 billion in FY 2001. It is comprised of six segments: Gas Turbine, Steam Power Plant, Boilers & Environment, Customer Service, Industrial Turbine and Hydro.

¹ Sales and employment figures represent totals after the sale of the electrical contracting business.

There are four primary players in the power generation gas turbine market; GE, Siemens Westinghouse, Alstom, and Mitsubishi. In 2001, Alstom estimated it controlled 15 percent of gas turbine market. It has an installed base estimated at 20 percent of the world's power generation capacity².

1.2 Project Description

The goal of the Alstom internship was to finalize development and implementation of an offline coating simulation tool that would allow for objective evaluation of coating thickness and porosity levels for both low-pressure plasma spraying (LPPS) and atmospheric plasma spraying (APS) processes. Upon completion, the simulation tool would allow users to target process development activities thereby reducing the time needed to identify acceptable production processes for new components.

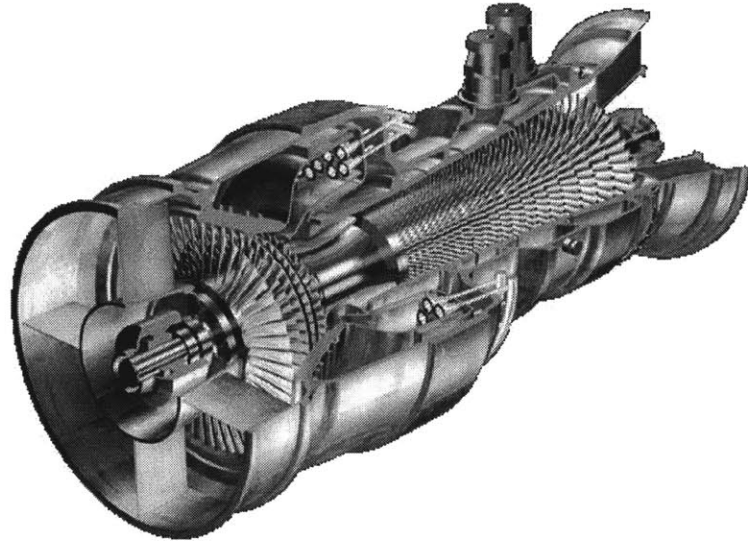
1.3 G-Segment Products

This thesis focuses on work performed with the Gas Turbine, G-Segment, at the factory in Birr, Switzerland. G-Segment products include turnkey power plants, gas and steam turbines, boilers, hydropower products and various power-related services. Gas turbines range from 50 to 260 MW for both the 50 and 60-hertz markets³. The GT24, shown in Figure 1, and GT26 combined-cycle turbines are the largest and most technologically advanced gas turbines currently marketed by Alstom.

² Alstom FY 2001 Annual Report, p. 71.

³ Alstom FY 2001 Annual Report, p.67.

Figure 1 – GT24 Gas Turbine

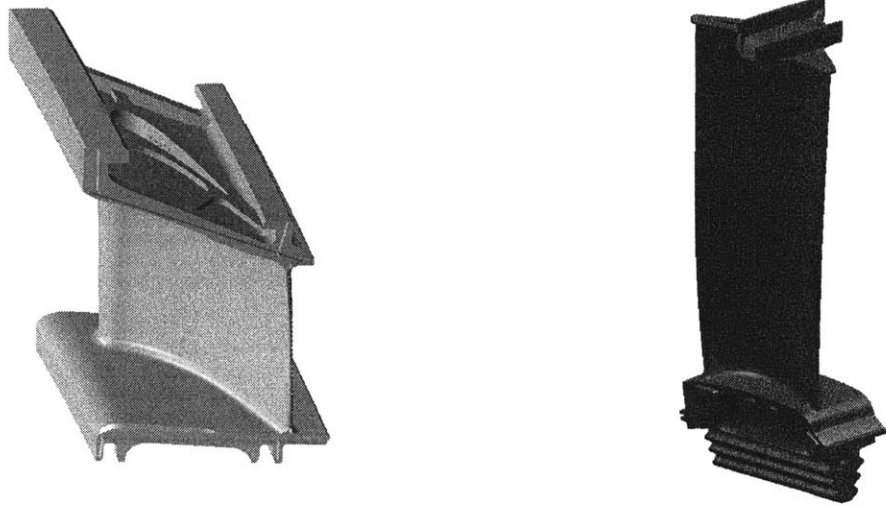


1.4 GFH Business Unit

In 1997, ABB launched a new business unit (GFH) to produce hot gas path turbine components within their Birr, Switzerland factory. This represented a strategic decision on ABB-Alstom's part to develop internal manufacturing capabilities for high value-added turbine components.

GFH produces turbine blades and vanes for the GT24/26 family of gas turbines. This internship focuses specifically on the coating of these blades and vanes. Vanes are stationary components in the turbine which redirect the gas flow. Blades are rotational components in the turbine which drive the rotor.

Figure 2 – Turbine Vane (left) and Blade (right)



GFH's primary customer is the G-Segment Logistics Group. Logistics is responsible for, among other things, procuring and delivering GT24/26 blades and vanes to the GFR business unit. GFR is another business unit, within the Birr factory, where the turbines are assembled.

The GFH business unit was designed to handle sixty percent of the estimated peak demand for GT24 and GT26 blades and vanes with external suppliers providing the remaining forty percent of demand. ABB-Alstom felt that the GT24/26 turbine blades and vanes had design advances which they wished to protect. For this reason, critical blades and vanes would only be produced internally, at the Birr factory.

2.0 COATING DEVELOPMENT PROCESS

2.1 GFH Production Processes

Alstom's manufacturing process for turbine blades and vanes is broken into four major production steps – casting, machining I, coating and machining II. The manufacturing processes associated with each production step are shown in Table 1. Casting and machining I are currently performed by external suppliers. The GFH factory was brought online with coating and machining II capabilities and will be expanded to include machining I capabilities in 2002.

Table 1 – GFH Manufacturing Processes

Production Step	Processes
Casting	Single crystal / directional solidified castings
Machining I	Grinding and EDM machining
Coating	Low-pressure and atmospheric plasma spraying
Machining II	Laser drilling, brazing and assembly

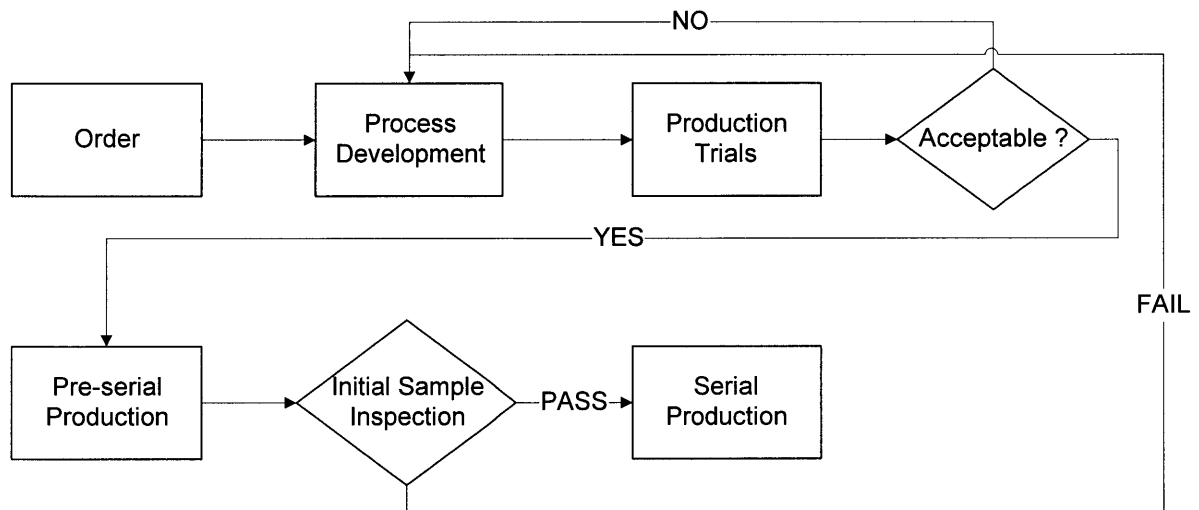
2.2 Process Development

The Manufacturing Engineering group in Birr is responsible for developing production processes for new parts. Manufacturing Engineering is a matrix organization with individual manufacturing engineers taking responsibility for developing new production processes for specific products while also providing support in their area of expertise. This requires close coordination between product managers and process experts in order to successfully complete process development for new parts.

2.3 Development Phases

GFH's development process follows a phased-gate approach which begins when the business unit receives an order for a new component from Logistics. The four primary development phases, shown in Figure 3, are process development, production trials, pre-serial production and serial production.

Figure 3 – GFH Development Process



During the process development phase, the Manufacturing Engineering group identifies, develops and delivers a stable and capable production process to the Production group. Manufacturing engineers determine the production operations, fabricate the necessary fixtures and write the numerical control (N/C) media used in production. Typically, a number of production trials are needed to identify a process that conforms to specifications. Once a conforming process has been identified and tested, the process is tested in pre-serial production. The Initial Sample Inspection (ISI) is used to determine when a part is ready to transition from pre-serial to serial production.

Because Initial Sample Inspection requires a demonstration of capability over at least six consecutive production batches, the Production group cannot begin serial production until, at the earliest, the seventh production batch. Pre-serial production is designed to allow for the sale of parts from the first production batches which were used to stabilize the process and collect preliminary cpk data. It is intended to be a temporary stage in the development process. Serial production begins only after successfully demonstrating the proposed process meets Initial Sample Inspection requirements.

2.4 Initial Sample Inspection

The Initial Sample Inspection (ISI) requires that production processes demonstrate a statistical process capability index (cpk) of 1.33 or better. Samples from five consecutive production batches are analyzed to determine the mean (μ) and standard deviation (σ) of the process. The calculation for cpk for a process with two-sided specification limits is as follows⁴:

$$cpk = \text{Min} \left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right]$$

where, USL = upper specification limit

LSL = lower specification limit

Because the ISI requirement is explicitly stated on the engineering drawing, failure to demonstrate process capability, whether the result of low cpk values or simply a lack of data, represents an engineering non-conformance. This means that each batch of parts produced prior to successful ISI is identified as discrepant and must be reviewed by a design engineer. Pre-serial parts that meet the engineering requirements are dispositioned “use-as-is.” Those that do not meet the engineering specification are either dispositioned for sale with limited life, reworked or scrapped. This engineering review process is time consuming and results in increased work-in-progress (WIP) since it represents a bottleneck in the production process. The

⁴ Memory Jogger, 1988 Pocket Guide, p.66.

engineering review process also requires a significantly greater level of effort from the G-segment support staff.

During Serial Production, parts produced under the approved processes are evaluated using Alstom's standard quality assurance procedure. While the traditional quality assurance process still requires one destructive evaluation per batch, it allows for immediate sale of acceptable parts. Only discrepant parts are identified as non-conforming and reviewed by the design engineers. This allows for significantly shorter production lead times and lower support costs.

2.5 Production Difficulties

While pre-serial production is intended to be temporary, because of schedule pressures, GFH was forced to enter production before completing ISI for a number of components. As a result, the Production group is working with unstable processes until new, more capable processes can be identified. This means that some of GFH's production is written up on non-conformance tags for design engineers to review. Increased administrative costs, increased costs associated with poor quality, increased inventory and life limitations on delivered parts are significantly hurting the financial performance of both GFH and the G-segment.

There are a number of theories as to why development engineers have not been able to identify statistically acceptable coating processes. Most involve a combination of design complexity, unstable production parameters, equipment limitations and a learning curve for process knowledge. GFH is currently working on a comprehensive plan to resolve production problems. The offline coating simulation tool fits into the comprehensive plan to improve process development for coated parts. Once the coating parameters have been identified and stabilized, the offline coating tool can be used to streamline the process of identifying a statistically acceptable coating process.

3.0 COATING PROCESSES

In order to understand the challenges associated with simulating the coating processes it is important to understand the functional requirements for the coating and how the part quality is evaluated with respect to these functional goals. This chapter also provides a short discussion of plasma spraying equipment and procedures.

The coating shop in Birr primarily works with two types of coatings; metallic coatings and thermal barrier coatings. While both coatings are applied to components with plasma spraying processes, the application environment and coating materials are dramatically different.

Metallic coatings are used to protect turbine blades and vanes from hot-gas corrosion and oxidation. The coating is applied using a low-pressure plasma spraying (LPPS) process in a vacuum chamber. The metallic powder has a MCrAlY composition as outlined in Table 2. The material properties of the coating, especially the thermal expansion coefficient, must closely match those of the base metal to allow for good adhesion as the part expands during turbine operation. Because of the similar composition of the base material and coating, it is not possible to evaluate coating thickness with standard non-destructive evaluation since these methods cannot differentiate between the metallic coating and the base metal.

Table 2

Metallic Coating Composition	
M	Cobalt, Nickel or Iron
Cr	Chromium
Al	Aluminum
Y	Yttrium (stabilizer)

Thermal barrier coatings (TBCs) are ceramic coatings used to insulate turbine components from high turbine operating temperatures. During thermal barrier coating a Zirconia powder is plasma sprayed onto a part in an atmospheric environment. Unlike metallic coatings, the material properties for the TBC coating are significantly different than those of the base part. This means that thickness can be evaluated with non-destructive methods. However, destructive tests are still needed to quantify porosity levels. Because of differing thermal expansion coefficients between the part and the coating layer, a certain amount of porosity is needed to prevent the brittle coating from failing as the turbine components undergo thermal expansion and contraction.

Thermal barrier coatings are critical to turbine performance. Better thermal barrier coatings allow for higher turbine operating temperatures and therefore higher operating efficiencies. This is one of the strategic reasons why Alstom chose to develop internal coating capabilities at the Birr factory.

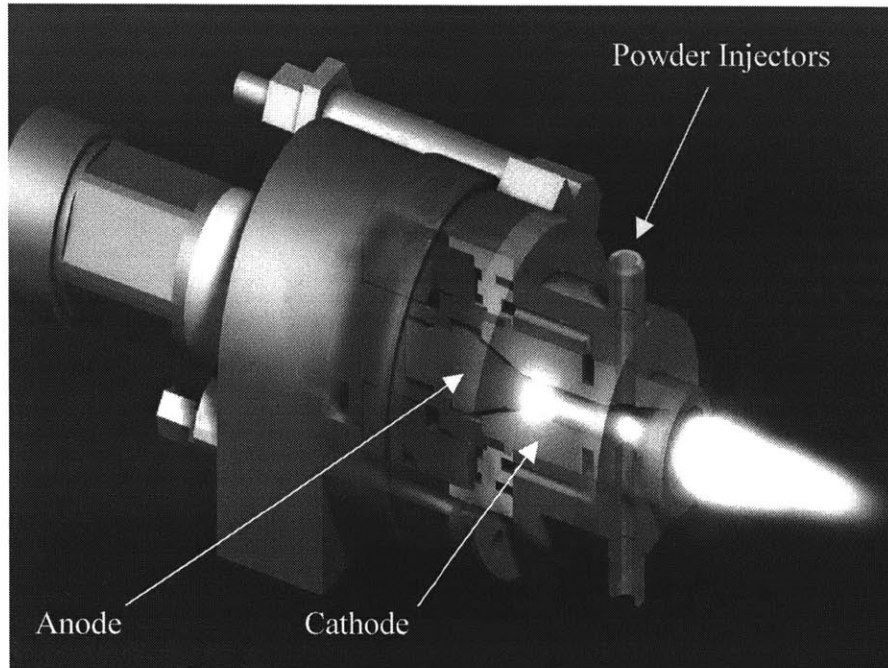
3.1 Plasma Spraying

Plasma is a state of matter where, in the presence of an electric field, ions and electrons travel independently. As these ions and electrons recombine, energy in the form of heat and light are released.⁵ The energy released during recombination heats the gas stream to temperatures between 6,600 °C to 16,600 °C (12,000 °F to 30,000 °F).

During plasma spraying, an inert gas stream is forced through the plasma gun shown in Figure 4. The gun has an anode and cathode which are used to create a DC arc. The arc provides the electric field needed to separate the ions and electrons. The coating material, in powder form, is injected into the gas stream where the plasma recombines. The resulting thermal energy is used to melt the powder particles as they are propelled toward the part surface in the stream of gas.

⁵ Equipment and Theory, A Lesson from Thermal Spraying Technology, Materials Engineering Institute, 1993, p. 27

Figure 4 – Plasma Gun



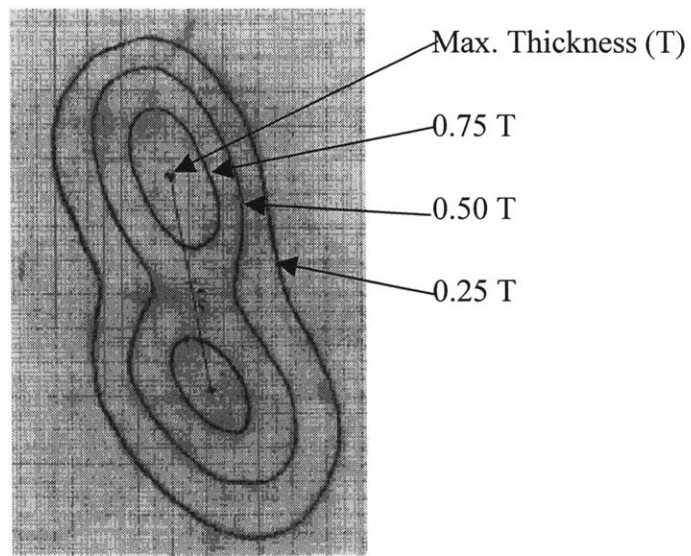
There are a number of variables involved in plasma spraying. The variables can be separated into two categories; independent and dependent variables. Independent variables, such as power, powder feedrate and carrier gas flow rates are directly controlled in the plasma spraying process. The specific settings for these independent variables are identified as a coating recipe. The GFH coating shop uses a number of different recipes in production.

Dependent variables, such as the surface temperature of the part, coating deposition rate and porosity level within the coating, cannot be directly adjusted; instead these variables must be monitored and controlled through changes to independent variables. It is difficult to target adjustments of dependent variables since they are often coupled to a number of different independent variables. A lack of quantitative understanding of these dependencies forces time-consuming, iterative production trials when developing new coating programs. This is a common industry problem which Alstom hopes to address, in part, through offline coating simulation.

Spray pattern tests are used to monitor a number of dependent variables. The spray pattern represents the coating footprint that comes in contact with part. Figure 5 shows the tracing of a typical metallic spray pattern as measured on a test plate. The metallic spray illustrates the effects of positional variation in coating thickness. If the measured spray pattern does not match that of the test standard for a given set of coating parameters, this is an indication that there is a problem with the coating process.

The coating is thickest at the maximum points in Figure 5. As you move outward from these maximums, the rings represent areas of constant thickness which are 75, 50 and 25 percent of the maximum thickness respectively. Each peak is formed by powder from one of the two powder injectors. The maximum points are formed from powder traveling at or near the center of the plasma stream and represent areas where the coating deposition rate and quality levels are highest. The majority of powder travels near the center of the plasma stream where particles are properly melted before surface impact. As you move out radially from the two maximum points on the spray pattern, these areas are formed from powder particles traveling further from the center of the plasma stream. These particles are less likely to melt in the stream before impacting the part surface. Improperly melted particles are either partially deformed on impact where they remain to form porosity or are deflected leading to lower deposition rates.

Figure 5 – Typical LPPS Spray Pattern

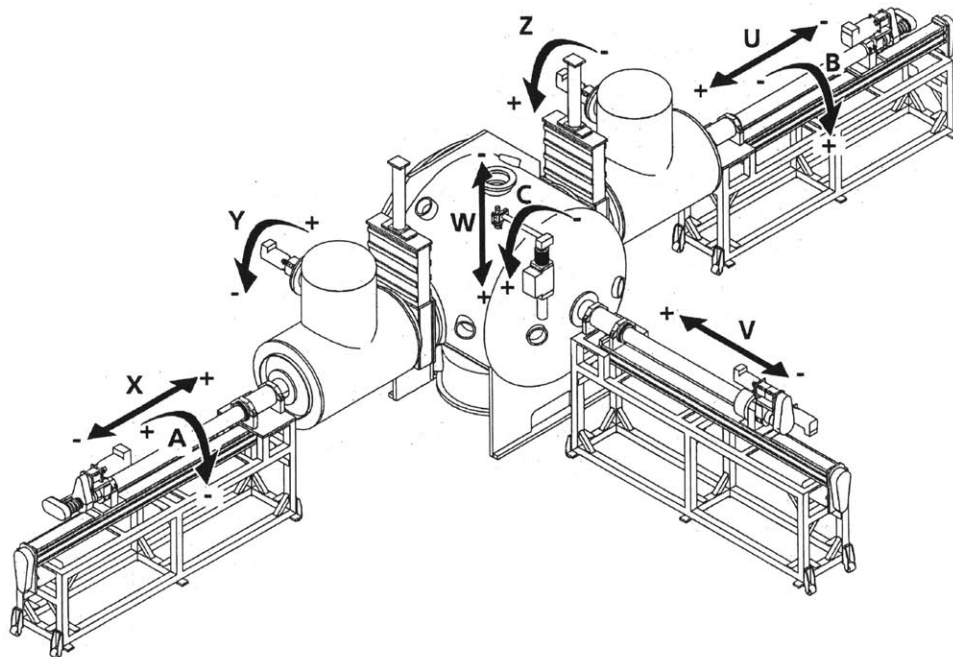


3.2 Metallic Coating Application

3.2.1 Low-Pressure Workcells

The Birr factory has four low-pressure plasma spraying (LPPS) workcells. Each workcell includes an LPPS machine (Figure 6), a robot, a pre-heat furnace as well as other equipment needed to operate and control the LPPS production process. The LPPS machine is configured with two pre-heat chambers, one on either side of the main-chamber. This design is intended to maximize coating time in the main-chamber. As one part is being coated in the main chamber, a second can be pre-heated and cleaned on the other side of the machine.

Figure 6 – Low Pressure Plasma Spraying Machine



3.2.2 Metallic Coating Process

Parts are heated in the furnace to a pre-heat temperature where they remain for a specified dwell time. When the operator is ready to begin coating, the coating routine is initiated. The process begins when the robot transfers a part from the furnace to the pre-heat chamber. In the pre-heat

chamber, the parts are cleaned and heated to desired coating temperature. During cleaning, a plasma gun in the chamber is used to burn off oxides on the surface of the part. Energy from the plasma beam and a transferred electric arc are used to heat the component. Once the part is clean and at the desired temperature, it is transferred to the main chamber. Ideally, the part should have a constant temperature after the cleaning operation. Instead, variations introduced by the numerical control (N/C) program for cleaning and complex part geometry result in gradients in the part's surface temperature at the end of the pre-heat/cleaning process. This temperature gradient represents a challenge for temperature prediction as is discussed later in chapter five.

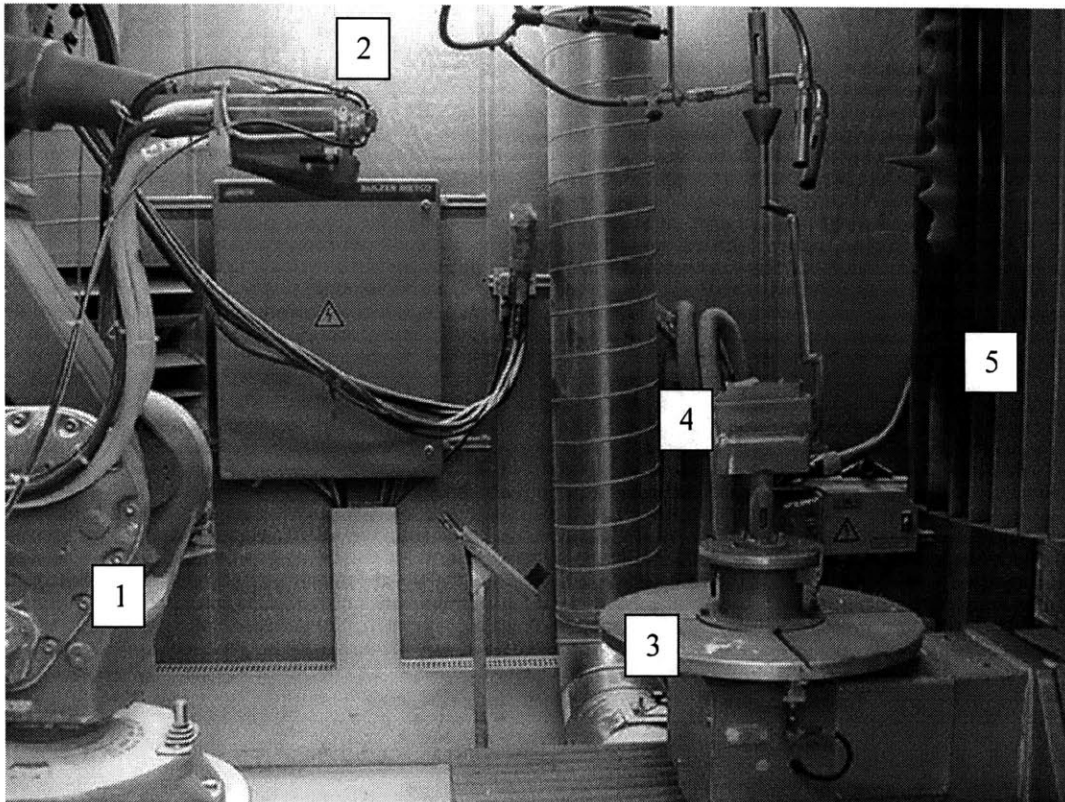
The plasma spraying is performed in the main vacuum chamber. The metallic powder is injected into the plasma stream as it exits from the plasma gun. The powder particles are rotated and heated in the plasma stream as they are projected toward the part surface. Upon impact, particles deform and adhere to the surface. The powder feedrate, deposition efficiency and the relative speed of the gun with respect to the part determine the thickness of coating deposited with each pass of the plasma gun. The spray pattern shape, which is a function of the coating recipe, determines the powder feedrate and deposition efficiency. The N/C program controls the speed of the part, the motion of the plasma gun and the number of coating passes. The resulting coating is a build-up of multiple layers of impacted powder particles. After coating, parts are diffusion heat-treated and then sent for further processing.

3.3 Thermal Barrier Coating Application

3.3.1 Atmospheric Workcells

The Birr factory has two atmospheric plasma spraying (APS) workcells. Each cell consists of a plasma gun mounted to a robot and a rotary table housed in a vented chamber as shown in Figure 7. The part is mounted in a fixture and loaded onto the rotary table. The workcells were designed with an automated handling system to shuttle fixtures with mounted parts into and out of the workcell.

Figure 7 – Atmospheric Plasma Spraying Workcell

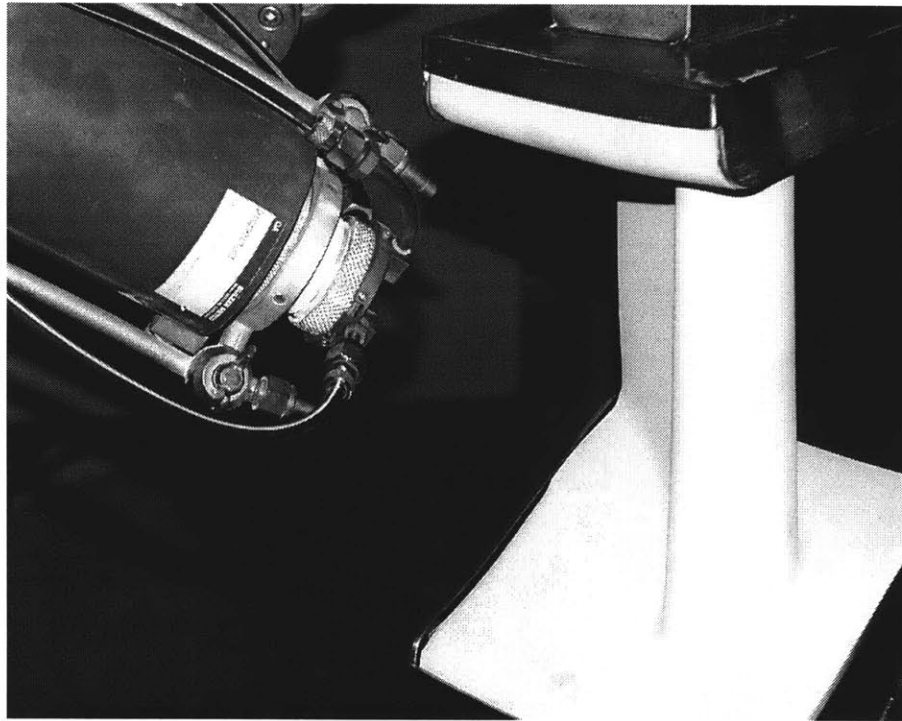


Atmospheric plasma spraying (APS) workcell elements: (1) Robot, (2) plasma gun, (3) rotary mounting table, (4) mounting fixture, (5) exhaust duct.

3.3.2 Thermal Barrier Coating Process

Thermal barrier coatings are plasma sprayed in an atmospheric environment at room temperature. Because APS spraying is performed in an atmospheric environment the process is very sensitive to the distance and orientation of the plasma gun relative to the coating surface. The plasma gun, shown in Figure 8, is held normal to the part surface at a constant offset distance from the part. Robot programs for parts with compound contours and complex geometry contain a great deal of information. This is a considerable change from LPPS plasma spraying where offset the distances are much greater and much less controlled.

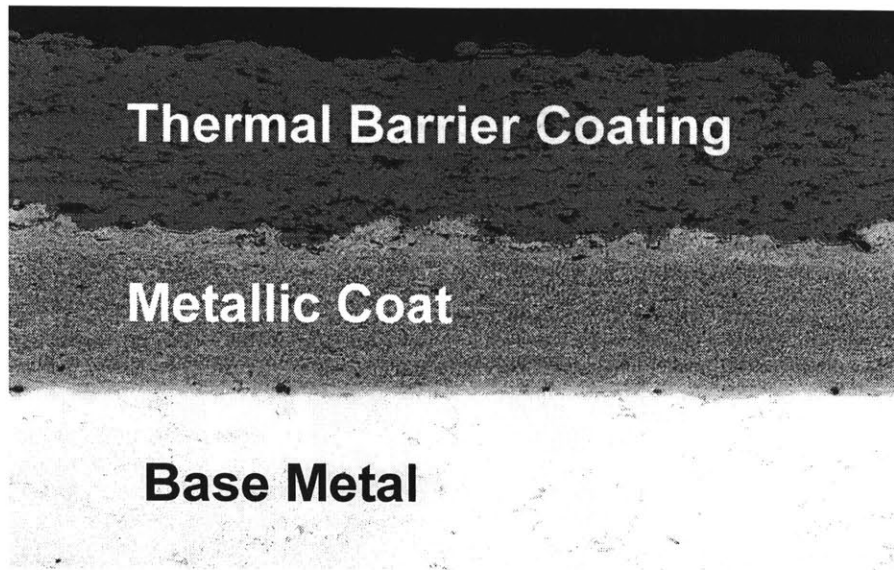
Figure 8 – APS Gun and Workpiece



3.4 Evaluating Coating Quality

A good coating is one which has a clean bond at the interface and has the desired thickness. Metallic coatings should also have low porosity and a rough surface finish. The rough surface of the metallic coating, as seen in Figure 9, is necessary to allow for adherence of the subsequently applied thermal barrier coat. Thermal barrier coatings should have the proper amount of porosity. If the porosity level is too low, the coating will crack during thermal cycling. If the porosity level is too high, spalling will occur during turbine operation.

Figure 9 – Photomicrograph of Coating



Alstom's internal laboratory assesses the quality of blade and vane coatings. The laboratory measures coating thickness, porosity, and bonding defects. Destructive testing is required to accurately determine coating quality. One representative part from each production run is cut into sections and analyzed at locations outlined in the inspection and test plan. Figure 10a shows the location of section cuts for the foot section of a typical part and Figure 10b shows the measurement points along one of the section cuts. Section cuts are mounted, polished and examined with a photomicrograph. Quality measures taken at these points are used to determine whether a production batch meets the engineering specifications and are tracked from batch-to-batch to evaluate the performance of the coating production processes. Results are published in a laboratory report and stored in a database. Laboratory analysis is labor intensive, time consuming and expensive.

Figure 10a – Identification of Section Cuts

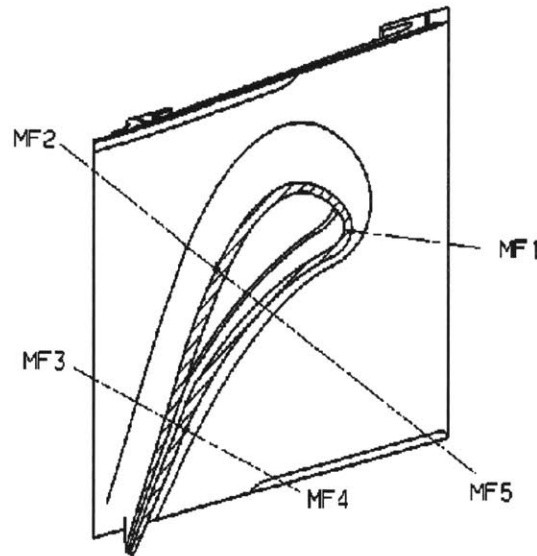
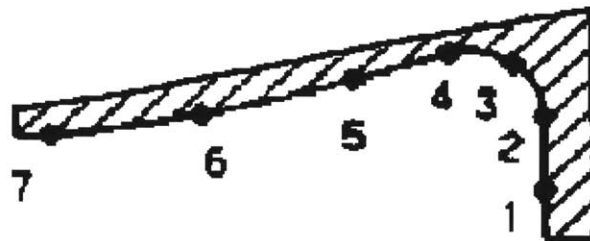


Figure 10b – Measurement Point Locations



While the laboratory procedures and specifications are well documented, the quality evaluations sometimes require the lab technicians to make subjective assessments. An example of this occurs with coating thickness evaluation. Frequently there is a layer of highly porous coating at the coating surface which is the result of errant coating, commonly referred to as overspray. This overspray layer is not included in calculations for thickness and porosity. The lab technician is responsible for deciding where the coating layer ends and the overspray layer begins. While there are guidelines to assist the technician, the final determination is subject to interpretation. These subjective elements of quality assessments will prove difficult when trying to reconcile coating predictions from the offline tool with results from the blade performance database.

4.0 PROJECT DESCRIPTION

4.1 Goal

The goal of this internship was to develop and implement an offline coating simulation tool. When complete, this tool would allow Alstom to improve the accuracy and timeliness of the coating development process for both low-pressure (LPPS) and atmospheric (APS) plasma spraying processes. This simulation would allow for objective, off-line assessment of changes to the N/C programs and fixtures. It would also allow Alstom engineers to test new concepts for component design, new N/C programming and fixturing techniques, as well as changes to the plasma spraying parameters.

4.2 Offline Tool History

The success of the coating shop had been hindered, in part, by difficulties in identifying and implementing statistically acceptable production processes. Alstom initiated a research and development project to create a computer-based coating simulation tool. The simulation tool would allow manufacturing engineers to streamline and target their efforts when creating or improving coating programs and fixtures. A cross-functional team led by the GFH manufacturing engineering group initiated the project in 2000.

The team began by simulating the low-pressure plasma spraying (LPPS) process. At the start of the internship, the team had already implemented an initial simulation tool which allowed users to create, modify and visualize numerical control (N/C) programs for the LPPS machine. The offline tool also provided the user with information on coating thickness and porosity. The users felt that the coating thickness predictions were not calibrated and therefore only used coating thickness data to manage thickness changes from one program iteration to the next. The offline tool results for porosity were also discounted because the offline tool did not consider the surface temperature of the part, a major contributor to the coating porosity.

The manufacturing engineers began process development by creating and simulating the new N/C program in the offline tool. After completing a production trial, they would compare the

laboratory result with that of the simulation. Usually there was enough disagreement to lead the engineer to discount the simulation results. The engineer would then determine, from the lab report, where the coating thickness was too heavy or too light and the desired magnitude change. Working with the simulation tool, the engineer would make changes to the N/C program that resulted in the same magnitude change in the simulation results. They would then run another production trial and check to see if the coating thickness change was as predicted. As mentioned earlier, these iterations would continue until a successful process was identified. While most of the time there was correlation between the predicted and actual coating thickness changes, there were several times where the magnitude change was not as correctly predicted leading to degradation in quality from one production trial to the next.

In early 2001, the project had temporarily halted because many of members of the team were working exclusively to resolve more pressing factory problems. This internship provided Alstom with resources for continuing the offline tool development.

4.3 Business Case

A detailed business case was prepared at the beginning of the internship. The approach taken for the business case was to determine the approximate cost of a production iteration and apply that cost to the estimated average number of iterations needed to identify a statistically acceptable production process for both the traditional and improved development efforts. Assuming a more streamlined development process and the elimination of on-machine robot teaching for atmospheric plasma spraying, the business case for the offline tool was quite favorable.

Each development iteration represents a significant investment. Parts are processed to the point of interest and then must be destructively tested to evaluate the coating quality. The cost of the casting, the processing costs and the laboratory costs are some of the primary cost drivers for coating process development. As new parts are able to demonstrate ISI requirements more quickly, the requirement for engineering review of each batch of production parts can be eliminated. This means that there will be less work-in-progress inventory and a reduction in costs for handling engineering non-conformances associated with pre-serial production parts.

A reduction of five in the average number of production trials needed to identify a statistically acceptable production provides significant savings potential to Alstom for the offline tool project. The process experts on the project team felt that the reduction target of five iterations represented a conservative estimate of the improvement potential for the offline tool. In June 2001, this business case was used to secure continued funding for the offline tool research and development project.

4.3 Simulation Tool Structure

The preliminary LPPS offline coating simulation tool merges the capabilities of an Alstom developed coating analysis program with the environment, analytical features and user interface from an off-the-shelf CAD package. The CAD package was already being used to simulate painting applications for other industrial customers. An external programming group wrote a series of customization macros to modify the CAD package for use as a coating simulation tool.

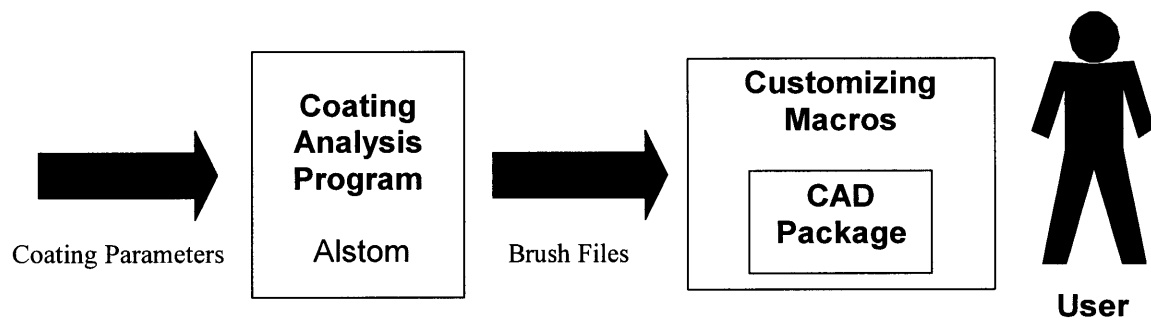
The structure of the offline tool is illustrated in Figure 11. In the CAD system's traditional painting simulation, paint is applied to a surface with a virtual tool referred to as a brush. The program's brush file contains information on the shape of the virtual tool as well as the paint application rate. The CAD program was modified for use in coating simulation by changing the brush files to allow for application of coating, porosity and/or heat instead of paint.

Data on the coating parameters, plasma gun geometry and environmental conditions are provided as inputs to the Alstom coating analysis program. This information is used to calculate spray patterns, porosity distributions and heat flux patterns which are written to brush files. Customization macros are used to combine the functions of the Alstom and CAD software programs. These macros are used to manipulate data, format inputs and outputs, perform coating calculations and tailor the CAD system for use by the coating developers.

In the CAD system, the part surfaces which will be coated are identified on the 3D solid. The coating surface is then meshed. The offline tool uses data in the parametric tables and

calculation macros to determine the coating thickness, porosity and surface temperature for each surface element in the mesh. The CAD program tracks the angle incidence of the plasma beam with respect to the element, the distance from the plasma gun to the element, and the location of the element with respect to the centerline of the plasma gun. This information for each of the elements is used to access information on coating thickness and porosity and heat flux patterns from the parametric tables. The custom-written macros track accumulation of coating thickness and porosity with each pass of the gun. The differential equations used to calculate surface temperature calculations are discussed in chapter five.

Figure 11 – Offline Tool Structure



4.4 Offline Tool Project Plan

The offline tool development team had two objectives. The first objective was to finalize development of the LPPS offline tool. This included expanding the functionality of the tool as well as analyzing and calibrating the results. The second objective was to modify the existing LPPS simulation tool for use with the APS process. Since the preliminary version of the LPPS offline tool has already been implemented, this process served as the lead effort with knowledge from the LPPS development being transferred to the APS project where applicable.

5.0 LPPS PROJECT RESULTS

5.1 Expanded Functionality

The following modifications and/or expansions to the offline tool were completed as part of the LPPS portion of the offline tool project:

- Addition of surface temperature prediction
- Expanding N/C programming capability to include radius and variespeed commands
- Creation of data extraction formats to allow for direct comparison with lab reports

5.1.1 Surface Temperature Prediction

Preliminary programming for surface temperature prediction was completed in December 2001. Surface temperature prediction in the offline tool is accomplished with two differential heat transfer equations. The first differential equation tracks the background temperature of the part. The second accounts for the localized heating from contact with the plasma beam. The sum of these two differential effects is tracked over time and used to provide an estimate of surface temperature.

The program begins with a single user-identified initial part temperature which is used as the initial background temperature. This background temperature is then adjusted with each time step to account for heat lost through convection to the surrounding environment. The background temperature of the element is also adjusted for local temperature gains resulting from contact with the plasma beam. The Alstom coating analysis program was modified to provide a heat flux pattern which was used to calculate the magnitude and position of local temperature increases with respect to the plasma gun.

While there are a number of simplifying assumptions with this approach to temperature prediction, the team felt this would provide enough information to allow for acceptable porosity predictions. One such simplification was the assumption of a uniform starting temperature. While thermography data shows that there is a non-constant temperature profile at the beginning

of the coating process, the team felt that the error introduced with this assumption was small when compared with the additional complexity associated with using a non-constant initial temperature. As the surface temperature prediction feature of the offline tool is implemented and the results analysed, the tool could be expanded to allow for incorporation of initial thermal profiles when there is a demonstrable need for the additional complexity.

5.1.2 Beta Testing

As new functions were added to the LPPS offline tool and as usage of the tool increased, a number of errors were identified. The effort to identify, document and resolve these errors proved to be substantial. In June 2001, the team learned that the original LPPS programmer was leaving the contracting firm. As a result, two new programmers were brought onto the project midstream. A significant effort was required to orient the new programmers to the coating processes and the code for the offline tool. This proved to be a challenge in both LPPS and APS portions of the development project.

5.2 Analysis and Calibration

The Alstom members of the offline tool team focused on analysis and calibration while the external programmers worked on expanding the functionality of the existing LPPS offline tool. Because the manufacturing engineers did not trust the results of the existing LPPS simulation, the tool was not being used as designed. The team felt it was important to assess the accuracy of the existing tool and to calibrate this tool, as necessary, in order to allow for full implementation.

5.2.1 Measurement System Analysis

As the team prepared to make a systematic comparison of the simulation results with actual results a number of concerns surfaced. Ideally, the data collection points in the simulation should be coordinated with the data collection points used by the laboratory. As the team attempted to align the measurement points in the simulation with those used by the laboratory it became clear that there was not sufficient data to allow for accurate and repeatable location of measurement points. While this presented a problem when trying to compare the simulated

values to actual production results, it presented a more significant problem when trying to compare production results from one run to the next. The team performed a detailed measurement system analysis to determine the impact of this positional variation on process measures.

There are three primary sources of variation in the accurate and repeatable location of measurement points: lack of clearly defined point locations, failure of laboratory fixtures to repeatably orient part when making section cuts, and laboratory procedures which allow for multiple grinding operations when preparing samples. The first source of variation is the failure to identify a single coordinated point for measurements. Surprisingly, data collection points are not specifically identified in either the engineering drawings or laboratory specification. The data collection points shown on the engineering drawings exist only as a reference; there is no data on three-dimensional location or positional tolerance. The laboratory specifications only provide guidelines for locating these measurement points. This lack of point definition allows for significant positional variation in analysis points from one sample part to the next.

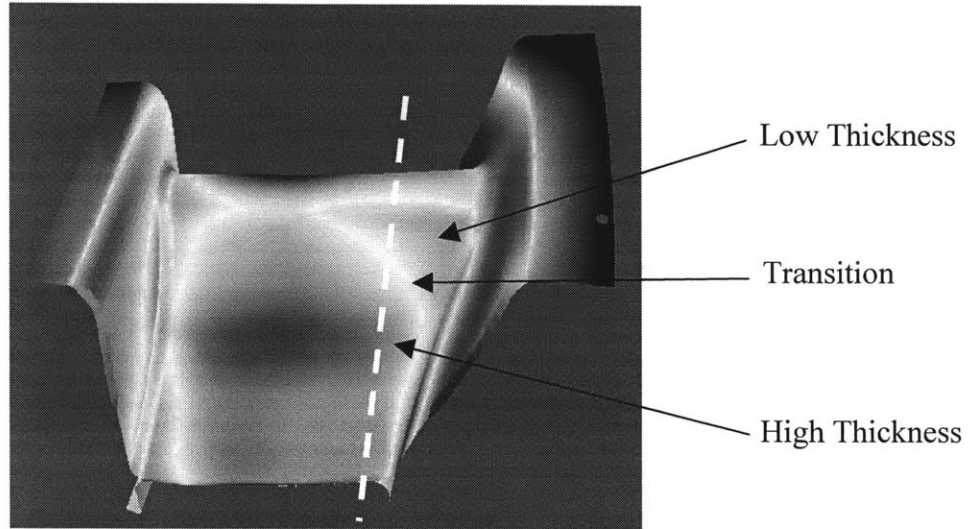
The second source of variation in thickness measures stems from variation in the location and angle of section cuts introduced during cutting operations in the laboratory. The laboratory fixtures ideally would allow for accurate and repeatable location of section cuts. Upon investigation, the team learned that the laboratory did not have adequate fixtures for making accurate and repeatable section cuts. Currently, the procedure for making section cuts is manually controlled. The technician begins by transferring a reference line for the section cut from a paper template to the part. The part is then clamped to a wooden block resting on the grinding machine bed for mounting during the cutting operation. The team estimated that variation at this stage of the process could produce significant variation in cut locations.

The final source of variation identified by the team was the result of laboratory procedure which allowed for regrinding dirty samples. Test specimens are mounted in epoxy and polished to allow for inspection of the coating at the cross-section cut surface. Grinding and polishing typically removes approximately 3 to 5 mm of material. If dirt or other contaminants damage the surface during grinding and polishing the inspection cannot be completed. In this case, samples

must be reground and polished. This type of internal contamination is not uncommon and can result in multiple regrinding operations. Each time the sample is reground and polished another 3 to 5 mm of material is removed resulting in further offset from the targeted cut plane. This introduces the potential for further positional variation in coating analysis point location. Currently there is no documentation of whether the samples are ground one or multiple times. While the need for regrinding is not likely to be eliminated, there is value in documenting which samples are reground and tracking how often regrinding is happening. For the purposes of statistical batch-to-batch comparisons, it would be best to eliminate the reground data from cpk calculations since this data represents assignable cause variation.

The magnitude of variation resulting from the mislocation or inconsistent location of measurement points depends, in part, on the geometry of the coated part. On the part shown in Figure 12, areas of the airfoil experience dramatic changes in coating thickness over short distances as a result of shadowing effects. In general, coating thicknesses range from 200 to 550 microns depending on the part and location. Figure 12 shows a contour plot of the coating thickness variation. The areas in red represent coating thicknesses near the top of the specification limit while areas in blue lie near the bottom of the specification limit. Coating thicknesses along a section cut through the airfoil, such as the one represented by the dashed line, would experience significant variation as a result of positional variation.

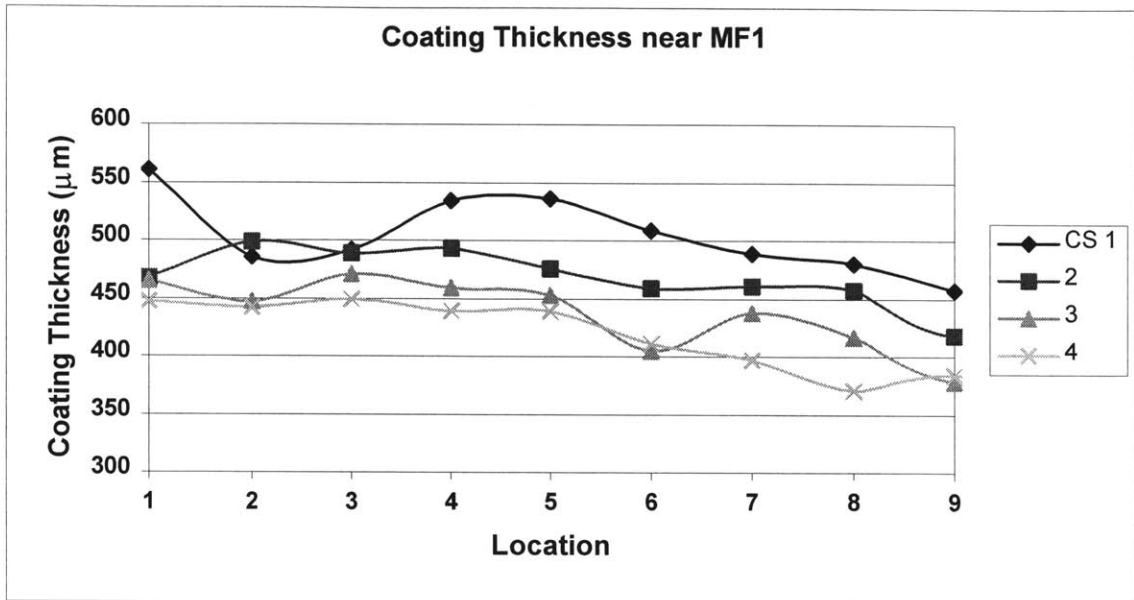
Figure 12 – Coating Thickness Contour Plot



This variation in location of the data collection points does not present a problem for the quality evaluations since the coating tolerances are the same for the hat, foot and airfoil sections. In other words, coated areas of the part within the same geometrical area have same nominal thickness and tolerances. However, variation in the location of data collection points does present a problem when trying to compare performance from one production batch to the next.

The team estimated that the total positional error could easily exceed 5mm if the variation from the sources identified is additive. The magnitude of difference seen as a result of 5mm shifts in the location of cross-sections for one of the production parts is shown in Figure 13. Data for coating thickness at points from five parallel cross-sections were plotted in an effort to understand the potential impact of variation in section cut locations. There is a 5 mm offset from one cross-section (CS) to the next. For example, at point 9 there is a difference in coating thickness from CS1 to CS3 that is equal to nearly 100 microns. This 10mm offset could easily be the result of repolishing done in the laboratory.

Figure 13 – Effect of Positional Variation of Section Cuts on Coating Thickness



As discussed earlier, Alstom requires processes to meet a statistical threshold by demonstrating a *cpk* of 1.33 or better before allowing them to enter serial production. It can be seen from the equation below that an increase in the standard deviation for the process results in a lower *cpk* value. The standard deviation for the measured process will be artificially inflated by variation in location of measurement points thus leading to lower *cpk* values. The team estimated that the sum of the maximum positional variation of 5mm from mislocation of the cut plane and 10mm from multiple grinding operations could result in up to 15 mm of mislocation which could result in a 30 percent reduction of measured *cpk*. The danger here is that good processes will not be recognized as such.

$$cpk = Min \left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right]$$

where, USL = upper specification limit
 LSL = lower specification limit

The team documented the findings and presented a proposed solution to GFH management and to the laboratory personnel. The proposed solution is as follows:

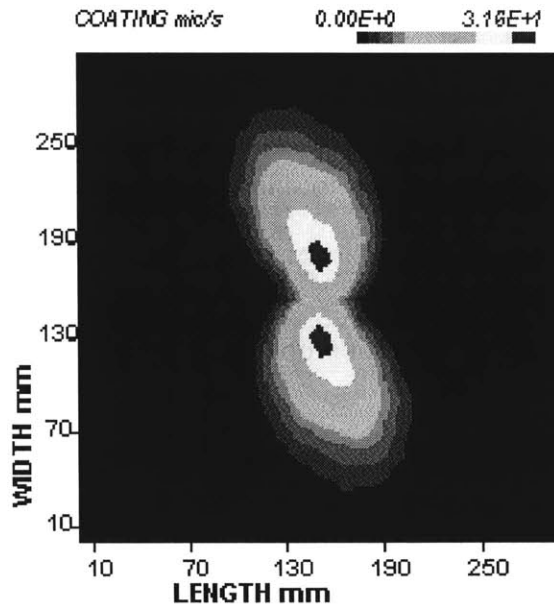
1. Coordinate with engineering, production and laboratory to agree upon a single nominal location for measurement points
2. Provide the laboratory with fixtures to allow for repeatable location and angularity of section cuts
3. Identify samples which are reground to allow that data to be removed from cpk calculations and to track the extent of problem

Knowing that the proposed solution could not be implemented prior to the end of the internship, the team was forced to continue with offline tool analysis and calibration recognizing that some error would likely be the result of failure to properly align the measures from the simulation with those from the laboratory database.

5.2.2 Coating Analysis Program Calibration

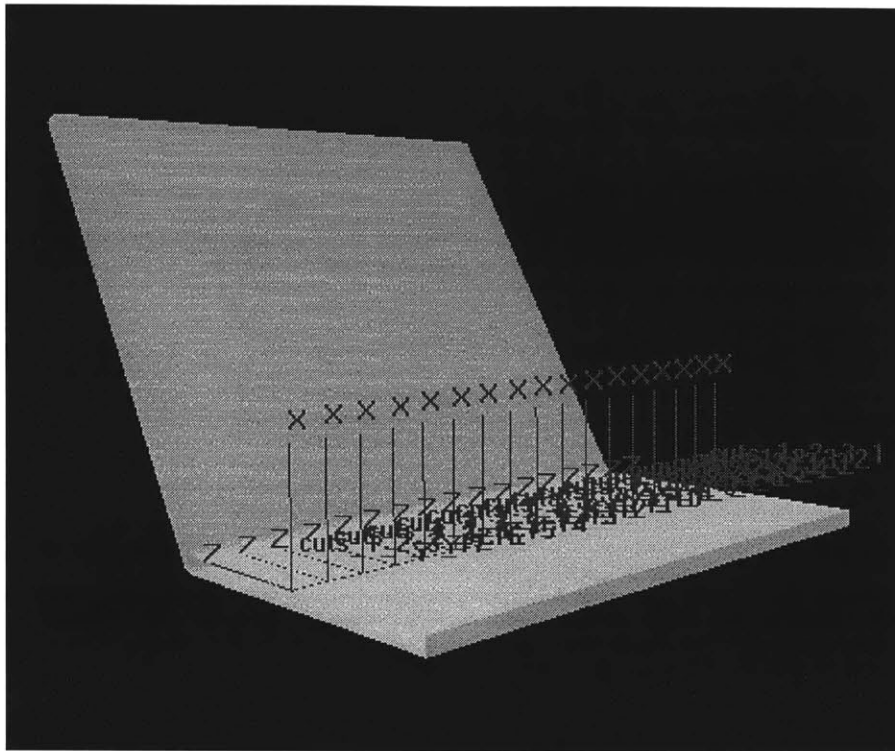
The following discussion outlines efforts to calibrate the coating analysis portion of the offline tool. The coating analysis program utilizes a number of process parameters as program inputs; plasma characteristics, powder properties and injection speed, ambient temperature and chamber pressure, spray distance and angle of incidence with the test plate, deposition efficiency and heat transfer characteristics for the workpiece. Some of the inputs are controlled in the process, others are measured, while the remaining were either calculated or empirically determined. The coating analysis program makes a number of calculations based on these inputs. The offline tool utilizes the program outputs; spray pattern, porosity distribution and heat flux distribution. Figure 14 shows a contour plot for one of the calculated LPPS spray patterns.

Figure 14 – Coating Analysis Program Output Spray Pattern



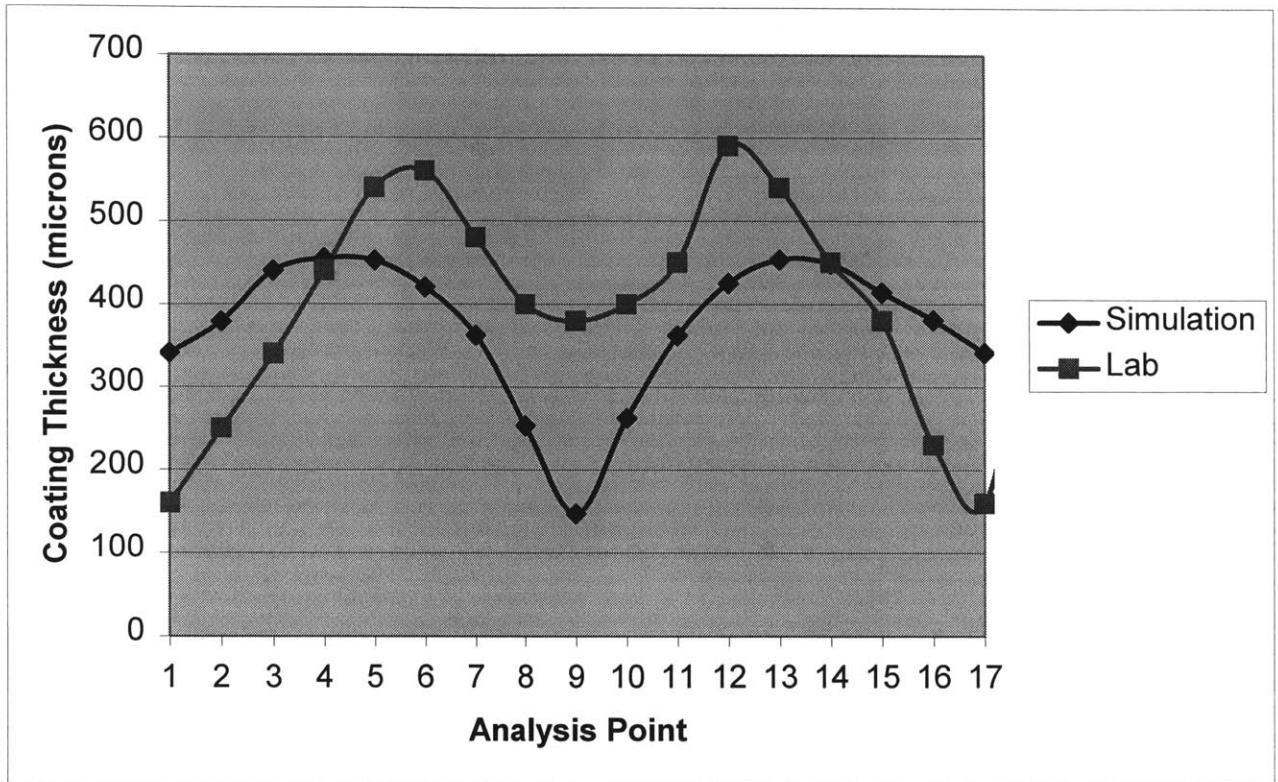
The team analyzed data from the experiment outlined in Appendix A. The experiment measured the impact of changes in the input variables on the shape of the spray pattern and the quality of the coating created by this spray pattern on an angled test plate. The experiment was originally designed for a different purpose, but the data was directly applicable to the work of this team and was therefore used in the calibration effort. Figure 15 shows the angled test plate. The coordinate axes indicate the location of the 16 data collection points. The offline tool team used this data to evaluate the results of the coating analysis program by comparing predicted shape of the spray patterns with the actual measured spray pattern geometries. The team also used the coating thickness data from the test plates to assess the coating thickness prediction capabilities of the offline tool for a basic workpiece with a simple N/C program and geometry.

Figure 15 – 120 Degree Angled Test Plate



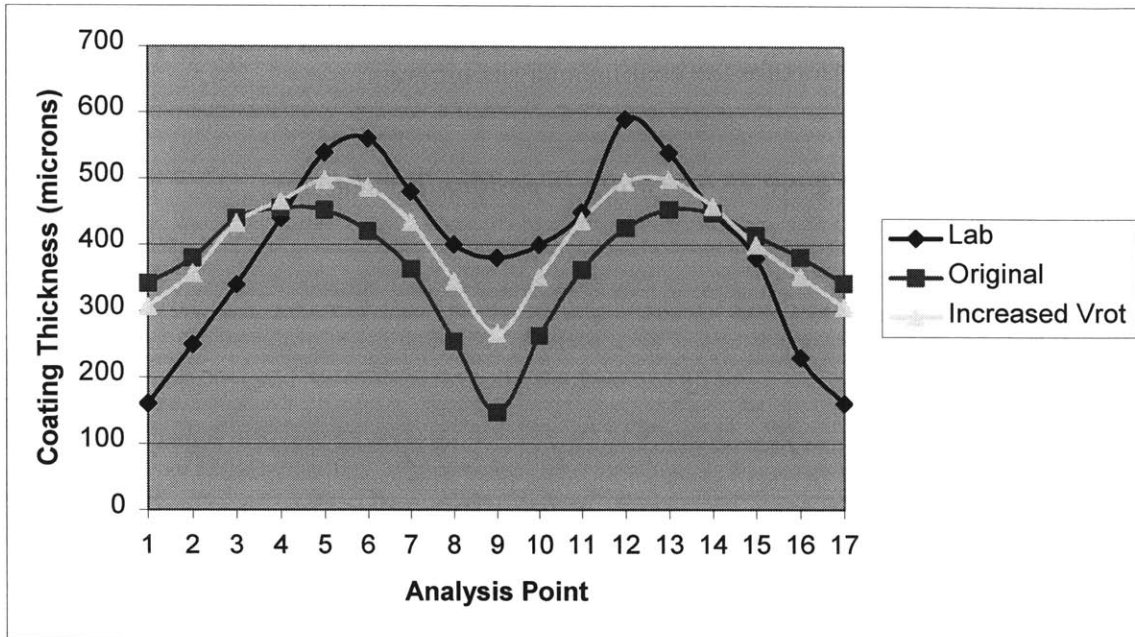
This analysis provided important feedback on the predictive capabilities of the Alstom coating evaluation program. A comparison of the spray patterns showed that the predicted coating deposition at the peaks was too low and that the peak separation was too large. This was confirmed with the coating thickness analysis from the test plates as shown in Figure 16.

Figure 16 – Test Plate Coating Thickness Comparison



The coating analysis program contains a number of variables that could not be directly measured. Initial values for these variables were based on calculations by the program developer. One of these variables is the rotational speed of the plasma stream. As the plasma stream rotates faster, the two powder trails in the plasma stream move further apart increasing the peak separation. Based on the results of the experiment, the rotational velocity was adjusted to an empirically determined value. While this adjustment resulted in improved correlation of the peak separation, there was still a problem with the magnitude of coating thickness and with the drop in coating thickness at the edges of the plate as shown in Figure 17.

Figure 17 – Test Plate Coating Thickness Comparison



The next change to the coating analysis program addressed the fact that particle deposition rates are highest at the spray pattern peaks and lower at the edges as reflected in the shape of the coating thickness distribution. Initially the model, based on a simplifying assumption, used a constant deposition efficiency to calculate the predicted coating thickness. The differences in the calculated and observed coating thickness provided justification for expanding the model to include the effects of variable deposition efficiency.

The variable deposition efficiency is calculated by analyzing the diameter of the impacted coating particles. When the hotter particles from the center of the spray pattern shown in Figure 18 impact the part surface, they deform. When the cooler particles from the outer edges of the spray pattern impact the part surface, they are not fully deformed and often do not adhere to the surface. While the coating analysis program already had the ability to calculate the dimension of an impacted powder particle, this feature had not been invoked. In order to incorporate variable deposition efficiency in the model it was necessary to utilize the experimental data to determine a critical particle thickness. Particles with an impacted thickness less than the critical thickness would adhere to the surface. Particles with an impacted thickness greater than the critical

dimension would not adhere to the surface. After making this programming change, the resulting coating thickness predictions were much more accurate as shown in Figure 19. This completed the calibration effort for the coating analysis program.

Figure 18 – Coating Deposition Breakdown

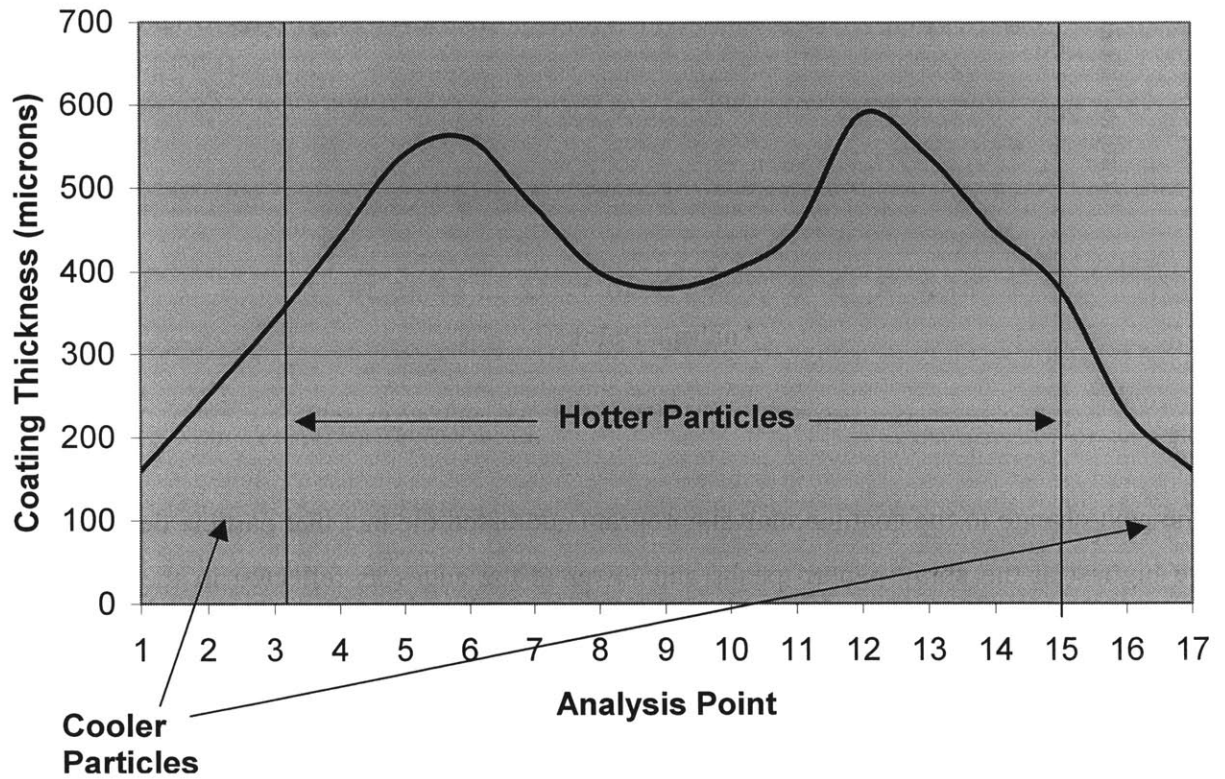
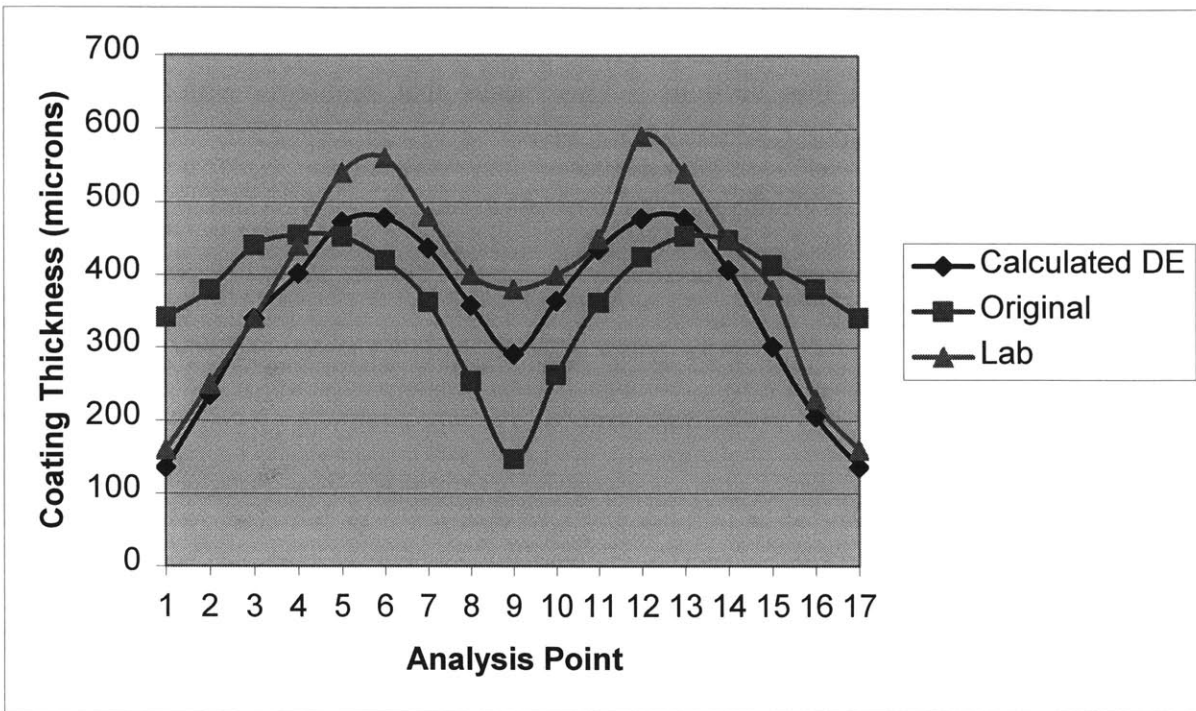


Figure 19 – Final Test Plate Coating Thickness Comparison



5.2.3 Offline Tool Analysis

In order to assess the accuracy of the coating thickness prediction, coating thickness data for a production blades and vanes were collected and systematically compared with coating thickness predictions from the offline tool. Historical data on coating quality was extracted from Alstom’s blade performance database. This database contains the laboratory results from the destructive tests for one representative blade or vane from each production batch. It is important to note that the N/C coating programs used in this comparison were chosen based on the amount of data available (i.e. number of lab reports in the database) and do not represent the best available production process. This analysis is not intended to assess the current state of production, but instead to provide a robust comparison of predicted and actual coating results.

Blades and vanes are broken into three primary geometric sections; airfoil, hat and foot. Overall, the offline tool simulation results compare favorably with the mean coating thickness. The best

results were seen with the airfoil sections, Figures 20a and 20b. In part, this is the result of having a large section of relatively uniform geometry. This is reinforced by the fact that results from the blade were better than those for the vane. The blade has a much larger airfoil section and much smaller hat and foot sections. This means that problems with overspray and shadowing will be minimized.

Figure 20a – Airfoil Section Cut for Blade

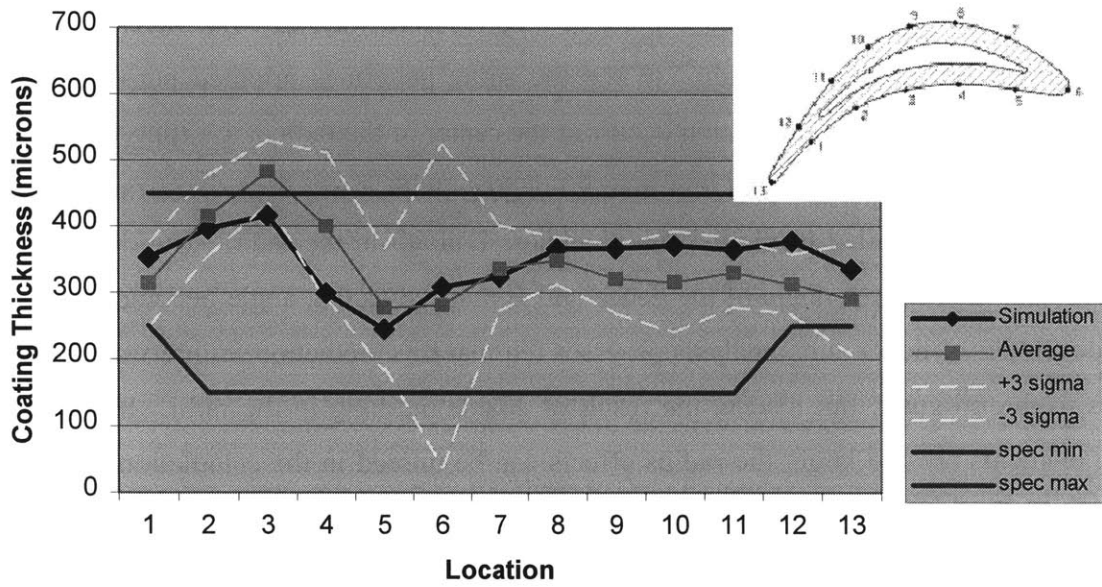
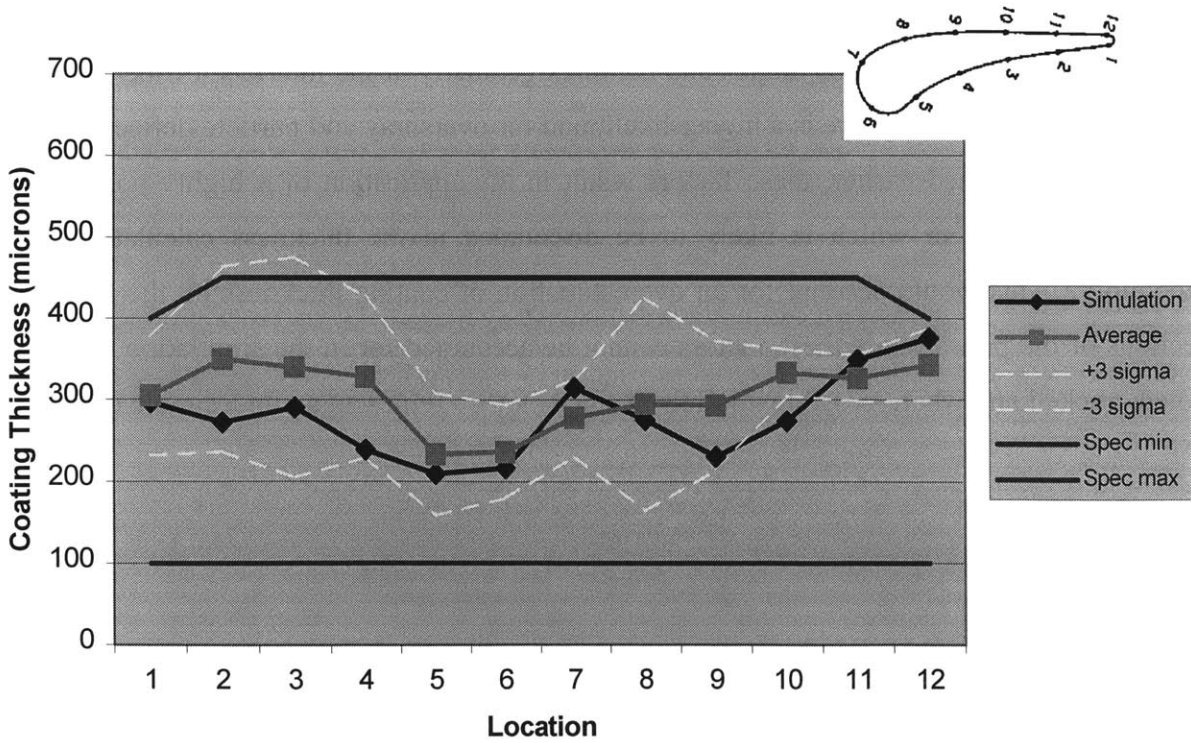


Figure 20b – Airfoil Section Cut for Vane



The correlation between coating thickness simulations and production results for the hat and foot sections of the blades and vanes, while acceptable, were not as good as that seen on the airfoils (Figures 21 and 22). There were a number of theories as to why this was the case. The biggest discrepancies occurred in the radii. When the spray pattern is oriented perpendicular to the radius, the highest coating deposition occurs at the center of the radius. Coating for areas outside of the radius is applied at angles less than 90 degrees with lower deposition rates. It appeared that the simulation failed to predict this thickness buildup in the radii. The deposition rate is highest with a 90 degree angle of incidence and is reduced as that angle becomes more shallow. The developer of the coating analysis program felt that this prediction failure was not a result of errors in the program, but instead the result of coarse meshing in the radii. In essence, if the mesh elements are too large, the radius effects can be missed in the calculation. The proposed solution was to decrease the element size in the radii to assure proper consideration of the geometric effects. Unfortunately, because of problems with the CAD interface, the team will not be able to test this proposed solution until the programming contractor resolves these problems.

Other potential sources of error effects in the simulation include overspray and particle deflection. Because of closed angles and complex geometry at the interface of the hat and foot sections with the airfoil, there is a higher likelihood for overspray and particle deflection in these areas. As mentioned earlier, these factors result in the application of a highly porous surface coating surface layer which is likely to be discounted in the thickness calculations by the laboratory. This would account for an overestimation of coating thickness on the hat and foot sections of the part. While these factors cannot be accounted for in the simulation, they can be noted, tracked and where possible minimized since they do represent an undesirable outcome.

Figure 21a – Foot Section Cut for Blade

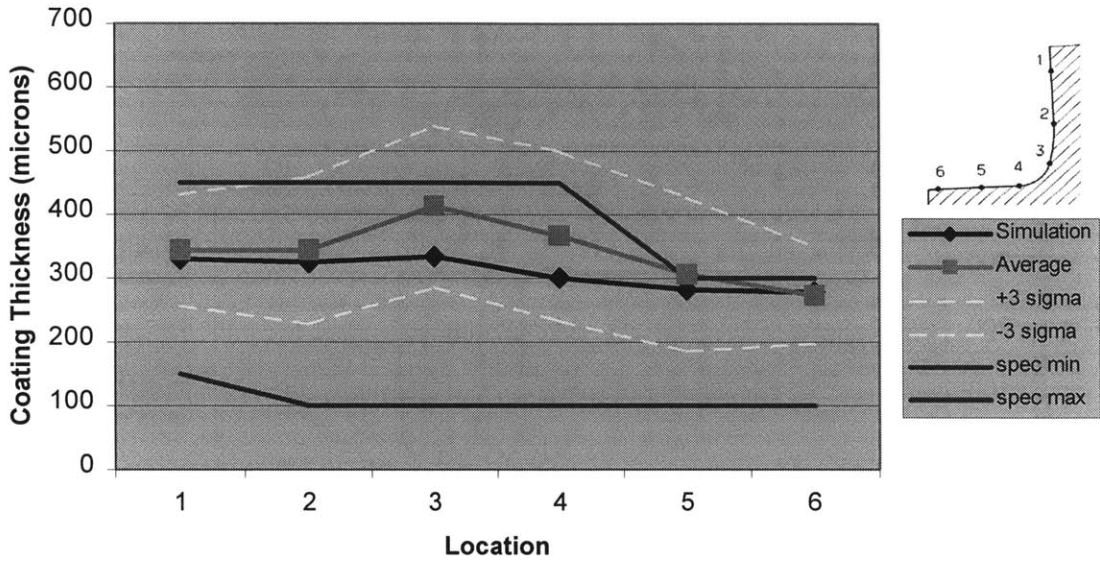


Figure 21b - Foot Section Cut for Vane

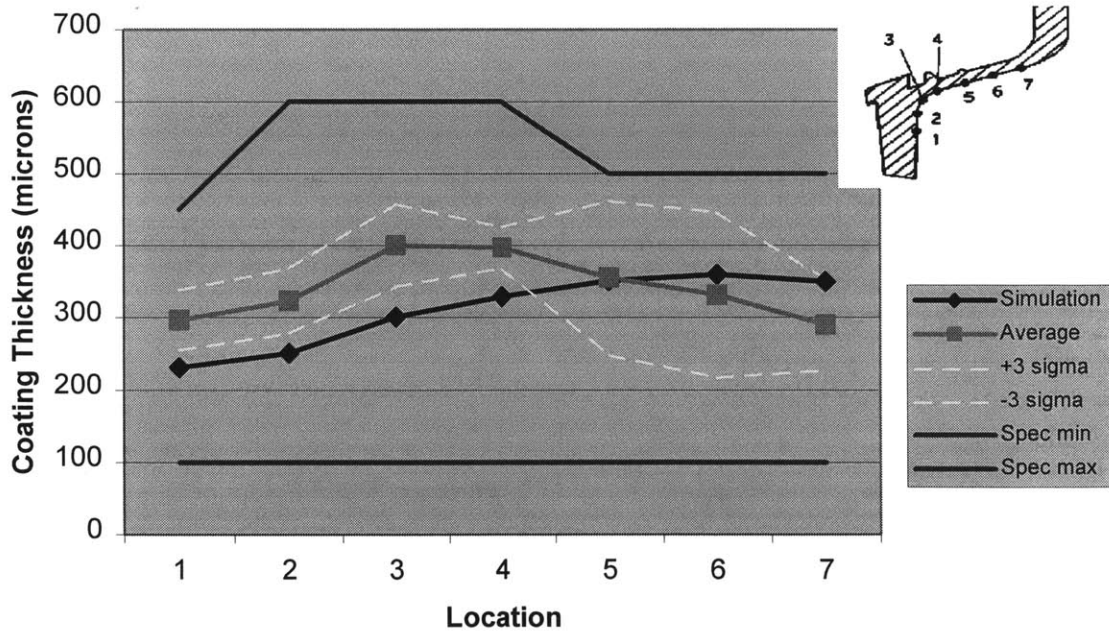


Figure 22a – Hat Section Cut for Blade

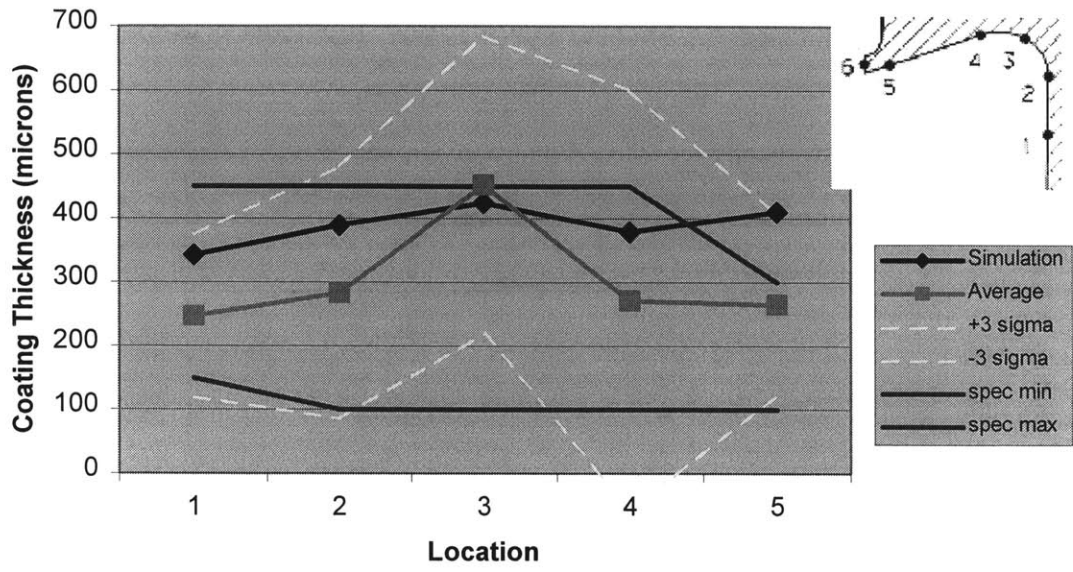
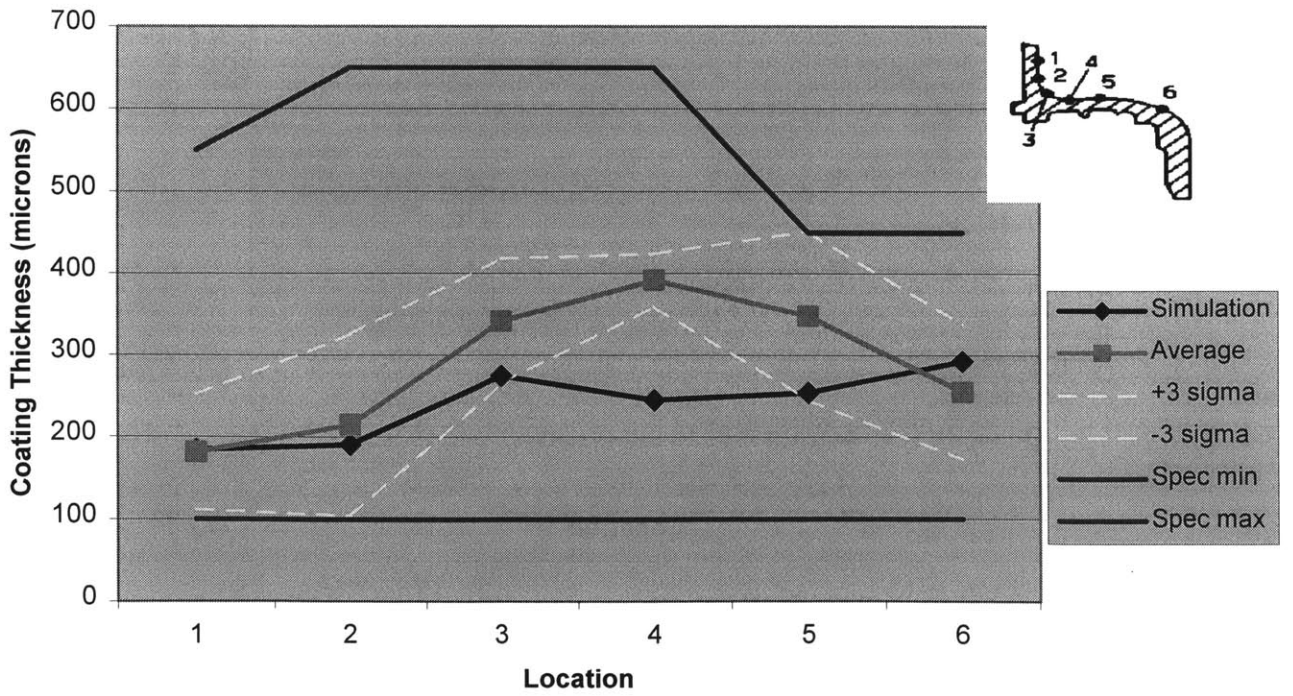


Figure 22b – Hat Section Cut for Vane



5.3 Proposed Offline Tool Method

As discussed earlier in this thesis, coating processes have a large number of variables which, when combined, lead to substantial variation in the final coating thickness. Because the offline coating tool does not incorporate stochastic elements, the results of the simulation are constant. As the data shows, this constant result is best compared to the mean of the production data. Significant variation in the process makes it unwise to try to compare a single production run with the output of the offline tool as was the practice at the start of the internship. Instead, the team recommends that the offline tool simulation result be compared with the mean of the process and that the confidence interval of plus and minus three standard deviations be used when making assessments of potential production processes.

Proposed method for using offline tool results:

1. Simulation results should be used to predict the mean values for coating thickness.
2. Use historical data for the part or for a similar family of parts to determine a suitable estimate for standard deviation of process.
3. Plot the estimated mean with the plus and minus three standard deviation estimates relative to process specifications to determine likelihood that the proposed process will produce acceptable parts.

5.4 Continuing Effort

The team was able to successfully expand the functions of the tool to include additional N/C programming commands, automatic formatting of results and surface temperature estimation. However, additional testing and training will be needed in order to implement. The temperature estimation functions add an additional level of difficulty to an already complex tool. It is important that the users are proficient with existing elements of the offline tool before they begin using the temperature estimation. For this reason, this function was programmed to allow for users to turn it on and off as needed. Once the temperature prediction has been incorporated, the

analysis and calibration effort just completed for coating thickness will need to be repeated for the porosity predictions.

6.0 APS OFFLINE TOOL

6.1 Development Plan

In June 2001, Alstom contracted with the external programmers to have the LPPS offline tool modified for use with the APS coating process. The functionality of the final APS offline tool will be similar to that of the LPPS offline tool. Where possible, the user environment and functions will be standardized. While there are similarities between the two plasma spraying processes, there are a number of significant differences that required expanding or modifying the LPPS offline tool platform for use with APS.

The original APS offline tool project plan called for two phases of development. The initial APS project scope was as follows:

Phase I

- Model APS workcell, including robot
- Develop APS offline tool functionalities
- Validation and on-site support
- Documentation and training

Phase II

- Expand APS offline tool functionality
- Optimise program based on Phase I results

This project scope was changed early in the internship to pull-ahead the robot programming deliverable from Phase I. A separate research project was initiated to develop new, more robust coating parameters for APS coating. New coating programs would be needed to implement the new parameters. Offline robot programming capability would be critical for timely implementation. The Phase I project scope was trimmed to focus on basic robot programming.

6.2 APS Robot Programming

One of the biggest differences between the LPPS and APS offline tools would be the procedure for writing coating programs. While both LPPS and APS offline tools would allow for the generation of coating programs, the APS programming task is much more complex and therefore represented a significant departure from the LPPS offline tool platform.

Because APS spraying is performed in an atmospheric environment the process is very sensitive to the distance and orientation of the plasma gun relative to the coating surface. The plasma gun is mounted on the arm of the robot which holds the plasma gun normal to the part surface at a constant offset distance. On a part with compound contours and complex geometry, this means that the robot program contains a great deal of information.

The CAD program for the offline tool, with some modification, would allow for offline creation of robot programs. This was an important functional element which, when successfully implemented, would allow for significant reductions in the development cost and the lead time of new APS programs. Currently, robot programming is performed on the production machine using teach points. Each teach point contains information on the location and orientation of the robot relative to the surface of the part. In order to capture the data for the teach points, the part must be loaded into the fixture and the robot manually moved to the proper position and orientation. Once the robot is in the right place, the data for the robot's position and orientation is recorded. This is a time consuming process considering some coating programs contain over 1000 teach points. The robot interpolates motion from one teach point to the next to create the final coating program. While other software programs are available for offline robot programming, Alstom preferred to incorporate these functions into the offline tool.

6.3 Workcell Modeling

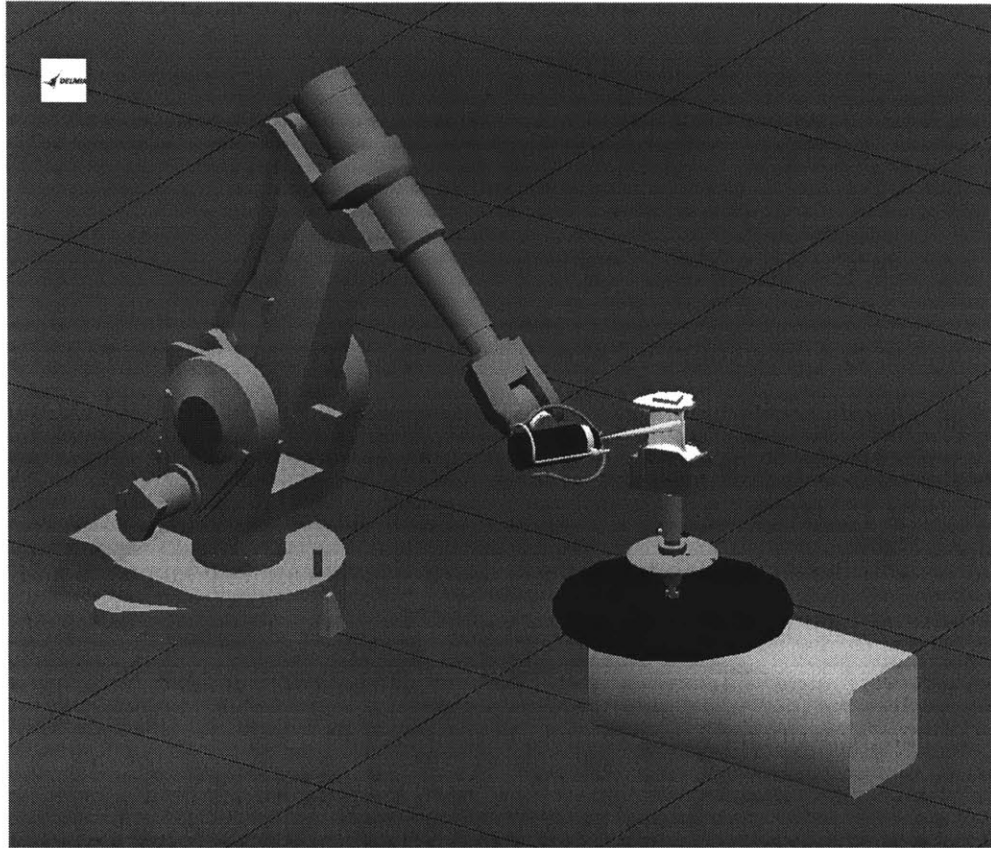
The first step in developing the APS offline tool was workcell modeling. The major features of the APS workcell include the robot, plasma gun, and rotary table as well as the part and mounting fixture. Data for the robot geometry and motion characteristics was already available

as an extension of the existing CAD package from the external programmers. Three-dimensional datasets were also available for the parts and some of the newer APS fixtures. The team developed simple, three-dimensional models for the remaining, relevant workcell components. Figure 23 shows the APS workcell model in the offline programming tool.

6.4 Program Conversion

The offline tool uses a different programming language than that of the robot. For this reason, programs generated in the simulation must be converted to the robot-compatible language during download. Existing robot programs would also require conversion before uploading to the offline tool. The CAD module for the robot included standard upload/download conversion functions to convert the simulation language to the robot programming language and vice versa. There was an additional upload/download step needed to convert from a standard format to an Alstom-specific format. This was accomplished through pre-upload and post-download customization macros written by the external programmers.

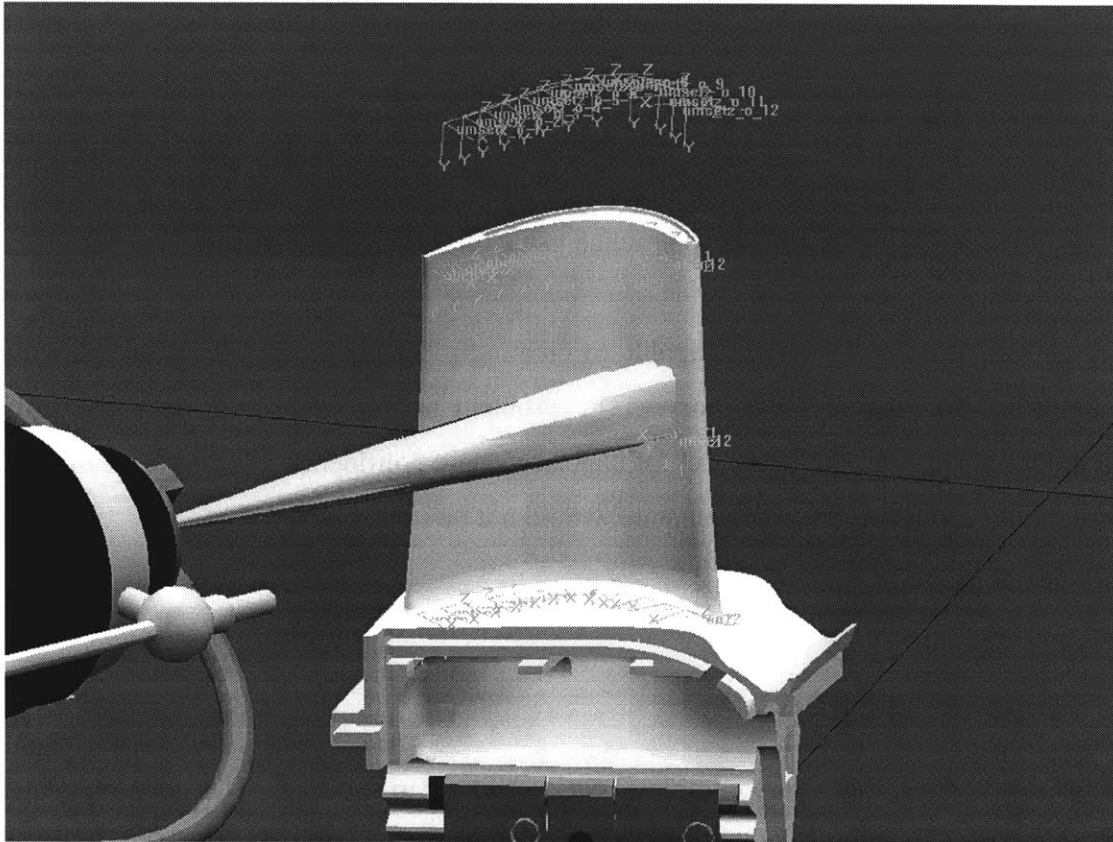
Figure 23 – APS Offline Tool Environment



6.5 Offline Robot Programming Methodology

In the offline tool, teach points are replaced with robot targets. The robot targets are axes which identify the location and orientation of the tool centerpoint. The tool centerpoint for plasma spraying is located at the center of the spray pattern at the specified offset from the part. Because the robot target points are not needed to identify the surface in the CAD package, programming can be accomplished with fewer targets points. Figure 24 shows the target points used to generate a coating path for the airfoil.

Figure 24 – Robot Programming of Airfoil



6.6 Phase I Implementation

Unfortunately the team encountered a number of difficulties with the Phase I implementation. Functional problems included persistent bugs and program complexity. While users anticipate a certain number of problems when implementing a new software package, the team felt that the number of coding errors and compatibility problems was excessive. Subsequent assessment indicates that these errors could be traced to a number of sources including new programmers, poor communication of expectations, errors within the OEM software, differences in programmer and user installations as well as incomplete beta testing. While the team was able to work with the programmers to resolve the majority of the program errors, the effort was significant and the errors resulted in decreased training efficacy which served to undermine the confidence of the new users.

The problems with program complexity, in part, could be traced to the streamlined Phase I scope. In order to speed implementation, much of the customization was intentionally left for Phase II. This meant that the APS offline tool would be substantially more difficult to operate than the LPPS tool. In the end, the APS parameters were not changed eliminating the pressing need for the offline robot programming. The manufacturing engineers were soon asked to focus on other shop concerns leaving them no time to practice using the APS offline tool.

By December, the offline tool was capable of creating robot programs offline and downloading these programs for use in the factory. The problem at this point was with the program's complexity coupled with the users lack of experience and confidence which meant that the APS offline tool, at its current development state, would not be implemented.

6.7 Continuing Efforts

The Phase I programming, while complete, was not likely to succeed. The team met, including the manufacturing engineers and external programmers, to agree on the following revised implementation plan:

Step 1 – Optimize Existing Programs

1. Resolve lingering upload/download problems with software OEM
2. On-site reprogramming of blade
3. Updates to programs/documentation
4. Training

Step 2 – Prepare New Programs

1. On-site programming of blade
2. Updates to programs/documentation
3. Training

The new plan focused on a more gradual mastery of program skills. The users would first attempt to modify existing programs. Once comfortable with that approach they would then move on to developing new programs. The team began implementing the new plan in late December with management support.

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7.0 ANALYSIS OF GFH IMPROVEMENT INITIATIVES

While the GFH work group was committed to improving their performance, it was difficult to assess the long-term effects of their efforts. The group was working a number of improvement projects simultaneously. While their efforts appeared to be on target, they were not having the desired near-term effects. Was this simply the result of delays in the system or was a different course of action needed? A systemic analysis was performed to assist in understanding the complex relationships and dynamics present in this system.

The following analysis of GFH's business unit performance was worked according to the standard method presented by Professor Jim Hines at MIT as outlined in Appendix B. The analysis provides a system-wide look at the problem and attempts to identify leverage areas for improvement. These potential leverage areas will be compared and contrasted with the existing policies to determine if additional efforts are warranted or if any existing policies are counter-productive. Information for this analysis was collected through interviews with a series of Alstom engineers, factory workers and managers.

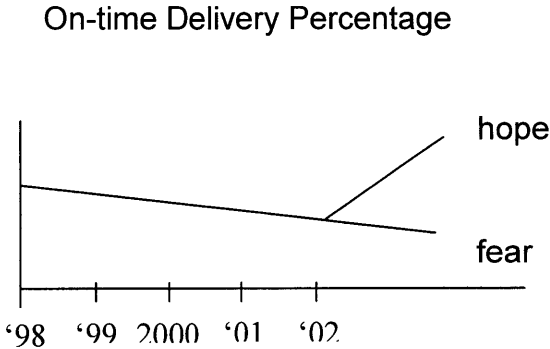
7.1 Clarification of Problem

Without specifically identifying the problem, the first step in the analysis was to list the variables associated with the problems that the GFH business unit was facing. Of this list, four or five of the most important variables were chosen for further analysis. For GFH's business performance, the following five variables were chosen:

1. Process Knowledge
2. Cost of Poor Quality
3. On-Time Delivery Percentage
4. Business Unit Profits
5. Average Process Capability

For each of the variables, a rough sketch was prepared outlining the historic trend as well as the hope and fear for future values. Figure 25 shows a sample sketch which is referred to as a reference mode.

Figure 25 – Sample Reference Mode



After reviewing the reference modes for the key variables, the following, more specific problem statement was crafted:

The GFH business unit needs to resolve performance problems in the near-term in order to increase profitability while also assuring long-term business unit competitiveness.

7.2 Momentum Policies

The next step in the analysis was to identify existing policies intended to address the problem as stated above. These existing policies are called momentum policies.

Momentum Policy: Increase Process Knowledge

Policy-Related Efforts:

- Hire consultants to supplement existing knowledge base
- Recruit experienced manufacturing engineers

- Provide additional training to operators, engineers and management
- Improve process documentation
- Benchmark other Alstom coating shops as well as suppliers

Momentum Policy: Improve Quality

Policy-Related Efforts:

- Identify more robust operating parameters
- Invest in new technology to improve coating processes
- Process versus product based organizational alignment
- Equipment standardization and upgrades
- Improve coating development process (Offline coating simulation fits into this category)
- Scrap reduction efforts

Momentum Policy: Maximize Revenue

Policy-Related Efforts:

- Focus production resources on delivering parts
- Emphasize production over R&D
- Shut down line to investigate process problems vs. continuing to produce potentially bad parts
- Align financial incentives with desired behavior (e.g. revenue booked on deliveries rather than orders)

Momentum Policy: Improve Morale

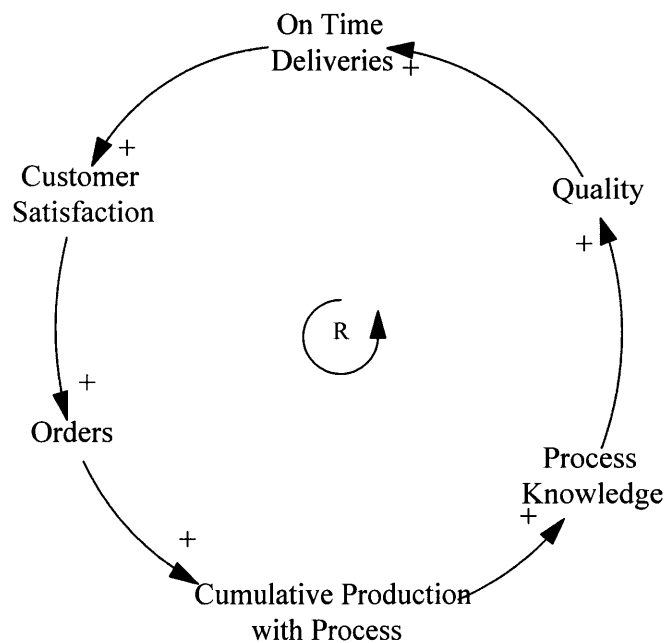
Policy-Related Efforts:

- Increased communication
- Return to process oriented organizational alignment
- Personnel changes

7.3 Causal Tracing

The next step in the systemic analysis was to prepare causal loop diagrams designed to highlight the behavior shown in the reference modes. In these diagrams, causes are linked to effects with arrows indicating either a direct (+) or inverse (-) relationship⁶. Figure 26 shows a reinforcing causal loop.

Figure 26 – Reinforcing Causal Loop

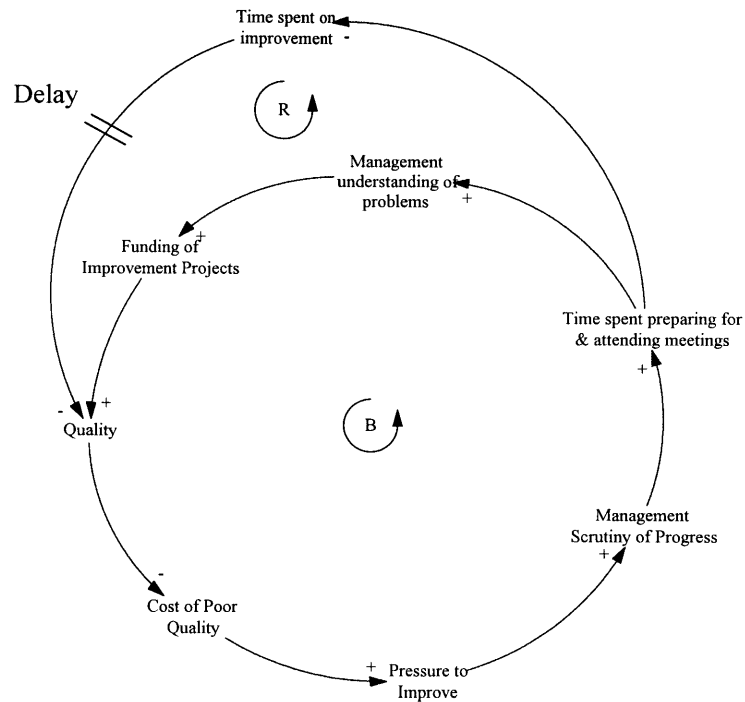


Tracing this loop we see that when all else is constant, an increase in process knowledge leads to higher quality which allows for improved delivery performance. As customers receive more on-time deliveries, their satisfaction increases thereby making them more likely to place additional orders. With increased orders, the cumulative production quantity will increase resulting in gains in process knowledge as the production group advances through the learning curve. In a reinforcing loop, good behavior is reinforced. However, the downside to reinforcing loops is that negative behavior is also reinforced. Reinforcing behavior is offset in the system by balancing causal loops. One of the balancing elements in this analysis is shown in Figure 27. In this loop, quality is influenced by the amount of time and money spent on improvement projects.

⁶ Sternman, Business Dynamics, p. 102

Decreases in quality lead to increased management scrutiny and increased funding which will improve quality in the short-term.

Figure 27 – Balancing Causal Loop



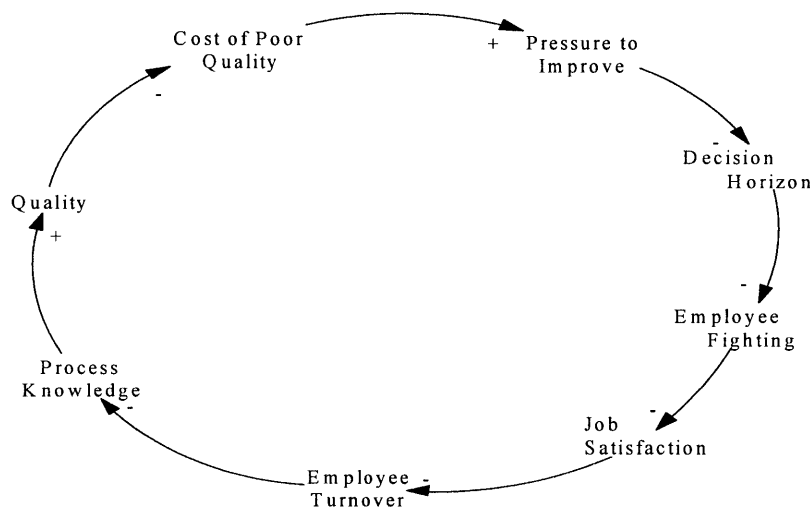
As you can see from the second loop in Figure 27, variables often have competing influences. Time spent in meetings has both positive and negative impacts on quality. In the short-term the meetings provide increased awareness of problems which is likely to lead to increased funding of improvements. However, if this pattern continues over time, increased time spent in meetings will lead to more quality problems as engineers are forced to divert time which should be spent on improvement efforts toward preparing for and attending meetings. In the long-run, this can lead to an increase quality problems rather than a decrease.

All of the causal loops combine to form a single causal loop diagram which is shown in Appendix C. This diagram illustrates the complexity of the improvement process.

7.4 Modeling

A single dominant loop, shown in Figure 28, from the center of the causal loop diagram was chosen for more in-depth analysis with the hope that the loop's central location and inclusion of many of the critical variables would help provide insight into the stated problem. During the modeling step, causal relationships are quantified using stocks designated by boxes in the graphical model shown in Appendix D, flows designated by pipes and valves, and variables designated by text. The modeling process provides insights into the important levers for controlling the behavior of the system. This helps the modeler understand the impact of proposed momentum policies as well as to frame new policies designed to utilize these levers.

Figure 28 – Central Causal Loop



7.5 Insights from Process Modeling

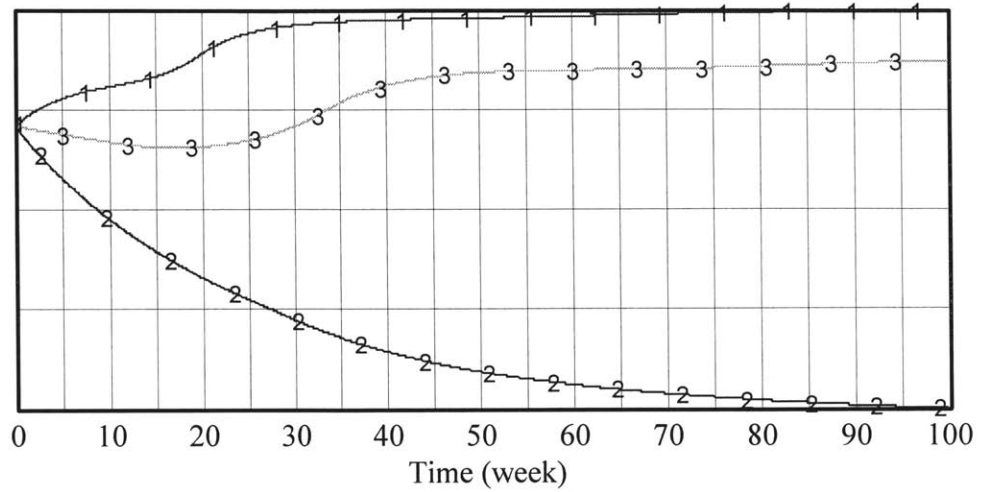
The model was analyzed using the causal tracing method where the effects of variable changes are traced through the model to understand the nature and strength of their relationship to the problem statement. The first causal tracing analyzes the effect of varying knowledge gain rates on business unit profitability. In the model for this loop, the cost of poor quality is used as a surrogate measure of business unit profitability recognizing their inverse relationship.

Process Knowledge

Figures 29a through 29c show the effect of a 50 percent reduction in the time needed to acquire knowledge (learn fast scenario) and a 50 percent increase in time needed to acquire knowledge (learn slow scenario). As the knowledge gain rate is increased, Figure 29a shows how the stock of process knowledge accumulates more rapidly.⁷ A 50 percent decrease in knowledge gain rate results in a scenario where knowledge is lost more quickly than it can be replenished. As the amount of knowledge decreases, it becomes increasingly more difficult to replace this knowledge therefore resulting in ever lower knowledge gain rates. Without an exogenous introduction of process knowledge, the knowledge base cannot recover.

⁷ While the scales for the vertical axes on Figures 29 through 31 have been removed to protect proprietary information, the graphs still provide information on relative performance of the scenarios.

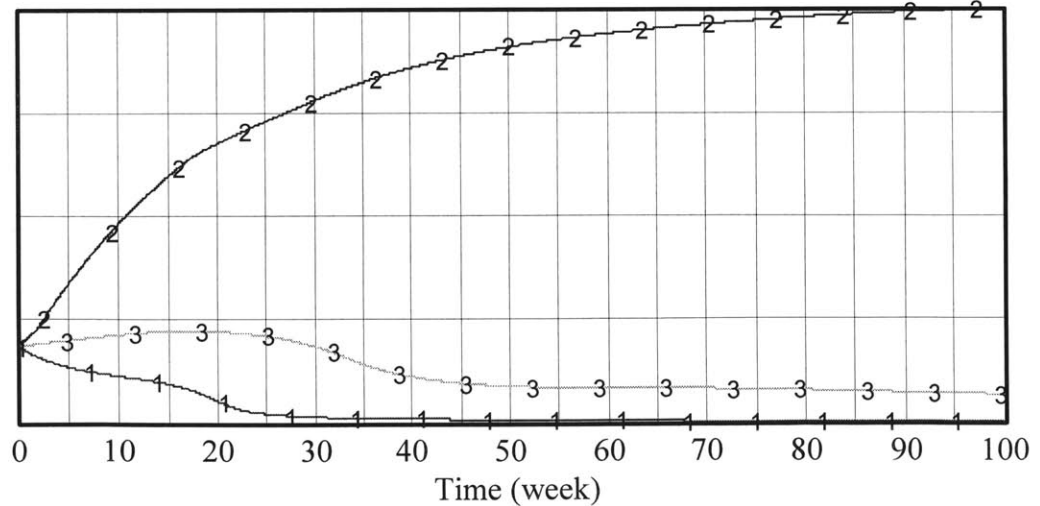
Figure 29a – Impact of Knowledge Gain Rate on Knowledge Base



Process Knowledge : learn fast — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — Dmnl
 Process Knowledge : learn slow — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — Dmnl
 Process Knowledge : base — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — Dmnl

Figure 29b shows the inverse relationship between process knowledge and the problem introduction rate. As process knowledge increases, the rate with which problems are introduced decreases as a result of prevention efforts and a smaller problem backlog.

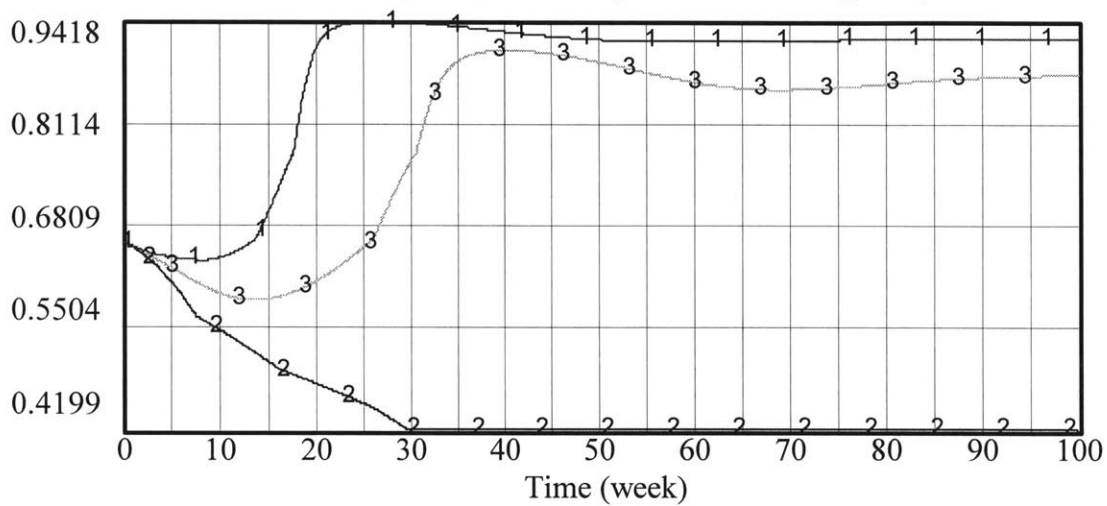
Figure 29b – Impact of Knowledge Gain Rate on Problem Introduction Rate



Problem Introduction : learn fast — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — problems/week
 Problem Introduction : learn slow — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — problems/week
 Problem Introduction : base — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — problems/week

The quality level in Figure 29c is inversely related to the number of process problems. As the number of process problems is reduced, the quality level rises. As the problem introduction rate slows in the base and learn fast scenarios, quality levels improve. The quality level peaks and then falls to a slightly lower equilibrium level. This drop from the peak level can be attributed to the increased influence of the balancing loop where attention and resources are shifted away from process improvement to other production concerns when the cost of poor quality is low.

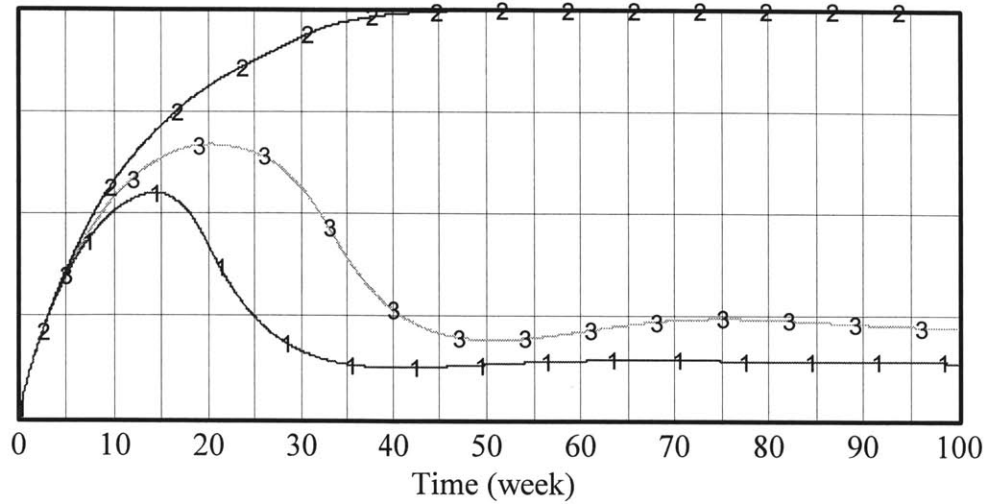
Figure 29c – Impact of Knowledge Gain Rate on Quality



Quality : learn fast 1 1 1 1 1 1 1 1 1 1 1 1 Dmnl
 Quality : learn slow 2 2 2 2 2 2 2 2 2 2 2 2 Dmnl
 Quality : base 3 3 3 3 3 3 3 3 3 3 3 3 Dmnl

Finally, in Figure 29d, the cost of poor quality is shown to be inversely proportional, with a production delay, to the quality level. The cost of poor quality in the model is the sum of scrap and rework costs. These costs are not realized until production and inspection operations are complete which explains why decreases in the cost of poor quality lag increases in quality levels.

Figure 29d – Impact of Knowledge Gain Rate on Cost of Poor Quality



Cost Accumulation : learn fast 1 1 1 1 1 1 1 1 1 1 dollars/week
 Cost Accumulation : learn slow 2 2 2 2 2 2 2 2 2 2 dollars/week
 Cost Accumulation : base 3 3 3 3 3 3 3 3 3 3 dollars/week

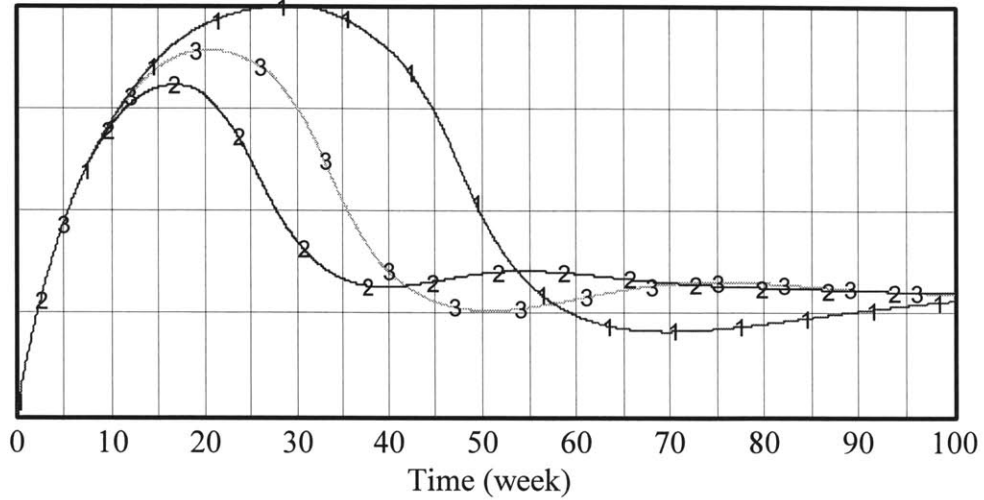
The causal tracing analysis highlights the importance of process knowledge on business unit performance. Knowledge and knowledge gain rates represent the strongest levers for reducing the cost of poor quality.

A causal tracing, similar to that shown in Figures 29a-d for process knowledge, was repeated for a number of other variables. The results of this analysis are outlined below.

Communication Timing

The timing of information related to quality problems has a significant impact on the cost of poor quality. Figure 30 shows the impact of both increasing and decreasing the perception time by 50 percent. More frequent communication leads to an earlier perception of problems within the organization. Until there is a perception of the problem, improvement measures will not be triggered. Figure 30 shows the potential for savings associated with early and frequent communication.

Figure 30 – Impact of Perception Time on Cost

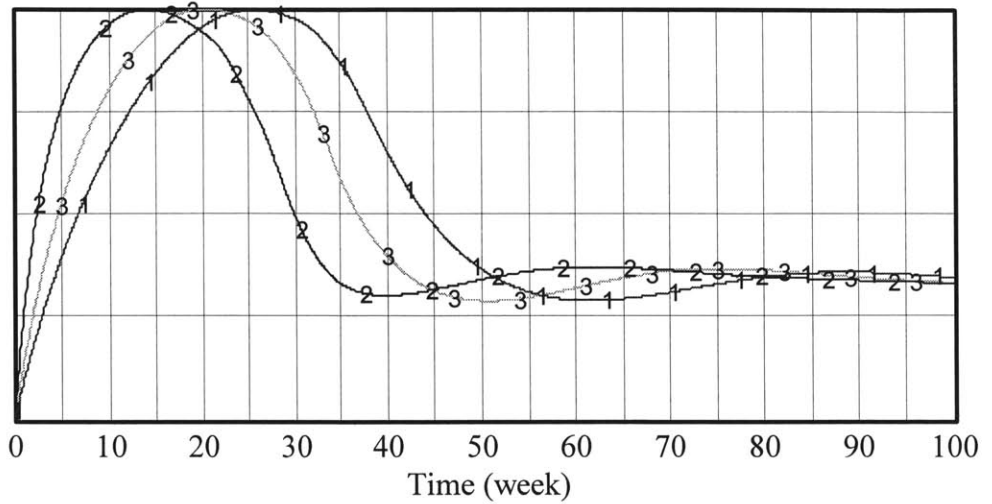


Cost Accumulation : long perception 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 dollars/week
 Cost Accumulation : short perception 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 dollars/week
 Cost Accumulation : base 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 dollars/week

Engineering Disposition Time

The engineering disposition time also indirectly affects the cost of poor quality. When quality problems are discovered and addressed more quickly, the worker efforts can be more quickly directed toward actual production and therefore the building of process knowledge, which then feeds back to better conformance/quality and lower costs as shown in Figure 31.

Figure 31 – Impact of Disposition Time on Cost

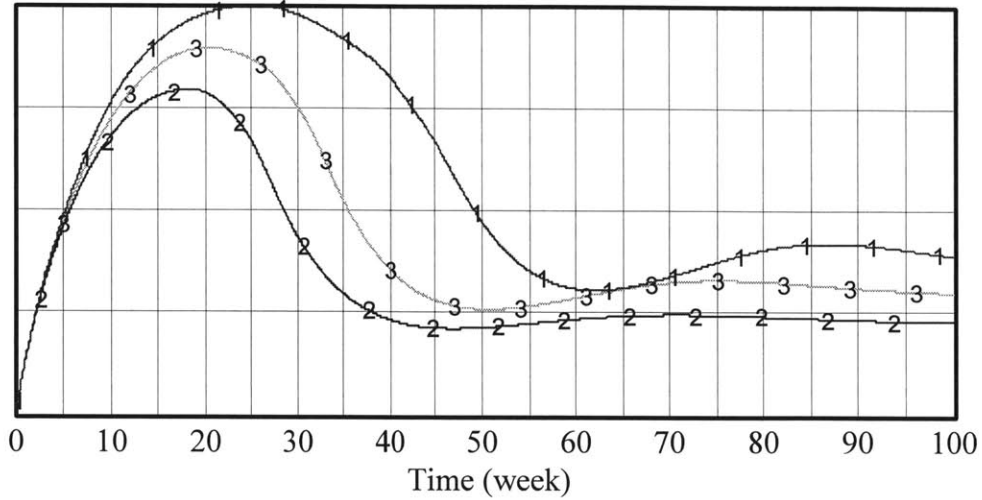


Cost Accumulation : long disp 1 1 1 1 1 1 1 1 1 dollars/week
 Cost Accumulation : short disp 2 2 2 2 2 2 2 2 2 dollars/week
 Cost Accumulation : base 3 3 3 3 3 3 3 3 3 dollars/week

Process Capability

The number of process problems can be directly linked to the capability of the process. To test the strength of the relationship between process problems and cost, a representative problem introduction rate was chosen and then increased and decreased by 50 percent as shown in Figure 32. As the number of problems increases, the process becomes less stable and costs are dramatically increased.

Figure 32 – Impact of Process Problems on Cost Accumulation



Cost Accumulation : less stable 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 — 1 dollars/week
 Cost Accumulation : more stable 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 — 2 dollars/week
 Cost Accumulation : base 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 — 3 dollars/week

7.6 Policy Recommendations

The results of the systemic analysis indicate a number of potential additional policies which would speed problem resolution through increased knowledge gain rates and reducing system delays.

Policy Recommendation: Implement policies that target knowledge redundancy.

Policy Benefits:

- Mitigates risk of employee turnover in short-term. Knowledge loss to attrition is a considerable problem when morale is low.
- Creates larger knowledge base which speeds knowledge gain rate.
- Increases scrutiny of process through job rotation.
- Redundant knowledge will help in solving process problems. Solutions for process problems, if supplemented with knowledge from other elements of the production process, are more likely to optimise the system as a whole.

Policy Recommendation: Consider stopping the production line to communicate process problems as they are identified.

Policy Benefits:

- The reduced delay will allow for earlier communication of quality problems.
- Reduces the magnitude of problem.
- Decreases the number of hours workers are diverted from knowledge gaining efforts.

8.0 CONCLUSIONS

GFH's currently policies for improving process knowledge, quality and morale support their goal for business unit recovery. The analysis of the dynamics of GFH's business environment highlights the leverage that knowledge gain rate provides for improving the business unit's performance. The offline coating simulation is an important tool for increasing the rate with which engineers learn about new production parts and processes. The offline tool allows manufacturing engineers to objectively evaluate proposed production processes as well as to assess the impact of proposed N/C programming changes, tooling changes as well as other improvements of existing processes real-time effectively eliminating the four to six week information delays associated with production trials.

The first objective of the offline tool project was to finalize development of the existing low-pressure plasma spraying (LPPS) simulation tool. The results from early implementation of the LPPS offline tool were used to identify areas for functional improvement as well as identify concerns about the accuracy of the prediction provided by the offline tool.

The development team was able to improve two primary structural elements of the LPPS offline tool; the coating analysis program and the interface with the off-the-shelf CAD program. The team used experimental data to calibrate the results of the coating analysis program. Estimated values for several critical variables were replaced with experimentally determined values which resulted in better correlation between simulated and actual coating thickness values. Improvements to the interface with the CAD package included expansion of the library of N/C functions, formatting of simulation results to facilitate comparison of offline tool results with laboratory reports, and expansion of the tool to include calculations for the surface temperature of the coated parts. Implementation of surface temperature prediction was a necessary precursor to implementation of the porosity simulation feature of the LPPS offline tool.

Based on the comparison of simulation results from the calibrated LPPS offline tool with historical data, the team agreed that the LPPS offline tool provided satisfactory results when compared to the mean coating thickness. The predicted process thicknesses, coupled with

information on expected process variation, would allow users to accurately assess the capability of proposed coating processes.

The second objective of the offline tool project was to utilize the existing LPPS offline tool as a platform for developing a simulation tool for atmospheric plasma spraying (APS). The scope of the development project was modified to allow for earlier implementation of offline robot programming features of the new APS offline tool. This scope change resulted in increased complexity for the user since much of the customisation was transferred to a later development phase. A delay in the offline robot programming requirements, coupled with difficulties during implementation, led the team to outline a revised development and implementation plan. In this plan, implementation would be delayed until after customizing macros could be written and software bugs fully resolved. A phased training plan was developed for implementation which emphasized more gradual mastery of skills for first-time users.

8.1 Recommendations

While the LPPS offline coating tool was fully developed and implemented for coating thickness predictions at the end of the internship, further calibration and analysis effort was needed to improve the accuracy of porosity predictions. Once this development is completed, the offline tool should allow for the estimated reductions in coating development iterations. In order to assess the impact of the implementation of the LPPS offline tool, it is important to compare the number of production iterations needed for process development for the next new coated part with the historical number of process development iterations for a similar, existing production part. This data was not available at the end of the internship.

Further development of the atmospheric plasma spraying offline tool should be accomplished according to the plan agreed upon by the cross-functional team. It is critical that management allow the manufacturing engineers time to work with the programmers to identify improvements, as well as time to learn and master the APS offline tool prior to implementation.

APPENDICES

Appendix A – Spray Pattern Test Matrix

Gas Flow Rates				
Test	Argon	H ₂	Carrier	
			Gas	Current
1	3	4	3	3
2	3	4	4	3
3	3	4	5	3
4	3	4	3	1
5	3	4	4	1
6	3	4	5	1
7	2	3	3	3
8	2	3	4	3
9	2	3	5	3
10	2	3	3	1
11	2	3	4	1
12	2	3	5	1
13	1	1	2	2
14	1	1	3	2
15	1	1	4	2
16	1	1	2	1
17	1	1	3	1
18	1	1	4	1
19	1	2	1	4
20	1	2	2	4
21	1	2	3	4
22	1	2	4	4
23	1	2	5	4

Appendix B – System Dynamics Standard Method

The “Standard Method”⁸

Jim Hines

What is the “standard method”? The standard method is the sequence of activities (or the process) most teams will follow in doing a “from-scratch” project.

Why do we call it the “standard method”? Most top system dynamics practitioners follow processes that are similar to what we do in class. On the other hand, all practitioners have their own modifications. We were in a quandary. If we called this the “Jim Hines Method”, everyone would say, “That’s not the Jim Hines Method, that’s the process that *everyone* follows. *I’ve* been doing it for years. Its standard!” Of course by calling it the “standard method”, everyone will now say, “That’s not the standard method, it’s just Hines’ method. What *I* do is the standard method, and it’s *totally* different”. We finally decided to go forward with the “standard method”, because it seemed less self-aggrandizing.

Steps in the standard method. The steps of the standard method will probably seem familiar to you. The steps are:

- 1) Problem definition
 - a) List of variables
 - b) Reference modes
 - c) Problem statement
- 2) Momentum policies
- 3) Dynamic hypotheses (i.e. causal loops)
- 4) Model first loop
- 5) Analyze first loop
- 6) Model second loop
- 7) Analyze second loop
- 8) Etc.

Conclusions and insights should emerge at every step and may emerge at any minute during the standard method. Be sure to record these conclusions and insights when they occur.

Quick example of the standard method. In this example, we’ll end up building a classic diffusion model. But, let’s pretend that we don’t know what a diffusion model is. (If you *don’t* know what a diffusion model is, this little exercise will show you).

We will take the viewpoint that we have a client (perhaps a team of managers) who is the substantive expert for the project and that our role is to be the methodological experts. Having a client simplifies the SD process considerably, because the client can be relied to explain how the

⁸ Prepared by Jim Hines, February 1999. Revised April 2000.

world works and to tell you what's important (to him). If you are your own client, keep in mind that the two roles still exist, but that you fill both of them – you might want to try to keep your roles separated. Our first meeting with the client begins in a conference room with the vice president of the automated products division, and his direct reports (marketing, manufacturing, research and development). The VP provides some introductions and context.

“Our Automated Fly Swatter is a great product. We need to understand the key drivers in the fly market, so I've hired these very smart folks from MIT. Why don't we go around the table and introduce ourselves?”

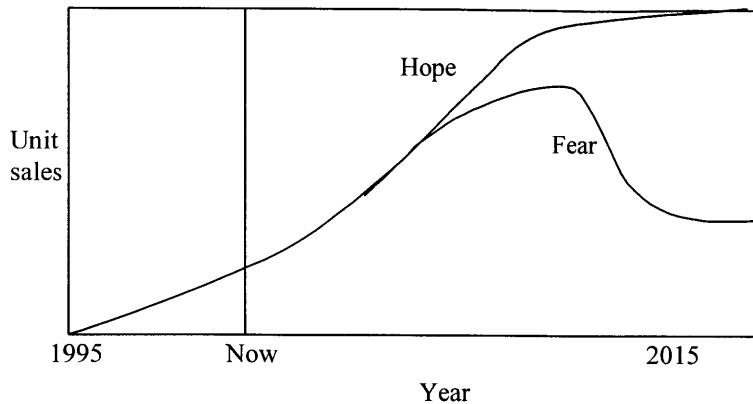
At this point everyone turns to you and expects you to say something brilliant. That's too hard, so instead you stand up and say I'd like to begin by simply listing important variables. Slowly at first and then with increasing speed the managers call out variables while you write them on a flip chart. You record:

Variables List:

- Fly population
- Revenues
- Unit Sales
- Annoyance at flies
- Market saturation
- Manufacturing costs
- Price
- Cost of batteries
- Word of mouth about our product
- Product recalls
- Health problems with our products
- ...etc.

Eventually, your managers run out of steam. You call a break, and ask that during the break people mark what they think are the five most important variables.

Reference Modes: Returning from the break, you explain that you want to graph the behavior of most important variables. Identifying the half dozen variables that received the most “votes”, you lead the group through a reference mode exercise drawing each one on a flip chart. For example, one of the reference modes might be



(Looking at the graph some one in the group says, “You know, for a long time we won’t be able to tell which trajectory we are on”. You add this to the ‘list of insights’ that you are keeping on another flip chart.)

Problem statement: One or more of your reference modes almost certainly will contain a true concern of the clients. You phrase it to the group (you do *not* need to write it down for the group)

We hope that AFS sales rise and stay up, but we’re worried that that they might take a nosedive. If we are successful in our project here we will increase the likelihood of the curve labeled “hope” and decrease the likelihood of the curve labeled “fear”.

Momentum policies. *Momentum policies* are the policies the client would implement now to solve the problem, if they had no further time to collect information or ponder. Once you have a problem focus, you are in a position to collect momentum policies.

Continuing with our example, you point out to your client out that the system dynamics process has already added something by crystallizing the problem. You explain, though, that you would like to be able to gauge at the end of the process, whether anything beyond this additional specificity has come out of the project. Consequently you’d like to record what the client would do *now* about the problem, if decisions had to be made *immediately*.

You record ideas like:

“We need to do a market study”

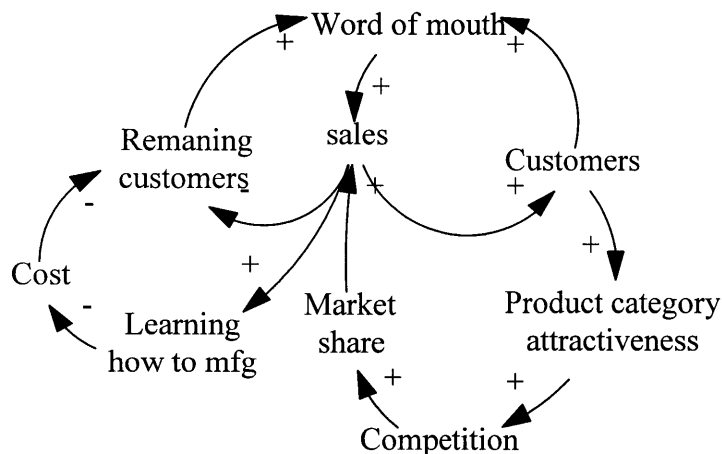
“We should start a competitor intelligence unit”

“We need to get data on the drivers of the market”

“We’ve got to get better forecasts from the Economics Group”.

Note that these policies are not all well thought out, and some are not even policies. No problem, simply record them. Store them away. You might want to use them to suggest tests or directions of inquiry, but at least (and in most cases at most) you will pull them out five weeks from now to say, “Look how far we’ve come”.

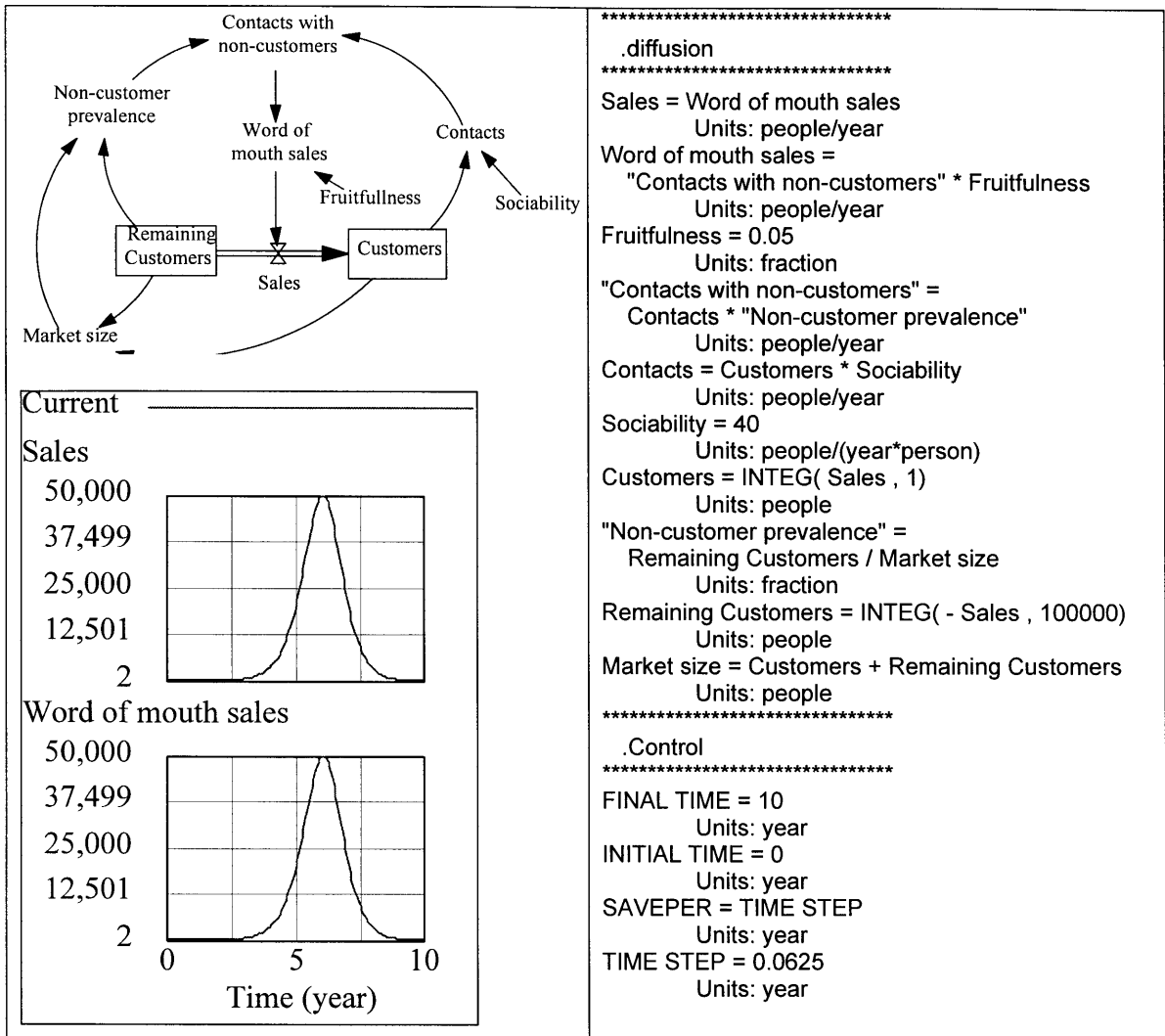
Causal loop diagram. With variables, reference modes, and a problem-focus, you will be in position to start coming up with dynamic hypotheses that is loops that describe feedback processes capable of generating the patterns in your reference modes. Each “idea” is a dynamic hypothesis and usually a dynamic hypothesis can be captured by one or two loops. Coming up with a diagram won’t be easy – keep in mind that you will only have time to model a single dynamic hypotheses, so don’t be too hard on yourself. Still, its good to be as comprehensive as possible in this stage. Insights from unmodeled loops are still insights.



Again remember to record insights as they come up. For example: “The learning loop, counteracts the running-out-of customers loop” and “We can strengthen the word-of-mouth loop with a sign-up-a-friend promotion”.

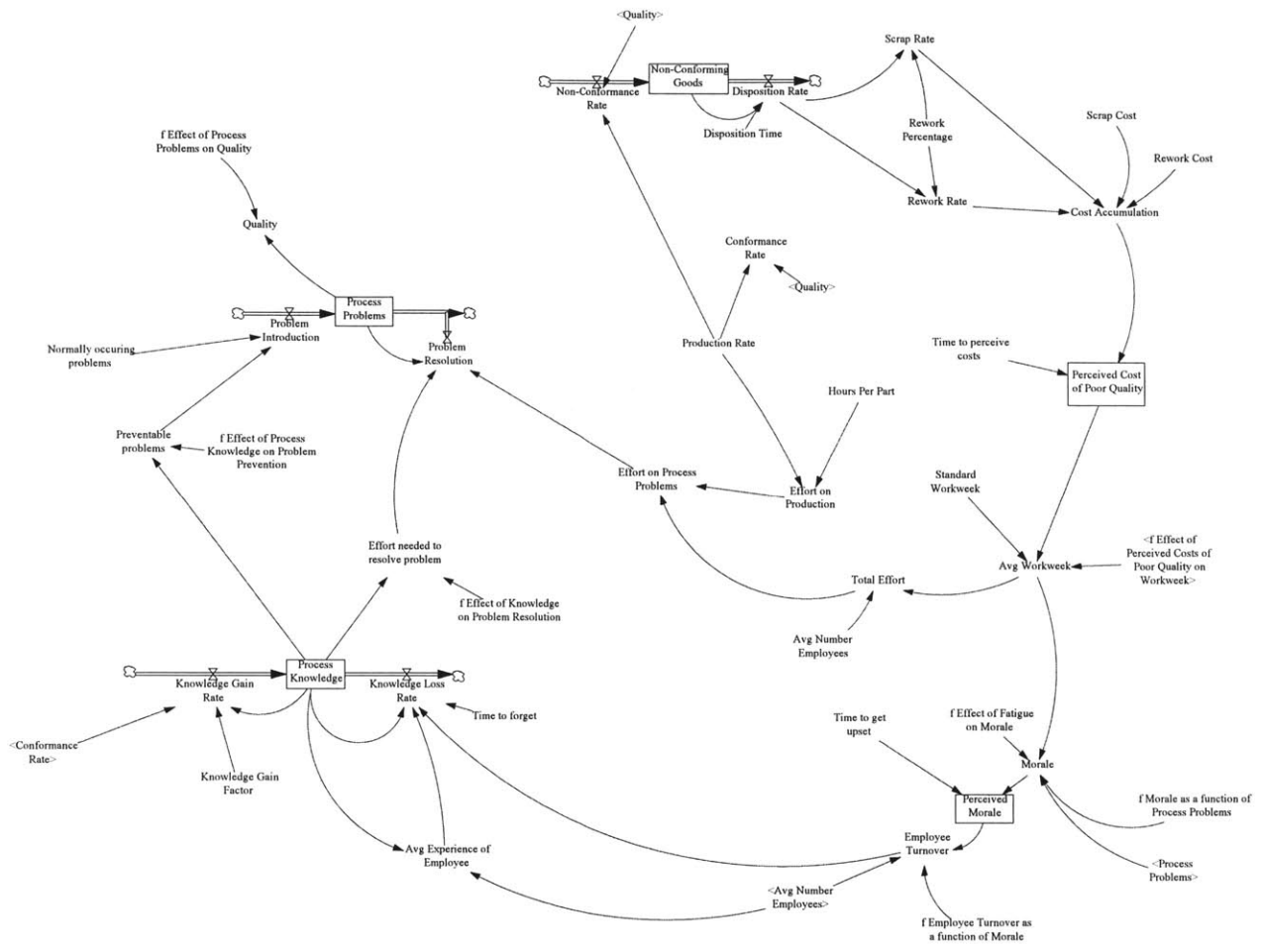
Modeling. Finally, you are ready to model. You will choose a single dynamic hypothesis (that is a loop or two), model it, simulate, analyze, and work with your client to develop insights and ideas. If there were time, you would choose another loop, add it to your growing model, simulate, analyze again, and work on further developing new or existing ideas. You will probably only have time to model a single dynamic hypothesis.

As always record insights and conclusions as you go along. For example, “Strengthening the positive word-of-mouth loop creates a faster rise and a deeper collapse.” and “Replacement sales may lessen the severity of the down-turn in sales”.



Final presentation. Technically, the final presentation is not part of the standard method. But for completeness we'll mention here. Your final presentation should summarize your project, stressing what the client discovered in the process and what the client may now want to do. The final presentation should be non-technical and oriented to managers.

Appendix D – Model and Documentation



The model uses the following equations to define the behavior of the system:

$$\text{Avg Workweek} = \text{Max}(\text{Standard Workweek} * f \text{ Effect of Perceived Costs of Poor Quality on Workweek}(\text{Perceived Cost of Poor Quality}/\text{Unit correction}), 40)$$

Units: hours/week/person

$$\text{Effort on Production} = \text{Hours Per Part} * \text{Production Rate}$$

Units: hour/week

$$\text{Production Rate} = 150$$

Units: parts/week

Effort on Process Problems=Total Effort-Effort on Production

Units: hours/week

Unit correction=1

Units: dollars/week

Problem Resolution=Effort on Process Problems/Effort needed to resolve problem*Process Problems/(Process Problems+2)

Units: problems/week

Cost Accumulation=(Rework Cost*Rework Rate)+(Scrap Cost*Scrap Rate)

Units: dollars/week

Radar Cost=2000

Units: dollars/week

Effort needed to resolve problem=f Effect of Knowledge on Problem Resolution(Process Knowledge)

Units: hours/problem

Conformance Rate=Quality*Production Rate

Units: parts/week

Rework Rate=Disposition Rate*Rework Percentage

Units: parts/week

Knowledge Gain Factor=0.001

Units: Dmnl/part

Employee Turnover=f Employee Turnover as a function of Morale(Perceived Morale)* Avg Number Employees/52

Units: people/week

Perceived Morale= INTEG ((Morale-Perceived Morale)/Time to get upset,0.5)

Units: Dimensionless

Time to get upset=52

Units: week

Disposition Time=6

Units: weeks

Hours Per Part=16

Units: hour/part

Process Problems= INTEG (+Problem Introduction-Problem Resolution,10)
 Units: problem

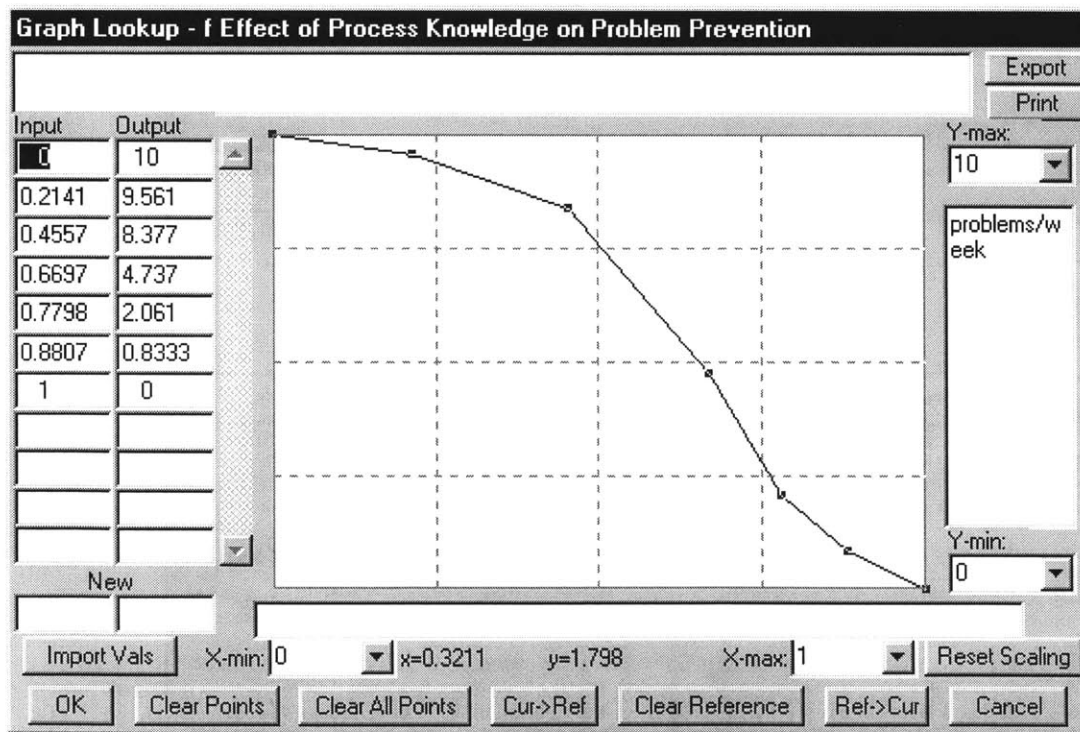
Preventable problems=f Effect of Process Knowledge on Problem Prevention(Process Knowledge)
 Units: problems/week

Problem Introduction=Preventable problems+Normally occurring problems
 Units: problems/week

Normally occurring problems=1
 Units: problem/week

capacity=150
 Units: parts/week

Table function: Effect of Process Knowledge on Problem Prevention
 Input: Dimensionless
 Output: Problems/week



Perceived Cost of Poor Quality= INTEG ((Cost Accumulation-Perceived Cost of Poor Quality)/Time to perceive costs,1000)
 Units: dollars

Scrap Rate=Disposition Rate*(1-Rework Percentage)

Units: parts/week

Time to perceive costs=12

Units: week

Avg Experience of Employee=Process Knowledge/Avg Number Employees

Units: Dmnl/person

Knowledge Loss Rate=((0.5*Avg Experience of Employee*Employee Turnover)+Process Knowledge/Time to forget)

Units: Dmnl/week

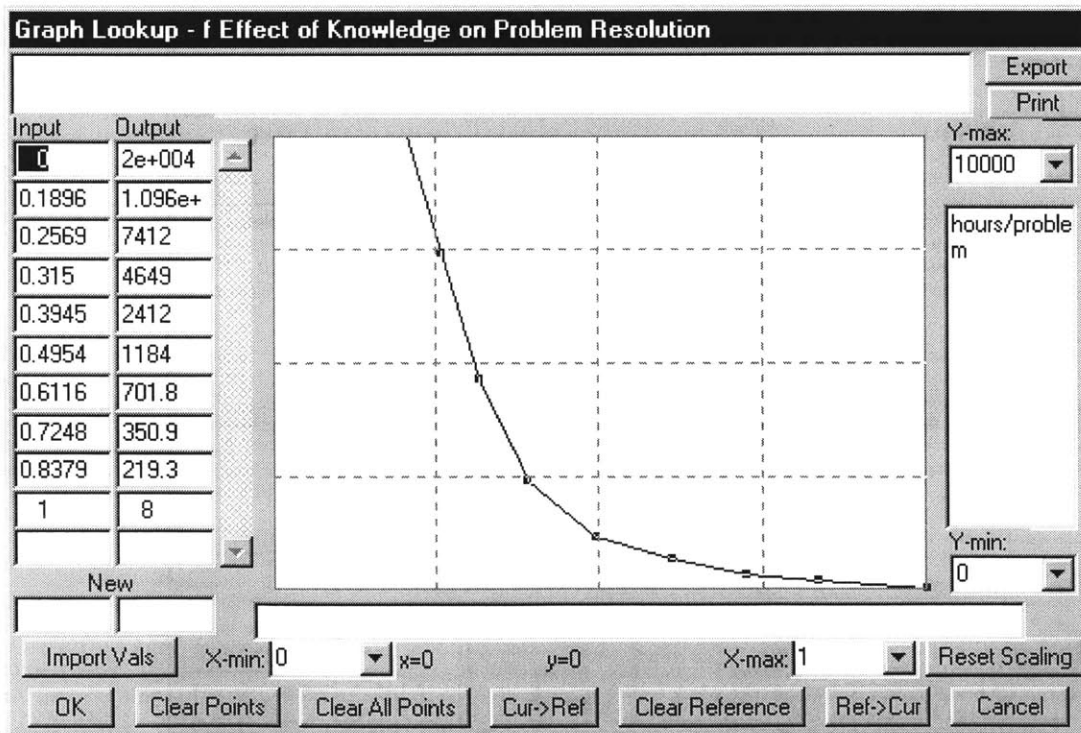
Standard Workweek=40

Units: hours/person/week

Table function: Effect of Knowledge on Problem Resolution

Input: dimensionless

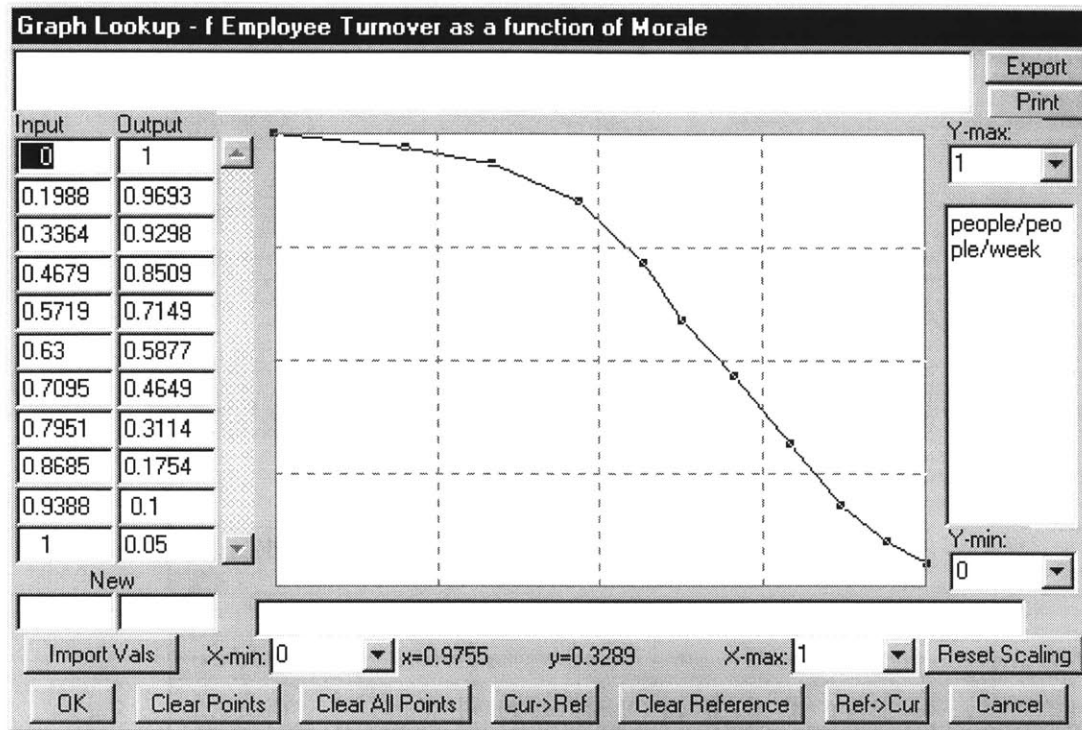
Output: hours/problem



Avg Number Employees=75

Units: people

Table function: Effect of Fatigue on Morale
 Input: Morale (dimensionless)
 Output: Employee turnover (people/people/week)



Disposition Rate="Non-Conforming Goods"/Disposition Time
 Units: parts/week

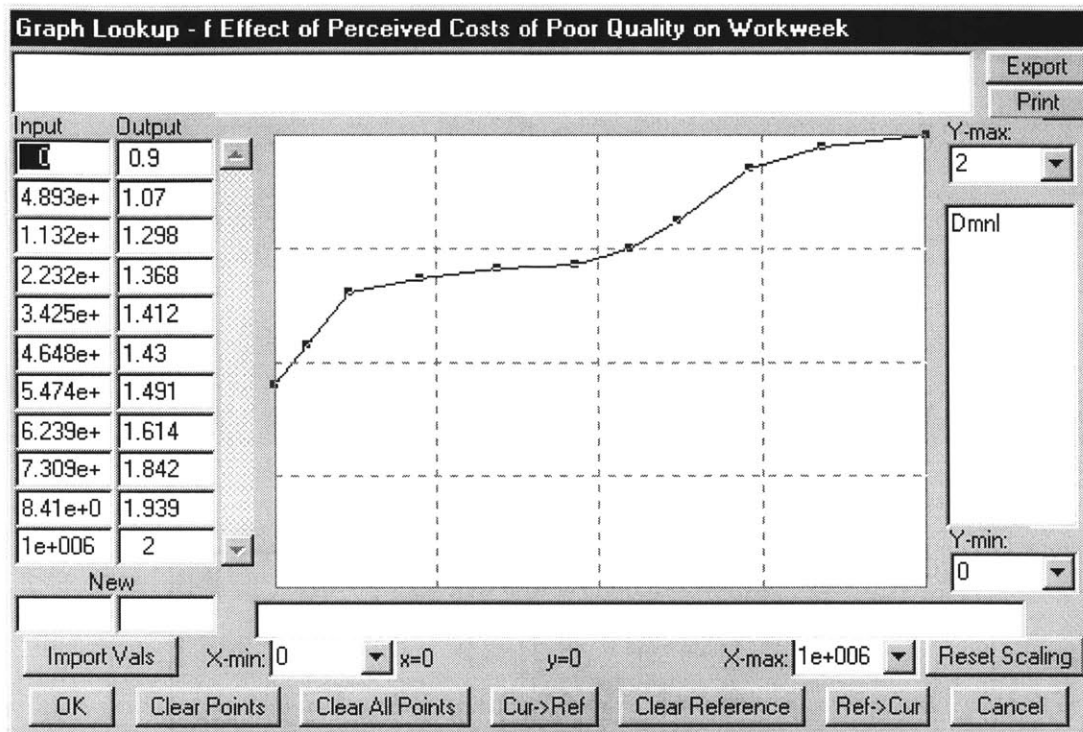
Morale=f Morale as a function of Process Problems(Process Problems)*0.75+f Effect of Fatigue on Morale(Avg Workweek)*0.25
 Units: Dmnl

Total Effort=Avg Number Employees*Avg Workweek
 Units: hours/week

Table function: Effect of Perceived Costs of Poor Quality on Workweek

Input: Dollars

Output: hours/week/person



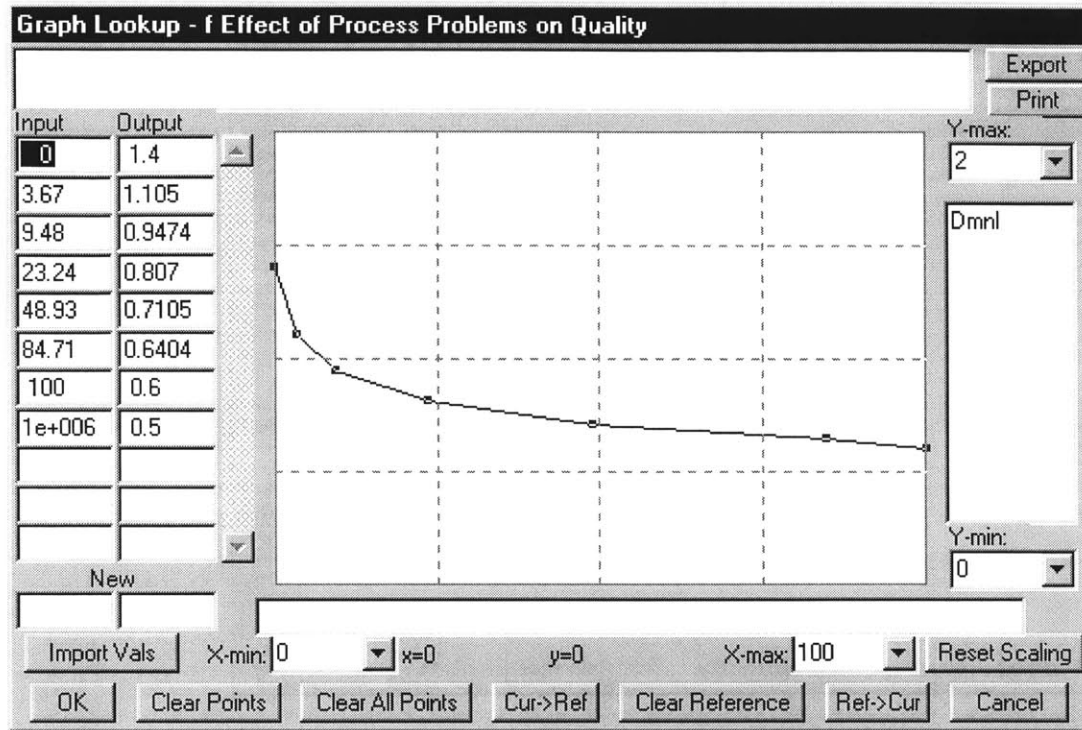
Process Knowledge= INTEG (Knowledge Gain Rate-Knowledge Loss Rate,0.8)

Units: Dmnl

Time to forget=52

Units: weeks

Table function: Effect of Process Problems on Quality
 Input: problems
 Output: Dimensionless



Quality=0.7*f Effect of Process Problems on Quality(Process Problems)
 Units: Dimensionless

Table function: Employee Turnover as a function of Morale

Input: Dimensionless

Output: People/people/week

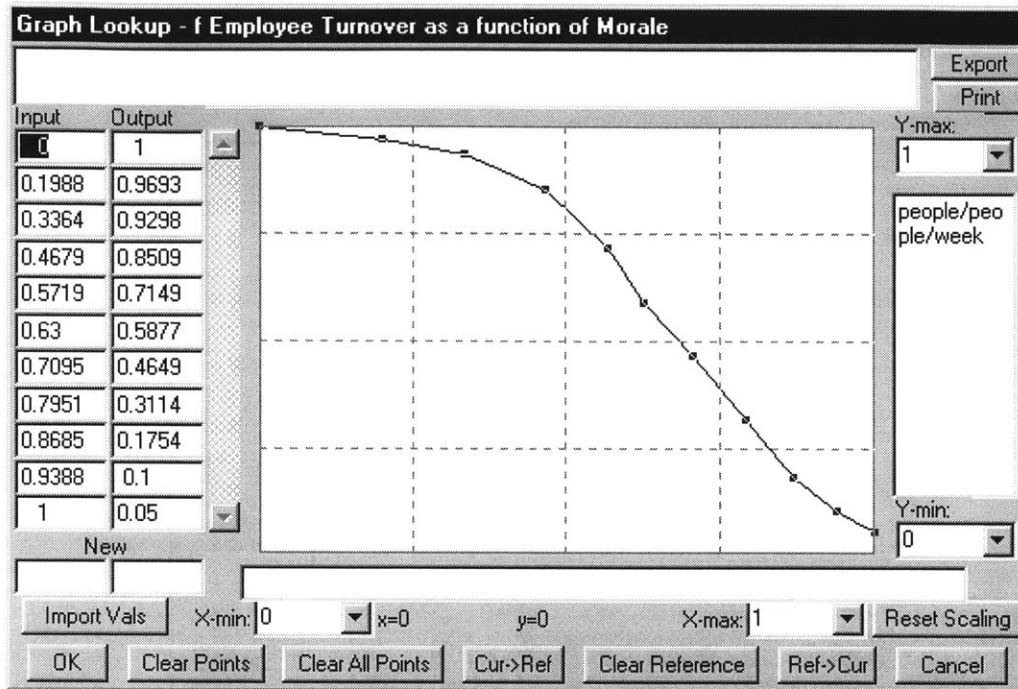
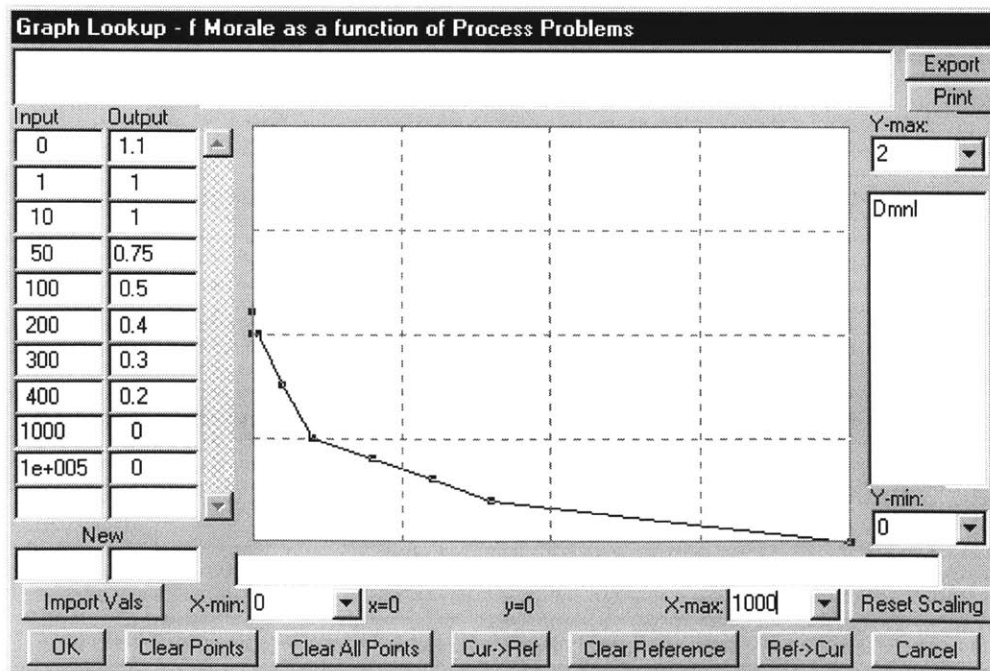


Table function: Morale as a function of Process Problems

Input: Process Problems (problems)

Output: Morale (dimensionless)



Rework Percentage=Proprietary
Units: Dimensionless

Scrap Cost=Proprietary
Units: dollars/part

"Non-Conforming Goods"= INTEG ("Non-Conformance Rate"-Disposition Rate,0)
Units: parts

Rework Cost= Proprietary
Units: dollars/part

Control

*****~

Simulation Control Parameters

"Non-Conformance Rate"=Production Rate*(1-Quality)
Units: parts/week

Knowledge Gain Rate=Conformance Rate*(1-Process Knowledge)*(Knowledge Gain Factor)
Units: Dmnl/week

FINAL TIME = 100
Units: week

INITIAL TIME = 0
Units: week

SAVEPER = TIME STEP
Units: week
The frequency with which output is stored.

TIME STEP = 0.0625
Units: week
The time step for the simulation.