

LIFE CYCLE COST MODELING OF AUTOMOTIVE PAINT SYSTEMS

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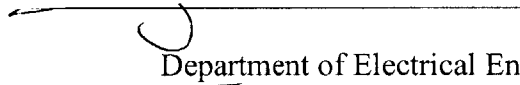
Submitted to the Sloan School of Management and the
Department of Electrical Engineering and Computer Science in partial fulfillment of the
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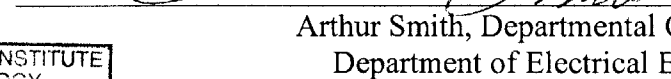
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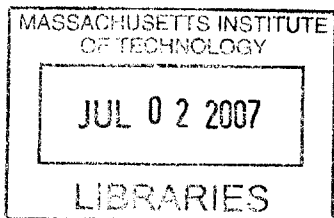
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BARKER

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Abstract

Vehicle coating is an important component of automotive manufacturing. The paint shop constitutes the plurality of initial investment in an automotive assembly plant, consumes the majority of energy used in the plant's operation, and generates significant waste from paint overspray. The coating process also results in the emission of polluting volatile organic compounds (VOCs). New paint technologies based upon powder coatings offer reductions in VOC emissions along with potentially reduced energy usage and the ability to reuse paint overspray. However, quantification of these advantages requires clear understanding of the life cycle costs associated with each paint technology, modeled over the decades-long time horizons within which a paint shop operates.

Life cycle cost models go beyond acquisition cost to consider all relevant cost drivers for a given system. This includes obvious candidates such as investment and operating costs, but also may include more subtle factors such as costs associated with variation, disruption, or flexibility, hereafter referred to as hidden costs. In this thesis, methods for estimating these costs for a paint shop are explored.

First, the development of a life cycle cost modeling tool, capable of quickly forecasting investment and operating costs and testing the sensitivity of life cycle cost to changes in input costs, is discussed. This tool is then used to compare the life cycle cost of three different primer surfacer application technologies. Next, the potential impact of hidden costs on life cycle cost for manufacturing systems are investigated, both through real-world examples and simulations. Finally, this thesis explores the wider implications of a shift to life cycle cost analysis for General Motors, in terms of both internal and external relationships for the Global Paint and Polymers Center at General Motors, and identifies situations in which a focus on life cycle cost can bolster managerial objectives.

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Problem Statement

In the broadest sense, this thesis is about using cost projections as a guide for future investments in manufacturing systems or new technologies. The specific goal of this project was to provide the engineers at the Global Paint and Polymers Center (GPPC) at General Motors a tool that would enable them to determine the life cycle cost of different automotive paint systems. Life cycle cost is defined as the total cost of a system over the time of its deployment and operation, and includes all relevant cost drivers. This tool was deemed important for GPPC management because paint shops require capital-intensive long-term investments in the face of great uncertainty -- in areas such as product volumes, future technology choices, government regulations, product requirements, and energy costs.

The technical work outlined in this thesis proceeded along two fronts, described in Chapters 2 and 3 of this thesis. In Chapter 2, the development of this life cycle cost estimation tool is documented, and an application to life cycle cost estimation of three different primer surfacer technologies is presented. The development process for this tool began early in my internship and continued throughout my time at General Motors. In this cost estimator, investment and operating costs are projected over the life of a manufacturing system, and some built-in methods of sensitivity analysis allow the user to test his or her assumptions. In this sense, this tool captures the main technical goals of the project.

However, early on in my internship, we identified cost drivers that were not easily categorized or quantified, but could account for a substantial portion of the actual cost of a manufacturing system. These so-called hidden costs -- variation, disruption, and flexibility -- are discussed in Chapter 3. Rather than prescribe specific methods for evaluating these costs, which are elusive, some general frameworks are laid out and specific real-world examples are provided. While determination of hidden costs requires more research and extrapolation than investment or operating costs, it is my hope that this thesis will impress upon the reader the importance of thinking about these costs when making projections.

Finally, during the course of my internship, I naturally began to examine the link between incentives and outcomes -- specifically, how an individual organization's focus on certain classes of cost (e.g. investment only, or investment and operating only) can lead to sub-optimal decisions for the company as a whole. In Chapter 4, the relationships that define GPPC's place

in General Motors are explored, and the implications of using the holistic life cycle cost perspective advocated in this thesis are discussed.

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Chapter 1: Introduction and Background

1.1 Automotive Industry Overview

One century after its inception, the automotive industry remains a dominant force in the global economy. Worldwide, more than fifty million new automobiles were sold in 2006,¹ with revenues of the fifteen largest automakers alone comprising approximately 2% of the gross world product.² Furthermore, the automotive industry is a key driver for a host of other large industries, including raw materials suppliers (e.g. steel, aluminum), components, and oil companies. While total car sales in the United States and Western Europe have stabilized in recent years, strong growth in Asian, South American, and Middle Eastern markets has resulted in approximately 2.7 % global sales growth over the past ten years.³ Finally, in terms of revenue, automotive manufacturers represented four of the largest ten companies in the world in 2005.

Despite its vast scale and maturity, owing to both internal and external pressures, automotive manufacturing cannot be described as stagnant. First, competition is fierce, particularly in North America where a growing number of automakers struggle for market share and revenue growth amidst a relatively flat market and rising domestic labor costs. In this competitive landscape, the market has become significantly more fragmented as manufacturers seek differentiation and new market niches. For example, in the United States, the top three automakers commanded a 59% market share in 2005,⁴ compared to 95% in 1955.⁵ Similarly, in 1955, six models accounted for over 80% of sales,⁵ while in 2005 the six most popular models accounted for only 17% of sales.⁶ This increased fragmentation has also been accompanied by shorter times between model

¹ Storey, J., *The World's Car Manufacturers: A Strategic Review of Finance and Operations*. Automotive World, <http://www.awresearcher.com>, (2006), p. 1.

² *CIA World FactBook*, <https://www.odci.gov/cia/publications/factbook/geos/xx.html> (2007).

³ Storey, J., p. 1.

⁴ Edmunds.com, *Edmunds.com Looks Back at 2005 and Forecasts 2006 Automotive Trends*, <http://www.edmunds.com/help/about/press/108914/article.html> (2006).

⁵ Womack, J.P., Jones, D.T., and Roos, D., *The Machine that Changed the World*. New York, Harper Perennial (1990), p. 43.

⁶ Edmunds.com, *Top 10 Best-Selling Vehicles for 2005*, <http://www.edmunds.com/reviews/list/top10/115851/article.html> (2006).

redesigns. Thus, in general, costly vehicle development programs have become more frequent, with their costs amortized over smaller volumes. This has led manufacturers to focus on developing flexible common vehicle platforms that can be used for several different vehicles, often deployed in markets worldwide, and factories capable of building these different vehicles at any given time.

External pressures, such as those exerted by regulations, have also dramatically impacted automotive manufacturing. For example, the United States' Clean Air Act has changed the basic nature of vehicle coating, and is thus of particular relevance to this work. In the past, coating processes emitted large quantities of volatile organic compounds (VOCs) that can react to form ozone, a pollutant, upon release to the atmosphere. The Clean Air Act has forced vehicle manufacturers to seek methods to curtail VOC emissions in their coating processes and caused a shift in coating processes away from VOC-emitting solvents.

Finally, in general, additional external pressures will likely continue to shape the future of automotive manufacturing, in both the near and far term. For example, rising commodity costs may force manufacturers to alter the materials mix in their vehicles. Escalating energy costs and geopolitical events will increase the industry's focus on energy efficient manufacturing and fuel efficient vehicles, possibly to the point of replacing the current gasoline-driven powertrain. Also, possible additional regulations regarding carbon emissions and fuel economy standards will escalate these trends.

It is in this dynamic environment, characterized by pressures toward flexible and environmentally friendly manufacturing processes, that this thesis considers the life cycle cost of manufacturing systems, with a focus on vehicle coating systems. Life cycle cost models include all possible costs over the life of the system of interest -- the system can be as simple as a single robot or as complex as an entire factory. The goal of determining life cycle cost of manufacturing systems is to make informed investment decisions that lead to the lowest overall cost after all inputs and risks are considered, allowing the manufacturer to mitigate risk and thrive in the face of the competitive pressures described above. Before considering these ideas in more detail, it is first useful to consider the entire automotive manufacturing process and the evolution of vehicle coating processes.

1.2 The Automotive Manufacturing Process

In today's automotive landscape, vehicle manufacturing is an extremely complex process involving many suppliers beyond the original equipment manufacturer (OEM). Unlike the early days of Ford's manufacturing, where Henry Ford sought to build a completely integrated plant at his Rouge River "city-state,"⁷ no OEM aspires to directly control the entire value chain of vehicle production. Rather, many vehicle systems are outsourced to suppliers, while OEMs tend to focus on vehicle architectures, engines, and drivetrains. It is in the final assembly plant where these systems are integrated into the finished product.

Final automotive assembly comprises three main processes: body, paint, and general assembly, depicted in Figure 1.1.

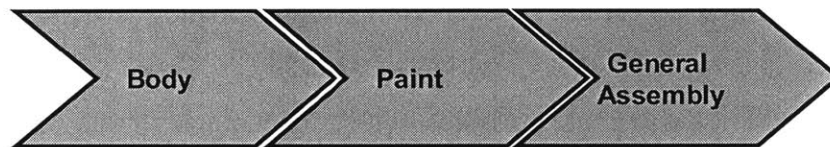


Figure 1.1. The three major components of an automotive assembly plant.

In the body shop, the basic frame of the vehicle is fabricated. Originally, car bodies were fabricated of wood, which precluded the use of elevated cure temperatures in the subsequent coating process. This created a massive bottleneck, as car bodies were air-dried for up to forty days before proceeding to general assembly.⁸ In the early twentieth century, Dodge was the first manufacturer to switch to an all-steel body, enabling much faster vehicle coating processes.⁹ The all-steel body also helped enable the unitary architecture, dominant in cars today, where the steel frame functions as both the chassis (frame) and body (external structure).¹⁰ After the body shop, the vehicle is then sent to the paint shop, where coatings and sealers are applied to both interior and exterior surfaces. These processes are outlined in detail below. Finally, in general assembly, the coated body is mated with the interior systems, engine, drivetrain, suspension, and wheels.

⁷ Halberstam, D. *The Reckoning*. New York, William Morrow and Company (1986), p. 87.

⁸ Andrews, D., Nieuwenhuis, P., and Ewing, P.D., "Black and Beyond – Colour and the Mass-Produced Motor Car," *Optics & Laser Technology* **38** (2006) 377.

⁹ *Ibid.*

¹⁰ *Ibid.*

Final assembly plants vary widely in the processes employed and capacities. In North America and Europe, most vehicle assembly processes are highly automated, with the greatest concentration of labor content in the final assembly steps. In countries with lower labor costs, significant labor inputs may be utilized in other assembly areas. The relatively wide variety of vehicles, both in terms of size and price, also generates variety in the assembly processes employed. However, in general, as common vehicle architectures proliferate, more commonality in processing will be employed. Also, assembly plants will tend toward higher flexibility to maximize capacity utilization, so the investments in product development and manufacturing can be amortized over a larger number of vehicles.

1.3 The Automotive Paint Process

Automotive coating is a complex, multistage process where vehicles are typically processed in a serial fashion. The main details of the coating process are outlined in Table 1.1; process times described below do not include vehicle inspection and routing times. The description below follows that of Andrews *et al.*¹¹

Table 1.1. Outline of the automotive paint process.

Step	Approximate Process Time (min.)	Purpose
Phosphate	30	Corrosion protection
ELPO	30	Corrosion protection
ELPO Oven	30	Cure coating
Sealer	10	Weatherproofing, corrosion protection
Primer Surfacer	10	Restore surface smoothness
Primer Oven	30	Cure coating
Basecoat	10	Provide vehicle color
Clearcoat	10	Protect basecoat, enhance appearance
Topcoat Oven	30	Cure basecoat and clearcoat layers

Vehicles enter the paint shop after body assembly, where the basic structure of the automobile gets defined. Bodies are first cleaned and then coated in a thin layer of zinc phosphate, which promotes adhesion of subsequent layers and provides corrosion protection. Next, vehicles are

¹¹ *Ibid.*

coated in an anti-corrosive polymer, commonly called E-coat or ELPO (electrodeposited polymer). These first two coating steps are often done in large dip tanks, where the entire vehicle is immersed in solution. Next, the ELPO coating is cured in an oven and vehicles are inspected for defects. After defect repair, accomplished via sanding, sealer is applied along seams and joints to provide additional corrosion protection and to weatherproof the vehicle. Next, vehicles are given a layer of primer surfacer, which primarily serves to provide a smooth surface for the subsequent paint layers. In some buried surfaces of the vehicle, such as under the hood or trunk lid, primer surfacer (matched to the body color) may be the final layer applied. After primer surfacer deposition, vehicles are baked in an oven to cure the paint and inspected for defects. Next, the topcoat layers are deposited, comprising both a basecoat that imparts the vehicle color and a clearcoat that protects the basecoat layer and improves the appearance of the finish. Finally, the topcoat layers are cured, and the vehicle is given a final inspection.

The flow time of vehicles through a paint shop is typically on the order of three to eight hours, and work-in-process inventory is typically a few hundred vehicles. Generally, the paint shop represents the bottleneck in automotive assembly, primarily due to three factors. First, the curing process, which occurs several times in the paint shop, is relatively slow. In this step, vehicles are exposed to elevated temperatures (approximately 350°F) for approximately thirty minutes in ovens that are hundreds of feet long. Secondly, coatings cannot be applied instantaneously, as the coating speed has to be balanced with the desire to efficiently transfer a uniform coating to the vehicle surface. For example, articulating robot arms or mobile fixtures apply primer surfacer and topcoat through applicators designed to minimize overspray (i.e. paint that does not reach the surface of the vehicle and is thus wasted) and yield a uniform and high quality surface. Finally, the paint shop is extremely capital-intensive, and additional capacity does not come without a cost. Of the three areas of final assembly, the paint shop represents the plurality of initial capital investment and a large portion of annual operating costs, each of which can reach hundreds of millions of dollars for a single plant. As a symptom of these reasons cited above, Howard and Graves cite some additional telling figures regarding the extent of operational

challenges in the paint shop: according to their figures, approximately 28% of vehicles are reworked in this area, and 40% of work-in-process inventory is held in the paint shop.¹²

1.4 Significance of Automotive Coatings

Schoff¹³ has noted that coatings present several interesting paradoxes, many of which are relevant to this work. For example, the coating process is both technologically sophisticated and very simple, involving both robots with specialized electrostatic applicators and significant manual inspection and defect repair. Additionally, coating processes are the subject of constant research and development, but discovery is often by trial and error due to the inherent complexity involved in the application of coatings over a variety of surface orientations. Finally, coating processes provide significant benefits that easily justify their cost, and yet the paint shop is under constant pressure to reduce its investment and operating costs. These paradoxes highlight some of the challenges in vehicle coating and the significance of the coating process to both customers and manufacturers.

For the customer, the coating process is of critical importance in terms of both initial appearance and long-term quality, as coatings serve to both enhance vehicle appearance and protect the body from corrosion. Paint is often the first vehicle attribute noticed by a customer, and certain vehicle / color combinations have become iconic (to cite but a few examples, Prince's song "Little Red Corvette," the Mary Kay pink Cadillac, the ever-popular Ferrari Red, and the trademark light blue color of Ford's LeMans-winning GT40 in the 1960s). Manufacturers thus place great importance on the appearance of their coatings. Interestingly, however, the quantitative measurement techniques that link coating metrics to perceived quality are still under development. Regarding long-term quality, the coating process has been rigorously engineered to protect the (usually) steel body from rust for many years, to the point where corrosion is a rarity in modern vehicles. In fact, the first two layers in vehicle coating exist solely to prevent the body from rusting and are invisible to the customer in normal circumstances.

¹² Howard, M. and Graves, A., "Painting the 3Daycar: Developing a New Approach to Automotive Coatings and Lean Manufacture," *Society of Automotive Engineers Automotive and Transportation Technology Congress and Exhibition* (2001).

¹³ Schoff, C.K., "Organic Coatings: The Paradoxical Materials," *Progress in Organic Coatings* **52** (2005) 21.

For the manufacturer, most of the energy used in the assembly process is consumed in the paint shop, largely in the curing and paint distribution and collection systems. Coating materials are also expensive, and yet paint overspray (the result of the inability to reuse the portion of sprayed paint that does not reach the vehicle surface; overspray must then be collected and disposed of) results in significant waste and disposal costs. Finally, the coating process results in the emission of volatile organic compounds (VOCs), chemicals that contribute to the formation of the pollutant ozone in the lower atmosphere. The United States Clean Air Act of 1977 requires automotive manufacturers to reduce their VOC emissions. These costs (both in traditional cost and environmental externalities) have created enormous pressure on automotive manufacturers to implement improved paint processes.

One relatively recent change in the coating process has been a shift in the types of materials used in paints, from VOC-emitting solventborne paints toward either lower solvent concentrations (achieved with higher percentages of solids and/or by replacing some portion of solvents with water) or VOC-free powder paints. In the powder coating process, solid paint particles are fluidized by compressed air, electrostatically charged, and directed at a grounded substrate.¹⁴ The coated substrate is then baked to achieve cross-linking of the individual particles and creation of a continuous film. Powder processes have two main advantages over liquid processes. First, powder can be reclaimed and recycled, reducing material and disposal costs. Second, powder does not require abatement systems to deal with this sludge, sharply reducing water and energy usage and simplifying facility design. However, while powder coatings offer great advantages, they cannot be universally employed. To date, powder coatings cannot support metallic finishes, eliminating their use in the basecoat layer. Multicolor powder processes can be deployed, but reuse of multicolor powder is more complicated and confined to the initial application layer.^{15,16} Also, manufacturers have been slow to adopt powder coatings for the clearcoat layer, as the visual quality of powder clearcoat layers is thought to degrade over time. Finally, the effect of powder processes on life cycle cost has not been well-characterized,

¹⁴ Barberich, B., "Application of Color Powder Paint in the Automotive Industry." Master's Thesis, Massachusetts Institute of Technology (2004), p. 12.

¹⁵ *Ibid.*

¹⁶ Johnson, J.C., Joyce, J.R., and Kolarik, W., "Multidimensional Design, Multicolor Powder Primer," *Metal Finishing* 98 (2000) 10.

as the ability to reuse paint is at least partially offset by the increased material costs, need for specialized equipment to deliver and collect the powder, and increased compressed air usage needed to maintain the fluid properties of the powder. For a detailed review of powder coating process development and implications, the reader is directed to recent reviews by Nallicheri,¹⁷ DeWitt,¹⁸ and Beuerle.¹⁹

Finally, some additional recent developments beyond the continued deployment of powder coatings help to demonstrate the automotive industry's intense focus on the economic and environmental costs of the paint shop. For example, Ford has announced plans to use paint emissions to generate electricity in one of their assembly plants.²⁰ Also, BMW is using methane gas generated in a nearby landfill to power one of its paint shops in South Carolina.²¹ Finally, several companies, among them PPG, DuPont, and Mazda, have announced two or three layer "wet on wet" processes that eliminate one or more of the oven drying steps in the paint process.^{22,23} It is thus clear that the industry is committed to reducing the net economic and environmental impact of the paint shop.

1.5 Key Players in Automotive Coatings

The automotive coating industry can be broadly divided into material and equipment suppliers. Prominent material suppliers include BASF, DuPont, and PPG, while representative equipment suppliers include ABB, Dürr, Eisenmann, Fanuc, Geico, Giffin, Sames, and Taiki-Sha. In the following paragraphs, a brief overview of each of these suppliers and their respective industries is provided. All financial data cited below was compiled using public financial reports.

¹⁷ Nallicheri, R.A., "Automotive Painting: An Economic and Strategic Analysis." Master's Thesis, Massachusetts Institute of Technology (1993).

¹⁸ DeWitt, C.M., "A Holistic Approach to Automotive Powder Coating." Master's Thesis, Massachusetts Institute of Technology (1995).

¹⁹ Beuerle, J.E., "A Study of Electrostatically Applied Powder Paint in the Automotive Industry," Master's Thesis, Massachusetts Institute of Technology (1996).

²⁰ Migliore, P., "Ford Makes Electricity from Paint Fumes," *Automotive News*, September 12, 2005.

²¹ "BMW to Operate World's First Green Paint Shop," *Business Wire*, May 5, 2006.

²² Truett, R., "Automakers Struggle to Wipe Out Paint Shops," *Automotive News*, August 7, 2006.

²³ Yamane, T., *et al.*, "Development of Eco-Friendly Coating Technology Paints and Coating System for Primer / Top Coat Wet-on Coating," *Review of Automotive Engineering* **25** (2004) 1999.

This is not meant to be an all-inclusive list; rather, the goal is to provide the reader with a sense of the competitive landscape faced by suppliers to automotive paint shops.

Material Suppliers. The coating materials industry has experienced robust growth in recent years, expanding at an average rate of over 5% in the past five years to a value of \$70 Billion in 2005.²⁴ Within this industry, approximately 40% of revenues are derived from automotive and industrial coatings. The three companies cited above, DuPont, BASF, and PPG, provide a broad range of coating materials to the automotive industry. Respectively, they are headquartered in Delaware, Germany, and Pennsylvania. Both DuPont and BASF are diversified companies serving a variety of market segments, such as chemicals, plastics, electronics, energy, health care, and agriculture. Both companies have used acquisitions to drive their growth in the coatings segment. In 2006, BASF's Coatings Division accounted for 4.4% of their €52.6 billion in revenues. In contrast, approximately 22% of DuPont's \$27.4 billion in revenues in 2006 came from its Coatings & Color Technologies division. PPG is smaller and more specialized than BASF or DuPont, with 57% of its \$11 billion in revenues coming from coatings. All three companies cite increasing raw material costs and decreased sales growth in the North American automotive market as important risk factors, though strong growth in Asian automotive markets has helped offset the latter.

Equipment Suppliers. In general, equipment suppliers are much smaller and less diversified than material suppliers. ABB and Fanuc manufacture robotics and automation equipment, while Dürr, Eisenmann, Geico, Giffin, and Taiki-Sha are systems integrators, supplying entire paint shop production lines or large systems within the paint shop. Finally, Sames supplies specialized paint application equipment. ABB is the largest and most diversified company in this group, with 2005 revenues of \$22.4 billion. The company is headquartered (HQ) in Switzerland. ABB has two main divisions, Power Technologies and Automation Technologies, with the latter accounting for approximately 54% of revenue. They have the largest installed base of robotics in the world and are currently the third largest in terms of annual sales with an approximate 20% market share. In contrast, Fanuc (HQ: Japan) is a much smaller company, with its \$3.3 billion in revenues in 2006 derived entirely from automation and robotics. However, it is also the world leader in robotics sales, with approximately a 25% market share. Dürr, Geico, and Giffin are

²⁴ Data Monitor, *Global Paints & Coatings Industry Profile*, www.datamonitor.com (2005).

much smaller companies that specialize in automotive systems; Dürr (HQ: Germany) reported sales of €1.36 billion while Geico (HQ: Italy) and Giffin (HQ: Canada) are privately held and do not disclose sales figures. Next, Eisenmann and Taiki-Sha are also systems integrators, but more diversified than Dürr, Geico, or Giffin; in addition to their respective automotive coating businesses, Eisenmann (HQ: Germany) supplies equipment for a number of industrial processes (e.g. ceramics processing, conveyors, lumber drying) while Taiki-Sha (HQ: Japan) also supplies heating, ventilation, and air conditioning (HVAC) systems to the semiconductor and biomedical industries. Taiki-Sha reported 2006 revenues of approximately \$1.7 billion, while the similarly sized Eisenmann does not disclose sales figures. Finally, Sames, a subsidiary of Exel Industries (HQ: France, privately held), manufactures electrostatic paint applicators and dust removal equipment for paint shops. As would be expected, those equipment suppliers that primarily serve the automotive industry, particularly in North America, have been adversely affected by the recent struggles in this industry.

In Chapter 4, the nature of material and equipment supplier relationships is explored in further detail. With this brief industry overview in place, we now turn to the task of conducting the economic and environmental analysis necessary to choose a paint technology. The former is addressed with life cycle cost analysis, while the latter is addressed with life cycle analysis. In short, life cycle cost projections assess the economic impact of a manufacturing process while life cycle analysis measures the externalities associated with that process.

1.6 Life Cycle Analysis

Life Cycle Analysis (LCA) is used to measure the net environmental impact of a process, in terms of both energy usage and pollution generation. There have been several recent LCA studies in the field of automotive manufacturing, some of which focus on automotive coatings. First, Keoleian *et al.* calculated the total life cycle energy contributions for an average vehicle, showing the vast majority of energy consumption (85%) occurs while the vehicle is in use.²⁵ In contrast, only 14% of total energy consumption occurs during raw materials production and vehicle fabrication, and the remaining portion is consumed during end-of-life recycling. While energy consumption during fabrication is low when compared to energy consumption in the use

²⁵ Keoleian, G., *et al.*, "LCI Modeling Challenges and Solutions for a Complex Product System: A Mid-Sized Automobile," SAE Paper 982169, 1988.

phase, it is still a significant cost driver for automotive manufacturing, particularly in the paint shop. Furthermore, emissions of pollutants during raw material fabrication and automotive manufacturing may be significant. Therefore, Pappasavva *et al.* compared the total environmental impact of several different automotive coating technologies,^{26,27} examining either powder or solventborne primer, waterborne basecoat, and powder or solventborne clearcoat. These comparisons involved rating energy consumption during raw material fabrication and atmospheric emissions (VOCs, CO, SO_x, NO_x, and particulates) during material production and vehicle manufacturing. In general, the combination of a powder-based primer, waterborne basecoat, and powder clearcoat were shown to have the least environmental impact of all options considered, though each technical choice exhibited trade-offs. These trade-offs were also identified by Dobson, who compared solventborne and waterborne basecoat processes.²⁸ Dobson argues that solventborne basecoats, where the emissions are incinerated to destroy VOCs, are environmentally superior to waterborne basecoats because of the reduced energy consumption and increased transfer efficiency in solventborne processes.

The LCA studies described above highlight some challenges with this approach. First, as shown by the possible conflict between Dobson's and Pappasavva's studies, the environmental accounting necessary to calculate emissions and energy consumption is quite complex and cannot provide exact figures. Second, as discussed by Gaines and Stodolsky,²⁹ there are no standard methodologies for conducting these studies or interpreting their results. The ultimate goal of LCA would be the ability to link a specific metric to a quantifiable environmental or economic impact, and therefore present a unified framework for evaluating the environmental costs of manufacturing processes. However, calculation of the cost of externalities is difficult and controversial, though recent methods in use for SO_x (and, more recently, CO₂) emissions

²⁶ Pappasavva, S., "Addressing Environmental Concerns in the Automotive Industry," *Materials Research Society Symposium Proceedings* **895** (2006) 27.

²⁷ Pappasavva, S., *et al.*, "Characterization of Automotive Paints: An Environmental Impact Analysis," *Progress in Organic Coatings* **43** (2001) 193.

²⁸ Dobson, I.D., "Life Cycle Assessment for Painting Processes: Putting the VOC Issue in Perspective," *Progress in Organic Coatings* **27** (1996) 55.

²⁹ Gaines, L., and Stodolsky, F., "Lifecycle Analysis for Automobiles: Uses and Limitations," *Society of Automotive Engineers International Congress & Exhibition* (1997).

may provide the way forward. Here, companies' emissions of these substances are capped (by regulatory or legislative fiat), and companies can purchase or sell emissions credits on the free market to enable them to, respectively, pay for emission or profit from emission control measures.

1.7 Introduction to Cost Modeling

The use of cost analysis is widespread, as firms seek to measure the benefits or costs of decisions they may have made – these methods are in fact the basis of finance and managerial accounting. However, more powerful cost modeling techniques allow managers to link physical attributes of products or processes to outputs (e.g. cost, gross margin) and assess the sensitivity of these outputs to fluctuations in inputs (e.g. commodity prices, process time) to project the impact of decisions before they are made. In essence, these cost models then link product and process design to cost and profit. For example, Field and Kirchain have advanced process-based cost modeling³⁰ in which process conditions are linked to cost inputs via mathematical representation of the underlying chemical and process physics. Simple variations on this technique are often used in paint engineering; for example, the material cost incurred when coating a vehicle with a liquid material can be linked to process parameters via the relation below.

$$\text{Liquid Material Cost} = \text{Unit Cost} \times \text{Film Thickness} \times \frac{\text{Surface Area}}{\text{Transfer Efficiency} \times \text{Solids Content}}$$

General Motors also has a wealth of detailed process information linking deposition conditions to process quality, which can ultimately be linked to cost via rework or warranty costs. In addition to engineering relations such as the equation given above, a full process-based cost model could also include logical functions linking operational parameters to cost, such as overall capacity to the number of separate assembly lines or shifts required to meet this capacity.

In a process-based costs model, sensitivity analysis can be limited to simple “what if?” scenarios, but can also be extended to more complex Monte Carlo simulations. In this method, one or more inputs are varied randomly according to statistical distributions defined by the user,

³⁰ Kirchain, R., and Field, F, “Process Based Cost Modeling: Understanding the Economic Impact of Technical Decisions,” *Encyclopedia of Materials Science & Engineering*, Elsevier Science Pubs, Oxford, 2001.

and the variation of output parameters is tracked over a large number of trials (usually in the thousands). The implementation of Monte Carlo simulations in a spreadsheet program such as Microsoft Excel is described in Appendix A.

Chapter 2: Life Cycle Cost Estimator

In this chapter, the development of a tool to estimate life cycle costs is described. First, the architecture of the tool is detailed, and this cost estimator is used to generate to a comparison of different primer surfacer technologies. Finally, the limitations of this tool are described.

2.1 Motivation

The impetus for the development of this estimation tool arose from the need to compare different coating application technologies. As described in the previous chapter, the paint shop is a very large investment, usually thirty to fifty percent of the total plant cost. This investment is typically expected to last for twenty to forty years, with significant upgrades in capital equipment occurring every five to ten years. Additionally, operating costs are substantial; while the labor costs in the paint shop are generally lower than in general assembly, the paint shop consumes the vast majority of the total energy used in the plant's operation. Finally, once built, the paint shop's processes and capacity are relatively "sticky;" that is, these decisions are difficult to alter later. Regarding process alterations, conveyors are difficult to reroute, space is at a premium, and the equipment is often very large and requires extensive facilities connections. Regarding changes in capacity, while additional shifts can be added, the line speed cannot be increased indefinitely without compromising quality. Thus, the initial choices made in the design of the paint shop play a critical role in manufacturing costs for years to come.

2.2 Taxonomy of Manufacturing Costs

The first step undertaken in creating the life cycle cost estimation tool was simply to classify various manufacturing costs. Figure 2.1 details the taxonomy of costs in an automotive assembly plant.

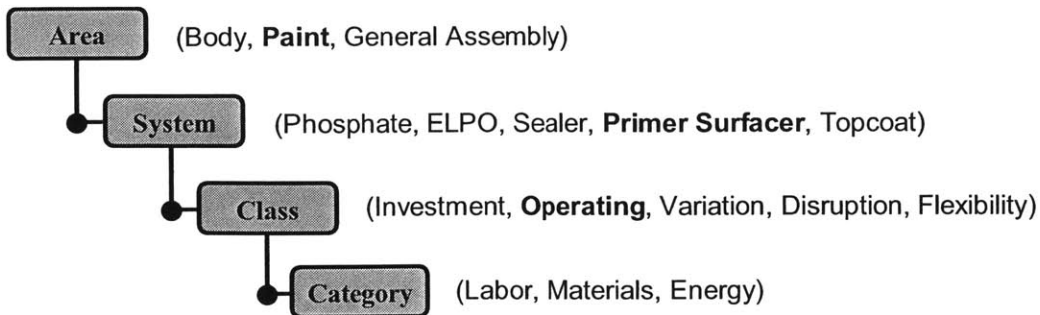


Figure 2.1. Taxonomy of manufacturing costs in an automotive assembly plant, revealing the hierarchy of cost classification and examples of entries along each level of the hierarchy. Items in bold are expanded in the level below.

The plant is divided into three different areas: body, paint, and general assembly. Each area has a number of different systems associated with it; the exact number depends on the level of granularity required in the model. For example, the paint shop can be divided into the five different systems shown in this figure, or further sub-divided as necessary (e.g. topcoat could be divided into basecoat and clearcoat). Next, each system's costs can be placed into five specific classes: investment, operating, variation, disruption, and flexibility. The investment class simply represents the one-time costs associated with building or maintaining the plant, while operating costs are incurred to run the plant over the years. While investment and operating costs are often sub-divided into different categories, these two classes represent the most common means of organizing cost projections. On the other hand, variation, disruption, and flexibility are not usually explicitly considered. In this work, the following definitions for these three additional cost classes are employed. The cost of variation is incurred when systems drift from their specification, resulting in problems such as rework, warranty costs, or unsatisfied customers. The cost of disruption comprises the costs associated with downtime in the plant. Finally, flexibility can either be a cost or a benefit – an initial cost may be incurred to install flexible manufacturing systems, and the benefits may be realized later.

Investment and operating costs can be represented simply as the product of the unit cost and the number of units (e.g. labor rate \times number of hours). However, variation, disruption, and flexibility cannot be represented in so simple a fashion. Rather, they need to be considered on a case-by-case basis, and may best be represented as cost differences between two or more

scenarios. The reasons behind this decision and implications, and additional methods to analyze these costs, will be outlined in Chapter 3.

Within this taxonomy, investment and operating costs were further decomposed into categories. In the cost estimator, pre-defined investment categories include equipment, installation, building space, and permits. Pre-defined operating categories include labor, material, utility, maintenance, and housekeeping.

While this approach seems rather simple, this framework can be used to classify costs in any area of automotive assembly. While more specific classification schemes could be useful for the paint shop, they would sacrifice the flexibility of this tool.

2.3 Description of Life Cycle Cost Estimator

The life cycle cost estimator was created in Microsoft Excel using built-in Visual Basic controls, enabling wide deployment throughout General Motors without requiring additional software. In essence, the cost estimation tool is used to generate specific scenarios, which can then be compared and rated using the tool described in Section 2.4. In the following section, the menus and resulting output for a sample scenario are briefly described. Rather than take the reader through the tedious process of documenting every detail of the cost estimator in this thesis, Appendix B walks the reader through generation of a cost model for a hypothetical factory system and presents some screenshots of the estimator at work. Also, the cost estimator was used to compare three different primer surfacer technologies, and the output is discussed in Section 2.5.

The estimator is a single file divided into five different worksheets. The first worksheet presents detailed annual cost estimates based on user inputs. The second worksheet defines depreciation schedules used for capital equipment. The third worksheet presents several tools for sensitivity analysis. Finally, the fifth and sixth worksheets detail investment and operating costs.

The first step the user must undertake when defining a scenario is to define basic inputs, which link unit costs to annual costs and net cash flows. These basic inputs include annual volume (decomposed into jobs per hour and annual work hours), annual work days, discount rate, tax rate, and time horizon.

Next, the user inputs line items, one at a time. Each line item is characterized by a unit cost, number of units, frequency of occurrence, year of first use (for depreciation purposes) or

occurrence (for operating costs), inflation rate (for recurring costs), and depreciation classification. For example, an operating cost could be incurred during every hour of production from year three onward, with a pre-defined annual inflation rate. In this model, annual costs are assumed to perfectly track inflation; hence, inflation rates input by the user are nominal.

After each line item is entered, the user clicks a button to compile life cycle cost, which is a multi-stage process. In the first step, each line item’s cost is converted to an annual cost and projected for each year. Table 2.1 summarizes the logic of each formula. The use of logical statements and active formulas over hard-coded values ensures that life cycle cost can instantly be updated during sensitivity analysis, greatly simplifying this task.

Table 2.1. Formulas used in cost estimator to link unit costs to annual cost in year j.

Cost Type	Frequency Basis	Formula Logic
One Time	Once at x years	If ($j = x$) then annual cost = unit cost × number of units
Recurring	Every x vehicles	If ($j \geq$ year of first occurrence) then annual cost = (unit cost × # units × annual volume / frequency) × (1 + inflation rate) ^j
Recurring	Every x hours	If ($j \geq$ year of first occurrence) then annual cost = (unit cost × # units × annual production hours / frequency) × (1 + inflation rate) ^j
Recurring	Every x work days	If ($j \geq$ year of first occurrence) then annual cost = (unit cost × # units × annual work days / frequency) × (1 + inflation rate) ^j
Recurring	Every x days	If ($j \geq$ year of first occurrence) then annual cost = (unit cost × # units × 365 / frequency) × (1 + inflation rate) ^j
Recurring	Every x months	If ($j \geq$ year of first occurrence) then annual cost = (unit cost × # units × 12 / frequency) × (1 + inflation rate) ^j
Recurring	Every x years	If ($j \geq$ year of first occurrence) and If (remainder(current year + year of first occurrence)/frequency = 0) then annual cost = (unit cost × # units) × (1 + inflation rate) ^j * in words, if the frequency of occurrence indicates that the cost is incurred in the current year

The formulas listed in Table 2.1 reveal that costs are annualized, an approximation that converts all costs to an annual basis. When costs are incurred frequently within a single year, this approximation is very accurate. However, when costs are incurred infrequently, this

approximation can result in slight errors. For example, a \$1.00 cost incurred every nine months will be converted to an annual cost of \$1.33 for all years of the model. In reality, the \$1.00 would be charged once in year 1 (9 months), once in year 2 (18 months), once in year 3 (27 months), and twice in year 4 (36 and 45 months). In this case, if higher accuracy is desired, the user can enter each instance as a separate line item charged to the appropriate year.

In the next portion of the life cycle cost calculation process, depreciation is calculated for each line item, which is used later for tax accounting purposes. The formulas are preset to use lookup functions to match the line item's row with the selected depreciation class on the depreciation workbook. For a given line item, the logic of the formula is:

If (current year \geq year of first use or occurrence) then depreciation cost = unit cost \times # units \times depreciation factor for current year (obtained by matching current year to year on depreciation table and reading the depreciation factor at that year)

The logic governing depreciation cost did not allow for the combination of depreciation with recurring costs, since a single compact statement governing the logic of this circumstance could not be derived.

After annual costs and depreciation are calculated for each line item, net costs are calculated for each year. Net costs are the annual costs after considering depreciation and taxes. Generally, for a given year

$$\text{Net Income} = \text{Revenue} - \text{Operating Costs} - \text{Depreciation}$$

When project revenues are zero (e.g. when we are making factory investments),

$$\text{Net Income} = - \text{Operating Costs} - \text{Depreciation}$$

Then,

$$\text{Tax} = \text{Net Income} \times \text{Tax Rate} = (- \text{Operating Costs} - \text{Depreciation}) \times \text{Tax Rate}$$

$$\text{Net Income After Taxes} = \text{Net Income} - \text{Tax}$$

$$\text{Net Income After Taxes} = (\text{Operating Costs} + \text{Depreciation}) \times \text{Tax Rate} - \text{Operating Costs} - \text{Depreciation}$$

$$\text{Net Cash Flow} = \text{Net Income After Taxes} + \text{Depreciation} - \text{Investment}$$

$$\text{Net Cash Flow} = (\text{Operating Costs} + \text{Depreciation}) \times \text{Tax Rate} - \text{Operating Costs} - \text{Investment}$$

In the cost model, Net Cost is defined as the negative of Net Cash Flow. Therefore,

$$\text{Net Cost} = \text{Investment} + \text{Operating Costs} - \text{Tax Rate} \times (\text{Operating Costs} + \text{Depreciation})$$

After net costs are determined for each year, discounted net costs are then calculated. For a cost i years from today,

$$\text{Discounted Net Cost} = (\text{Net Cost}) \times (1 + \text{Discount Rate})^i$$

Finally, life cycle cost is then simply the sum of discounted net costs for each year of interest.

$$\text{Life Cycle Cost} = \sum_i (\text{Discounted Net Costs})$$

While life cycle cost represents a comprehensive projection of investment and operating costs over the life of the project, a single cost estimate is a deceptive quantity given the uncertainties inherent in the projection process. As a result, a series of sensitivity analysis tools were developed within the life cycle cost estimator that allows the user to quickly provide bounds for life cycle cost, rather than a single number.

The first of these sensitivity analysis tools allows the user to enter simple bounds for unit cost, number of units, frequency of occurrence, year of first use or occurrence, or inflation rate. Any number of inputs can be selected at one time. The resulting output is the resulting best case and worst case life cycle cost, for each set of bounds taken individually and in aggregate. This tool thus provides a quick check on the bounds of life cycle cost in the best and worst case.

The next component of sensitivity analysis allows the user to determine the leverage of individual inputs. This enables quick ranking of life cycle cost sensitivity to variations in each input. Input leverage is defined as the percent change in life cycle cost resulting from a one percent change in unit cost (equivalently, the first derivative of life cycle cost with unit cost). The resulting output is an ordered ranking of input leverage for each input providing guidance on how changes in unit cost will affect the resulting life cycle cost. This component of sensitivity analysis is important for two reasons: it provides insight into which costs are the main drivers of life cycle cost and therefore which costs must be correctly estimated to provide accurate life cycle cost projections.

Next, another tool allows the user to view the sensitivity of life cycle cost to variations in annual volume, decomposed into jobs per hour and annual work hours. The user is prompted to enter the range over which to vary these inputs, as a percentage of the nominal, and a graph is automatically generated that plots life cycle cost over this range. This tool thus allows the user to quickly see how changes in volume affect life cycle cost. As will be discussed in Section 3.3,

production volume over the years can vary widely from the originally planned capacity, making this an important component of sensitivity analysis.

Finally, the user can elect to do Monte Carlo analysis, enabling stochastic variation of the unit cost, number of units, frequency of occurrence, year of first use or occurrence, or inflation rate of any number of inputs. The user chooses the parameter to vary the statistical distribution that defines the variation (uniform, triangular, or normal), and the parameters that characterize the variation (respectively: minimum and maximum; minimum and maximum, with the peak occurring at the nominal value; and mean and standard deviation). Random inputs are then generated over a pre-set number of trials, and a histogram of life cycle cost is presented.

Taken together, these sensitivity analysis tools avoid the trap of false precision provided by presenting a single life cycle cost.

2.4 Scenario Comparisons

A separate tool was created to compare different scenarios generated in the life cycle cost estimator and rate them with financial metrics. In isolation, these metrics do not apply to an investment, where only costs are occurred, but relative differences in investments enable determination of these values. The first step is to calculate relative cash flows for scenario x over each year, taken with respect to the baseline scenario.

$$\text{Relative cash flow} = (\text{Net Cash Flow})_x - (\text{Net Cash Flow})_{\text{Baseline}}$$

Defining net cash flow as the negative of net cost, we can arrive at an equivalent expression linking relative cash flow to cost.

$$\text{Relative cash flow} = - [(\text{Net Cost})_x - (\text{Net Cost})_{\text{Baseline}}]$$

These relative cash flows define the annual cost (if negative) or savings (if positive) of scenario x relative to the baseline. Using these relative cash flows, each scenario (relative to the baseline) can then be rated. First, net present value (NPV) can be calculated as below, where i represents a given year.

$$\text{NPV} = \sum_i (\text{Relative Discounted Cash Flows})$$

An NPV greater than zero indicates that, when compared to the baseline, project i reduces total cost and should thus be selected. Next, internal rate of return (IRR) is calculated.

$$0 = \sum_i (\text{Relative Undiscounted Cash Flows}) / (1 + \text{IRR})^i$$

IRR is the discount rate that results in an NPV of zero for a given set of cash flows. In some cases, IRR may not converge or may be less than zero, particularly when initial relative cash flows are much greater in magnitude than later cash flows. In general, IRR is more problematic than NPV because of the complex decision rules (outlined in Table 2.2 below) and the possibility that IRR does not exist for a given scenario, as IRR is not defined if NPV is less than zero. However, IRR does not depend on discount rate, eliminating the assumption of a static discount rate over the life of the project.

Table 2.2. Logic defining the interpretation of internal rate of return.

Undiscounted Relative Cash Flow Pattern	IRR Decision Rule
Initially negative, then positive	Invest if IRR > Discount Rate
Initially positive, then negative	Invest if IRR < Discount Rate
Several sign changes	IRR may not be uniquely defined

Finally, payback is simply the length of time required to recoup a given investment, which means that payback is only a valid metric when NPV is greater than zero and when relative cash flows are initially negative and eventually positive. This occurs when comparing a scenario with high initial cost and low operating cost to a scenario with high operating cost and low initial cost. There are two types of payback: simple and discounted. Simple payback uses undiscounted relative cash flows while discounted payback uses discounted relative cash flows. If NPV is greater than zero and relative cash flows are initially positive and eventually negative, payback is essentially instantaneous. If NPV is less than zero, payback will not be defined.

2.5 Application of Life Cycle Estimator

In the following section, the life cycle cost estimator described above is used to compare three different primer surfacer application technologies. These three methods entail solventborne, waterborne, and powder primer surfacer application. To briefly recap: in solventborne primer application, the paint is dissolved in organic solvents, which evaporate during the curing process. Solventborne paint application was long the dominant technology in the automotive industry, though there has been a steady shift away from this method over the past ten to twenty years in

an effort to curtail VOC emissions. Still, every major automotive manufacturer uses solventborne coatings on at least some of their products, and VOC emission reductions have been achieved in solventborne coating processes through increases in the solids content of the paints and incineration of paint emissions. In waterborne primers, a portion (but not all) of the organic solvents is replaced by water. When compared to solventborne paints, waterborne paints are considered to be environmentally friendly and are relatively well-established. The shift from solventborne to waterborne coatings also does not entail great changes in factory equipment, though the rheology of waterborne paint is slightly different than that of solventborne paint. The primary process change is the need for a flash-off step (a low temperature, short duration bake) to evaporate the water. Finally, powder primer represents a major technological shift away from liquid paints, but this technology has by far the lowest VOC emissions of any coating method.

The goal of this portion of the study is to determine which of these methods yields the lowest life cycle cost given the best information currently available. The costs gathered for this section comes from discussions with GPPC staff, data from existing plants, and examination of historic trends; much of the underlying data was collected by experts at the GPPC.³¹ The systems were chosen to be as similar to one another as possible given the different technologies, and costs were projected over a twenty year horizon. Rather than reference actual numbers, most of this section will be used to point out qualitative trends and, when applicable, costs will be indexed relative to a baseline to protect confidentiality.

Before comparing life cycle cost data, the basic parameters of the coating system must be defined. The basic inputs used in this model are given in Table 2.3 below.

Table 2.3. Basic inputs common to the three different primer surfacer deposition systems compared in this section.

Jobs per hour	50
Annual production hours	5640
Annual volume	282,000
Annual work days	235
Discount rate	15%
Corporate tax rate	37.5%

³¹ Schoening, P., and Leddy, L., Personal Communication (2006).

Time horizon	20 years
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Annual volume was chosen to be representative of a three shift plant, appropriate for a high volume product. Film thicknesses, solids content, and transfer efficiency were chosen relative to standard values for each technique, and each system was assumed to coat an identical surface area. These quantities are described in Table 2.4 below. The stated transfer efficiency for powder assumes that powder is being continuously reclaimed, an assumption that will be tested later.

Table 2.4. Comparison of film thickness and transfer efficiency for the three methods of primer surfacer application compared in this section.

Method	Film Thickness (mil)	Solids Content	Transfer Efficiency
Solventborne	1	65%	80%
Waterborne	0.8	30%	85%
Powder	2.5	N/A	95%

The equations that relate total usage (in gallons for liquids or pounds for powder coatings) are:

$$\text{Liquid usage} = \text{Film Thickness} \times \text{Surface Area} / \text{Transfer Efficiency} / \text{Solids Content}$$

$$\text{Powder usage} = \text{Film thickness} \times \text{Surface Area} \times \text{Specific Gravity} / \text{Transfer Efficiency}$$

The baseline life cycle costs are given in Table 2.5 below, and analysis of investment and operating costs are described in the following paragraphs.

Table 2.5. Comparison of twenty year life cycle costs for the three primer surfacer technologies considered.

Method	Normalized Life Cycle Cost	Normalized Investment Cost	Normalized Operating Cost
Solventborne	1.00	1.00	1.00
Waterborne	1.02	0.96	1.18
Powder	0.97	0.98	0.97

First, Table 2.5 reveals that there are not dramatic differences in cost among the three methods. In terms of equipment investment, each of these methods is within 5% of each other,

as the additional specialized equipment required to support one technique over another tends to be offset by other pieces of equipment no longer required. For example, solventborne systems require extensive booth abatement, while waterborne systems require a lengthy heated flash tunnel, and powder systems require a distribution and collection system to reclaim the powder. Operating costs display more divergence than investment costs, with waterborne primer commanding nearly a 20% premium over powder primer. This difference can largely be attributed to differences in material cost; specifically, the relatively high cost of waterborne primer, given its low solid content. Material costs for powder are kept low by use reclaimed powder, offsetting the high cost of virgin powder. Powder-based application systems with reclaim also eliminate the associated with cleaning solvent (required to remove residual paint from equipment) and waste paint disposal. Labor, a significant cost driver, is roughly identical for each deposition system.

Taken together, the similarities in investment and operating costs yield similar twenty year life cycle costs for these three methods. Powder primer has the lowest life cycle cost, while the life cycle cost of solventborne primer is 3% above that of powder and the life cycle cost of waterborne primer is approximately 5% above that of powder. Given these relatively minor differences in life cycle cost, it is worth considering the sensitivity of these costs to various assumptions. The following analyses were chosen to be illustrative of the long-term trends that may occur that could affect life cycle costs, and demonstrate how the cost estimator could be used to analyze these trends, and were thus not intended to be an exhaustive analysis of various scenarios.

The most simple sensitivity analysis involves the effect of possible changes in the operating conditions of powder primer systems. First, there is often the perception that the use of reclaimed powder may cause quality problems. If one were to eliminate the use of reclaimed powder, transfer efficiency would be reduced dramatically and the twenty year life cycle cost would rise by 9%. Thus, under these conditions, powder becomes the most expensive deposition method of the three. A second possible change in operating conditions would involve increases in the thickness of the primer layer, often perceived to ensure a high level of surface quality. If this change were to occur, the twenty year life cycle cost rises by 3%, placing costs on par with solventborne and coatings. Thus, for powder to remain a cost effective option, reclaimed powder

must be utilized and plant management needs to maintain thickness at the specification limits defined for the process.

The second component of sensitivity analysis describes how changes in material and energy costs would affect life cycle cost, using the best case / worst case analysis tool described in Section 2.3. Since solventborne and waterborne coatings are relatively well-established, it is unlikely that their material costs will drop considerably. However, powder costs have dropped rapidly over the past decade, so further drops are conceivable. Thus, an annual drop in powder costs of 2% was chosen. Regarding energy costs, each method was tested with a flat 5% annual increase in all utility costs (natural gas, compressed air, electricity, heated water, and chilled water), a relatively steep inflation rate but not outside the realm of possibility. The results of this analysis are given in Figure 2.2.

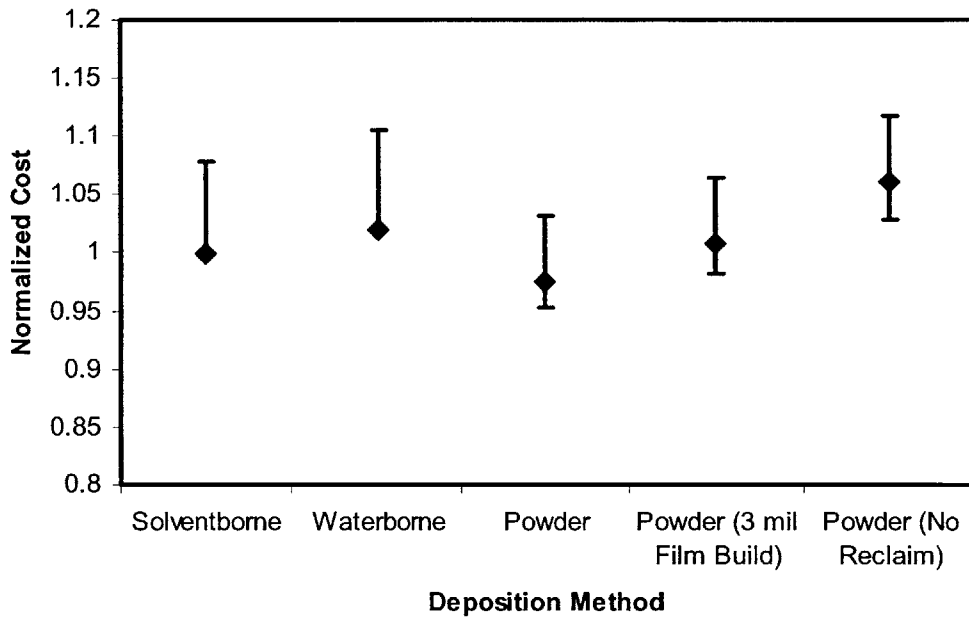


Figure 2.2. Comparison of the range of twenty year life cycle costs of three primer application technologies with increasing energy costs and, in the case of powder deposition, decreasing material costs.

This analysis reveals very little overlap between waterborne and powder primer systems, indicating that, under the conditions of rising energy costs, powder primer systems (with standard coating thicknesses and using reclaimed powder) will yield a lower life cycle cost than waterborne primer systems. Also, if powder costs were to decrease in the future (which may be expected for a new technology), powder primer systems with higher film builds can be cost-

competitive with solventborne systems. Finally, Figure 2.2 appears to indicate that rising energy costs affect each method more or less identically.

To further investigate the impact of energy costs, input leverages can be compared. Differences in input leverage reveal that changes in the unit cost of line items will affect systems differently. The results of this analysis are summarized in Figure 2.3, which compares leverage of selected inputs.

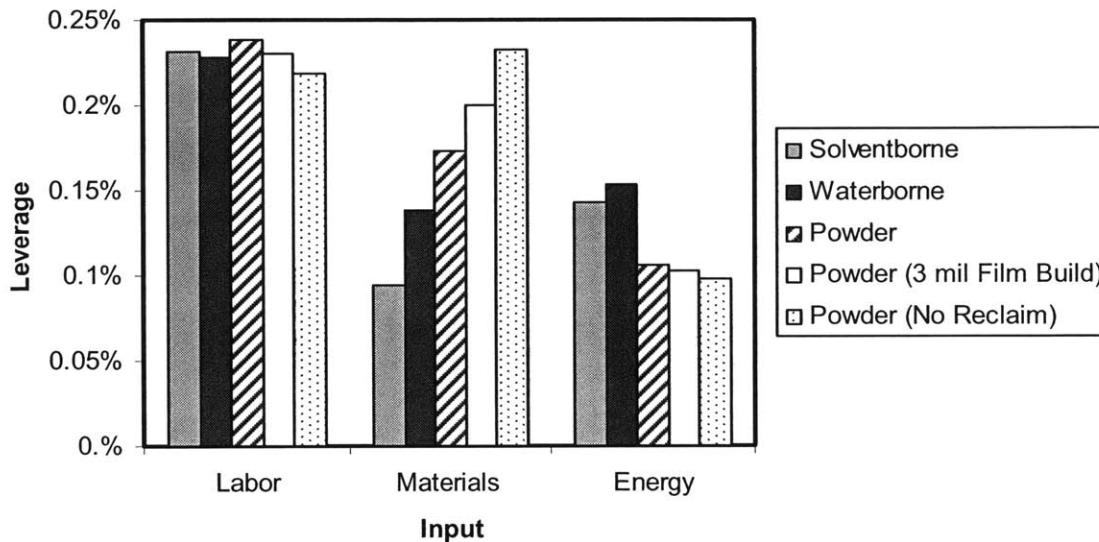


Figure 2.3. Comparison of input leverage of labor, paint material, and energy for the three primer surfacer deposition methods. The leverage for energy is the sum of leverages for natural gas, electricity, compressed air, chilled water, and hot water consumption.

This figure reveals that, when compared to liquid systems, powder systems are highly dependent on material costs, since powder material is more costly. All systems display similar dependence on labor, as staffing requirements are nearly identical. Liquid systems tend to have higher dependence on energy cost, largely driven by the increased energy required for the flash-off step.

Finally, the effect of changing volume can be explored with Monte Carlo analysis. For this analysis, annual production volume was varied by independently varying annual production hours and the jobs per hour to be processed. Annual production hours were varied according to a truncated triangular distribution, with a minimum of 3500, a most likely value of 5640, and a maximum of 5640. The maximum annual production hours was kept at 5640 under the assumption that additional production time could not easily be added to a three shift plant. Line speed (jobs per hour) was varied according to a triangular distribution, with a minimum of 35,

peak of 50, and maximum of 60. With these assumptions, the annual volumes could then vary between 122,500 to 338,400, a very wide range. The implicit assumption in this analysis is that the plant is more likely to be under-utilized than over-utilized. In each analysis trial, a random volume is input and used over every year in the projection – an unlikely occurrence, but remedied by running many trials. The results of this analysis are given in Figure 2.4.

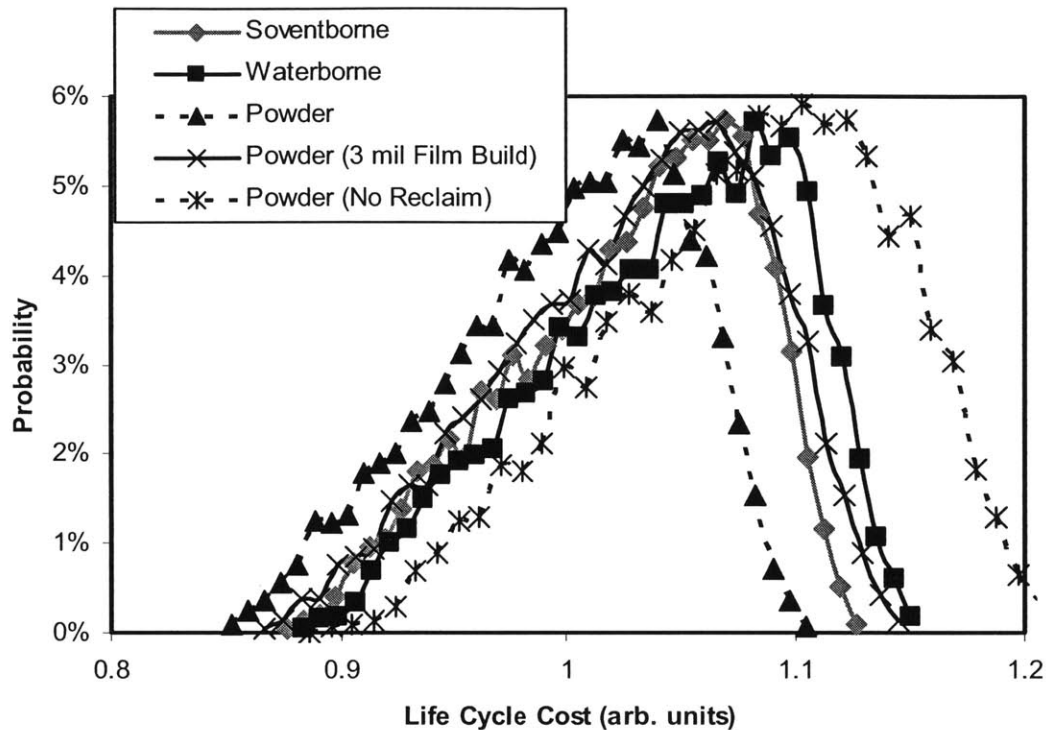


Figure 2.4. Histograms of twenty year life cycle cost resulting from the Monte Carlo analysis described above. The analysis was run for each technique over 10,000 trials.

Because of the similar operating costs for each deposition method, the spread in life cycle cost for each technique is similar, though the clear benefit of conserving powder material is evident by the shift in the histogram to the right when film thickness is increased or the powder is not reclaimed.

2.6 Tool Limitations and Hidden Costs

The comparisons described in section 2.5 dealt solely with investment and operating costs, and revealed significant overlap between the three primer surfacer deposition techniques. However, other factors might further separate the life cycle costs of each method, particularly

additional costs or benefits described by the hidden costs outlined in section 2.2. In the next chapter, methodologies for analyzing hidden costs will be described.

Chapter 3: Modeling Hidden Costs

In the following sections, hidden costs are considered. Since the situation-dependent nature of these costs precludes standardized analysis, frameworks for analysis of the cost of variation, cost of disruption, and cost or value of flexibility are instead presented. In each case, a sample cost calculation is given, with data either taken from actual product figures or generated via Monte Carlo simulations using reasonable initial assumptions.

3.1 Cost of Variation

The cost of variation is incurred when deviation from process specifications result in a degradation in product quality. This is potentially the simplest hidden cost to analyze, as straightforward statistical analysis of historic data will reveal this cost. The main barrier to this analysis is the difficulty in correlating variation in a specific system to warranty costs that are typically collected after the fact and are thus reflective of the variation of and interactions amongst many systems.

The following paragraphs provide an illustrative example of the statistical analysis required to analyze this class of cost, which can then readily be extended to other data sets. In this example, we test whether differences in the performance of liquid and powder primer surfacer systems may lead to higher warranty costs for one method over the other. To undertake this analysis, then, the null hypothesis (H_0) is that the average warranty costs for vehicles coated with powder primer surfacer (WC_{PPS}) are equal to the average warranty costs for vehicles coated with liquid primer surfacer (WC_{LPS}), while the alternative hypothesis (H_a) is the reverse:

$$H_0: WC_{PPS} = WC_{LPS}$$

$$H_a: WC_{PPS} \neq WC_{LPS}$$

Figure 3.1 presents normalized warranty costs for General Motors' North American paint shops in 2004.



Figure 3.1. Normalized warranty cost comparison for vehicles coated with powder- and solvent-based primer surfacer.

To test the null hypothesis, the relevant test statistic is

$$t = \frac{WC_{LPS} - WC_{PPS}}{S_p \sqrt{\frac{1}{n_{LPS}} + \frac{1}{n_{PPS}}}},$$

where n_{PPS} is the number of data points for powder, n_{LPS} is the number of data points for liquid, and S_p is the pooled variance.³² The pooled variance is calculated in the formula below:

$$S_p = \frac{(n_{LPS} - 1)\sigma_{LPS}^2 + (n_{PPS} - 1)\sigma_{PPS}^2}{n_{LPS} + n_{PPS} - 2},$$

where σ_{LPS} is the standard deviation of liquid primer surfacer systems and σ_{PPS} is the standard deviation of powder primer surfacer systems.³³ The resulting test statistic can then be compared to a t-distribution to confirm or reject the null hypothesis.

Using this analysis, the test statistic is -0.14. Note that there is an apparent outlier in the warranty costs for powder-coated vehicles, attributable to a single plant with a demanding coating process. However, when this outlier is removed, the test statistic is 0.24. In either case, for standard confidence levels (e.g. 95%) we fail to reject the null hypothesis; that is, this analysis demonstrates that, using the data at hand, warranty costs for vehicles coated with

³² Montgomery, D.C., *Introduction to Statistical Process Control*, Fourth Edition. United States, John Wiley & Sons (2004), p. 118.

³³ *Ibid.*

powder primer surfacer are no different than warranty costs for vehicles coated with liquid primer surfacer. There are of course limitations with this analysis. For example, vehicles coated with powder primer surfacer may be subject to different standards when deciding whether or not repairs are warranted, or these different primer technologies may be used to serve entirely different customer segments. Finally, warranty costs could be offset by process modifications that may increase operating costs elsewhere in the paint shop. However, this sort of statistical analysis provides at least an important first-pass assessment of the cost of variation, and similar analysis can be extended elsewhere if the data is available.

3.2 Cost of Disruption

Analysis of the cost of disruption is more open-ended than the calculation of the cost of variation described above. Generally, disruption costs are incurred whenever an interruption in the production line affects the throughput of the plant, as this disruption affects the ability of the plant to convert inventory into cash flow. Disruption also occurs whenever a process change results in increased rework or warranty costs. This cost can play a critical role in assessing the merits of different factory investments, particularly since investment and operating costs of competing technologies are often very different.

One possible method to evaluate the cost of disruption would be to correlate downtime events of the system under consideration with lost production time, and determine the cost of this lost production time. However, this type of analysis is fraught with complications. First, downtime events are inherently unpredictable, and past events may not correlate well with future occurrences. In particular, a single catastrophic event, which should occur with low frequency, could dominate these estimates. Second, the production data for the system of interest may simply not exist, particularly for new equipment. Equipment suppliers may be able to furnish their downtime estimates, but data from the laboratory is notoriously difficult to translate into a production environment, with multiple operators and interdependent systems. Finally, automotive plants employ extensive buffers, offline processing capabilities, and scheduled maintenance intervals to help maintain flow through the plant during normal production hours. Thus, an isolated event may not be sufficient to interrupt production. Given these complications, this work uses another framework for analyzing the cost of disruption.

To simplify the analysis required to derive the cost of disruption, a second method can be employed wherein focus is placed on the bottleneck in the process. As described by Goldratt's Theory of Constraints, lost time at a bottleneck is equivalent to lost production time for the entire plant, while lost time elsewhere will not affect overall flow through the plant.³⁴ Thus, extending this approach, the cost of disruption could simply be expressed as the amount of time lost at the bottleneck multiplied by the potential revenue lost during this time. On the other hand, when non-bottleneck systems fail, no cost of disruption would be incurred provided flow through the bottleneck is not affected. While this theory offers a simple framework for maximizing flow through a plant, it is more restrictive than the original description of the cost of disruption outlined in Section 2.2. For example, when a non-bottleneck system fails in an automotive plant, significant resources may be expended to bring this system back on-line. Additionally, new systems (whether or not they are bottlenecks) incur significant learning effects that may not be captured using the analysis suggested by the Theory of Constraints. Thus, this method of analyzing the cost of disruption was also rejected.

The final method of analysis utilizes a top-down approach derived from experience curves and is the simplest of the three. Experience curves describe the reduction in effort required to manufacture an item as the cumulative output of that item increases. Effort can be a variety of metrics, such as direct cost, labor content, manufacturing cost, or throughput time. This phenomenon, first observed at the Wright-Patterson Air Force base in 1936³⁵ and later extended by Bruce Henderson at the Boston Consulting Group in the 1970s,³⁶ has been shown to apply to a wide variety of manufacturing systems. The general shape of an experience curve is given in Figure 3.2 below.

³⁴ Goldratt, E. *The Goal*, Third Revised Edition. Great Barrington, MA, North River Press (2004).

³⁵ Wright, T., "Factors Affecting the Costs of Airplanes," *Journal of the Aeronautical Sciences* 3 (1936), 122.

³⁶ Henderson, B., "Perspectives on Experience," Boston, MA, Boston Consulting Group (1972).

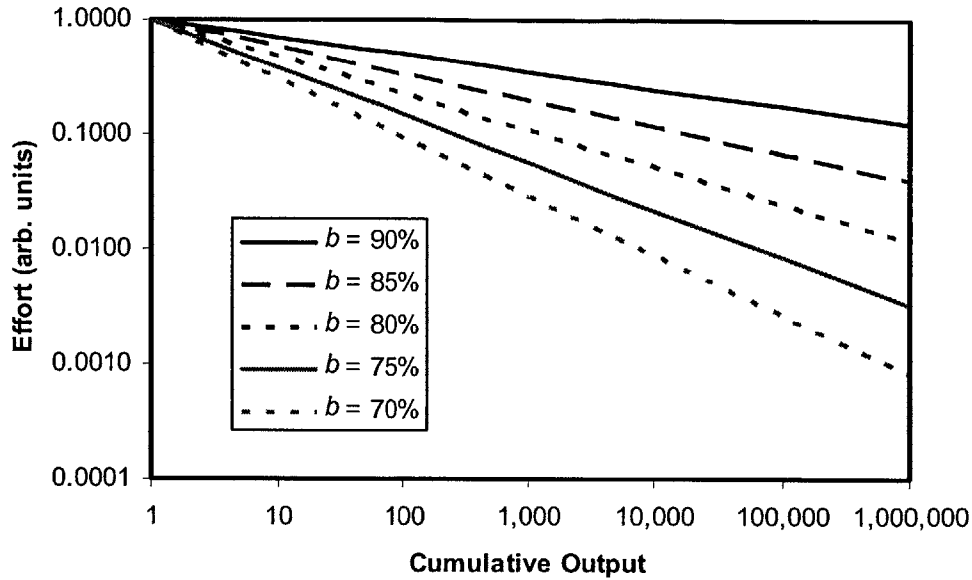


Figure 3.2. General representation of an experience curve, using a variety of values for b . Both axes are logarithmic scales.

The equation governing experience curves is

$$y_x = y_1 x^z,$$

where y_x is the effort required to produce the unit x th unit, y_1 is the effort required to produce the first unit, $z = \ln(b) / \ln(2)$, and b is a constant experience curve factor.³⁷ The experience curve factor b describes the percentage of effort that is retained when production output is doubled. For most manufacturing systems, b is in the range of 70% - 90%.³⁸ The primary danger in analyzing experience curves is the potential intermingling with economies of scale (where fixed costs are amortized over increasing output). Thus, this method is best employed in areas where scale economies do not apply.

Because the experience curve describes an aggregation of phenomena that reduce manufacturing effort, this is a simple and powerful method with which to analyze the cost of disruption, and applicable to many different areas in automotive manufacturing. For example, two types of experience curves, taken directly from General Motors manufacturing data, are given in Figure 3.3.

³⁷ Kalligeros, K., "Platforms and Real Options in Large-Scale Engineering Systems." Ph.D. Thesis, Massachusetts Institute of Technology, 2006, p.30.

³⁸ *Ibid*, p. 31.

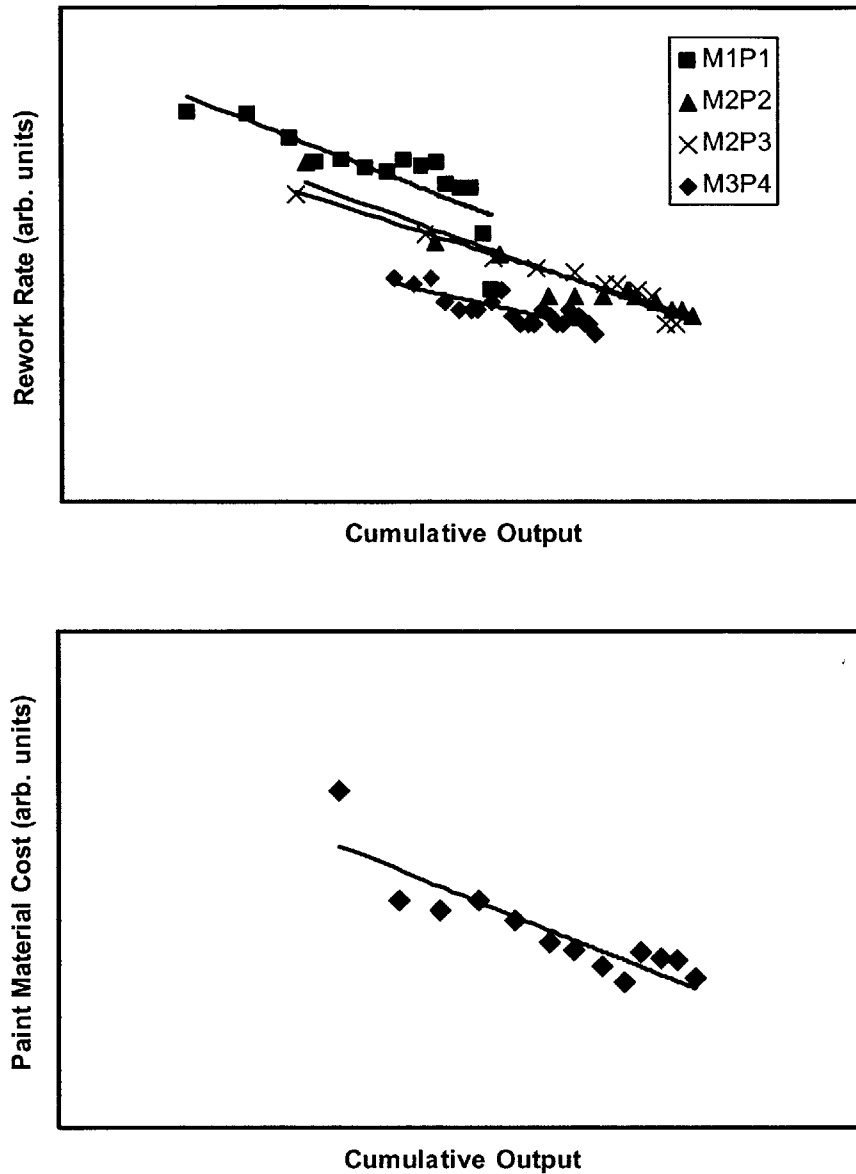


Figure 3.3. Sample experience curves from General Motors manufacturing. (a) Reduction in rework rate of vehicles after new model introduction. The M designation refers to vehicle platform for those models, while the P designation refers to the plant at which production occurs. (b) Reduction in paint material costs after new model introduction. Both axes are logarithmic scales.

Figure 3.3(a) shows the evolution of rework rate for several new model introductions, indicating that rework rates show an initial spike and gradual drop as production output increases. For all curves, the fitted experience curve factor b was between 75% and 85%. Generally, the new models that showed the highest initial spike in rework rates were those that differed most from

their predecessors, either in vehicle design or production methods. Note that platform 2 was produced in both plant 2 and plant 3 (M2P2 and M2P3), and their rework rates are nearly identical. This indicates that learning has been effectively transmitted between the two plants. Figure 3.3(b) shows the evolution of per-vehicle paint material cost with cumulative output in one of the plants and models cited in Figure 3.3(a) (M1P1). While per-vehicle labor and warranty costs display strong economies of scale, as shown in Figure 3.4, per-vehicle paint material costs do not, indicating that this drop can be attributed to the cumulative effect of experience. In Figure 3.3(b), the fitted experience curve factor b was equal to 86%. Both of these examples demonstrate the strong cumulative effect of experience, and are both independent of any economies of scale that may be at play.

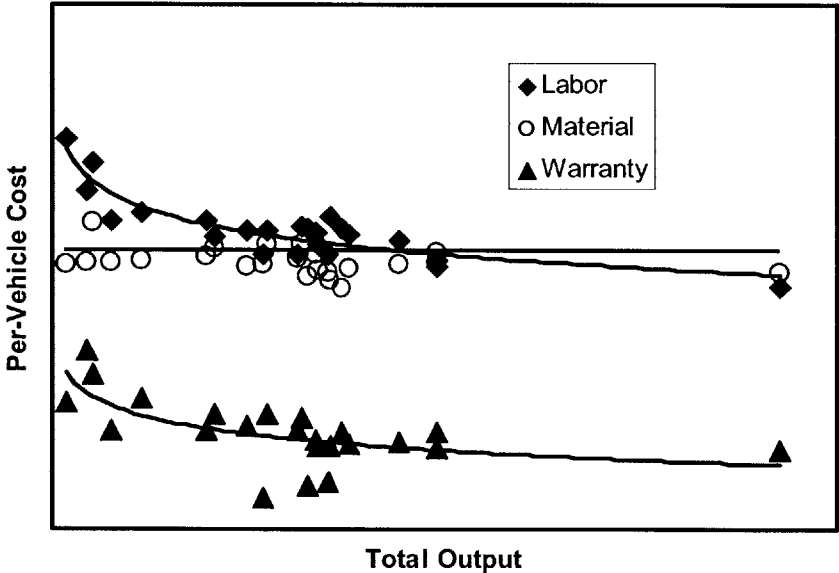


Figure 3.4. Comparison of per-vehicle labor, material, and warranty costs for selected General Motors paint shops. Data is taken from 2004 for United States and Canadian plants. Labor and warranty costs display strong economies of scale while material costs do not.

Before translating experience curves to the cost of disruption, two notes of caution are warranted. First, as noted above, reductions in effort that accompany increased experience are sometimes difficult to separate from economies of scale. Great care should be taken to ensure that the cost reduction being observed cannot solely be attributed to the amortization of fixed costs over increasing output. Second, experience curves, particularly those that cover broad swaths of data, often represent an aggregation of phenomena with their own individual

experience curves and values of b . For example, a new piece of equipment processing a new design may have two relevant experience curves -- one associated with learning how to produce the design and the other with using the equipment. Also, the rate of learning may change with turnover of personnel within an organization.³⁹ Therefore, when making extrapolations from past data, it is imperative to consider whether the sorts of actions that reduced effort in the past will continue in the future.

With these disclaimers in mind, to translate an experience curve to the cost of disruption, one simply needs the initial spike in effort, the experience curve factor b , and the target level of effort. For the initial spike in effort, similar situations to the one in question can serve as a valuable guide. When the basis of effort is not cost, as in Figure 3.3(a), effort must be translated to cost. For example, one could translate rework rate to cost by determining the average cost to rework a vehicle in each of the situations described in Figure 3.3(a). For the experience curve factor b , if previous estimates are not available, a rate of 85% can often be assumed without too much error. Finally, the target level of effort is often dictated by management policy. With these values in place, one can integrate the area under the experience curve to derive an estimate for the cost of disruption, as shown in Figure 3.5 below.

³⁹ Argote, L. *Organizational Learning: Creating, Retaining, and Transferring Knowledge*, Boston, Kluwer Academic (1999), p. 22.

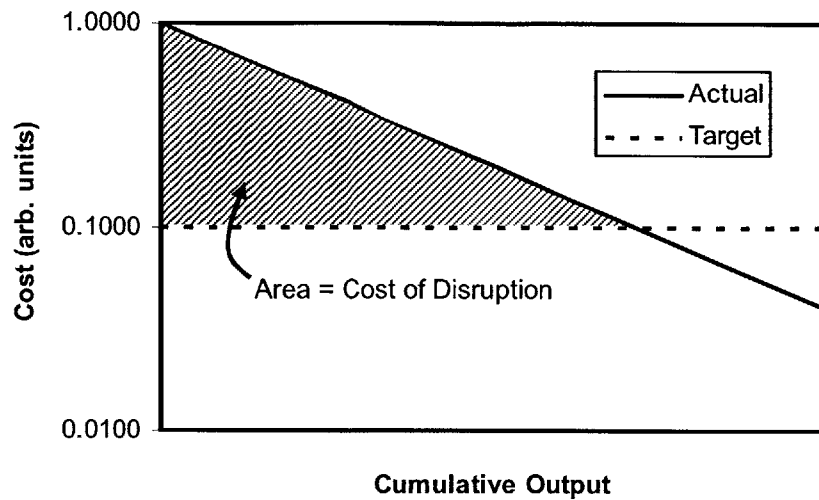


Figure 3.5. Illustration of the cost of disruption, derived from an experience curve and a target effort for the process in question. Both axes are logarithmic scales.

While this estimation method may seem crude, it quickly allows one to estimate the magnitude of the cost of disruption and compare it to the life cycle cost described in the previous chapter. If the cost of disruption appears significant, more detailed estimation methods can be employed.

3.3 Cost and Value of Flexibility

The final class of hidden cost to be considered is the cost of flexibility, which must be balanced against its benefit. In general, these costs and benefits are realized when a manufacturer chooses to pay an initial premium for flexibility to derive some later benefit. These situations represent so-called “real options” and can be analyzed using techniques analogous to financial options. In this section, Monte Carlo analysis will be employed to calculate option value for two distinct situations. In the first case, the cost and value of having the flexibility to process two different vehicle platforms in a single paint shop will be considered. In the second case, the value of staging upgrades to operations in two different facilities, where the upgrade in one facility is delayed until it is evaluated in a second facility, is determined. These situations are meant to provide a guide for how the cost and value of flexibility can be determined, and the exact numbers used are highly situation-dependent.

The cost and value of flexibility is a particularly relevant topic for paint shops, as they are the inherently the most flexible areas of automotive assembly.⁴⁰ Hypothetically, any vehicle can be coated in any given paint shop, provided that the coating equipment and conveyors will accommodate the vehicle and the desired color palette is available. Furthermore, though different coating processes are chosen for different plants and vehicles, there is a large degree of commonality between processes. Therefore, this is an area of automotive assembly in which the cost of flexibility could be low and the benefits may be quite high. However, practical limitations mean that today's paint shops are not completely flexible. A key question remains as to how much additional flexibility is economically justified.

3.3.1 Case 1: Processing different vehicle platforms in a common facility

In this example, a new paint shop has been planned as part of a new assembly plant devoted to a new platform, and the crux of the decision is whether this new paint shop should accommodate a second (existing) vehicle platform as well. If the second vehicle platform were accommodated in this plant, an existing plant could be closed. This sort of aggregation of different products into an existing plant has been cited as a means of reducing chronic excess capacity, holding steady at 20% over the past fifteen years and plaguing the entire automotive industry.⁴¹ However, there will be a premium for this flexibility. First, the facility cost will increase, as the paint shop needs to be designed with a second platform in mind. This means that the facility will likely need to be higher capacity than if it were dedicated to a single platform. It also means that the facility layout, size, and specific systems are different than if a single platform were to be processed there. For example, the second platform may require larger clearances in the furnaces used to cure the various coating layers, or additional steps to conform to product or market requirements. There will also be a premium in operating costs, as the complexity inherent in flexibility will likely require plant personnel to undergo significant learning before the plant runs smoothly.

In exchange for this premium, we assume that an existing plant can be idled, as production will move to this new flexible facility. We also assume that the existing plant can be idled

⁴⁰ Zielke, A., *et al.*, "Race 2015: Refueling Automotive Companies' Economics." Germany, McKinsey & Company (2005) p. 71.

⁴¹ *Ibid*, p. 57.

without cost; in reality, closing a plant may involve significant costs. Ignoring this complication, by closing an existing plant, we can eliminate the operating costs associated with this existing facility. Additionally, the aggregation of demand for each of these two platforms could help smooth production scheduling in the new facility, leading to higher average capacity utilization.

The Monte Carlo simulations described below will thus consider when having flexibility in this new plant results in lower total cost over the life of the model. Note that all costs considered below are for the paint shop only; in principle, however, the conclusions of the model can be extended to an entire assembly plant. The baseline scenario is one in which we elect not to pay the premium for flexibility in this new plant and keep the existing plant open, thus lowering the required capacity of the new facility. With this description in mind, an overview of the simulation is described by Figure 3.6.

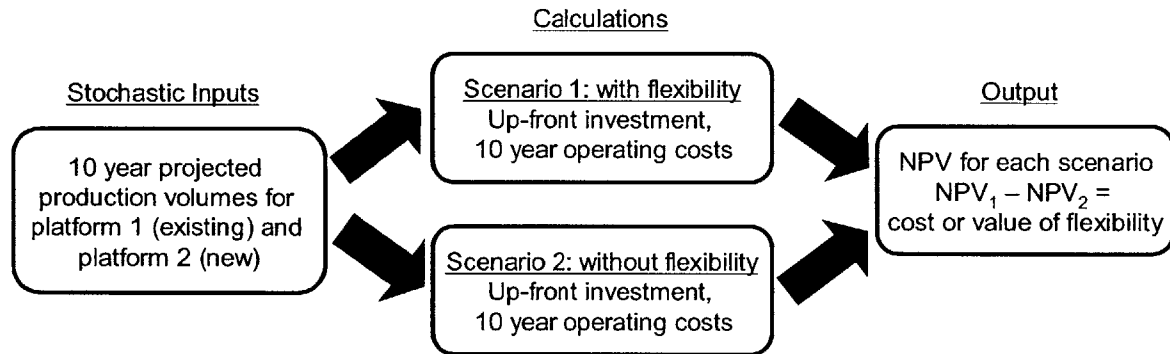


Figure 3.6. Description of the model used to derive the value of flexibility in Case 1.

The steps required to determine the cost or value of flexibility in this scenario are outlined below.

1. Determine the distribution that governs expected capacity utilization in the assembly plants. This will be used to generate production volumes over the ten years of the simulation.
2. Determine the investment and operating costs associated with this capacity in each of these plants. Operating costs are driven by simulated production volumes.
3. Compare the baseline scenario, where the existing plant is kept open and the new facility is inflexible, to the scenario where the new plant is flexible and the existing plant is closed. The difference between these two scenarios represents the cost or value of flexibility.

Next, details of these steps are outlined below.

In this simulation, the stochastic inputs that form the basis for the subsequent operating costs are the volumes of each vehicle platform demanded over a ten year span. For simplicity, this model assumes that demand and production are identical, so plant managers do not have the option of delaying orders in times of high demand in order to supplement periods of low demand. In a lean production system, this should largely be the case. The shape of the distribution function that governs the production volumes for a given year must thus be determined. To do so, monthly capacity utilization for the past five years was determined in eight General Motors paint shops, all located in North America. The distribution of capacity utilization over this time span is given in Figure 3.7.

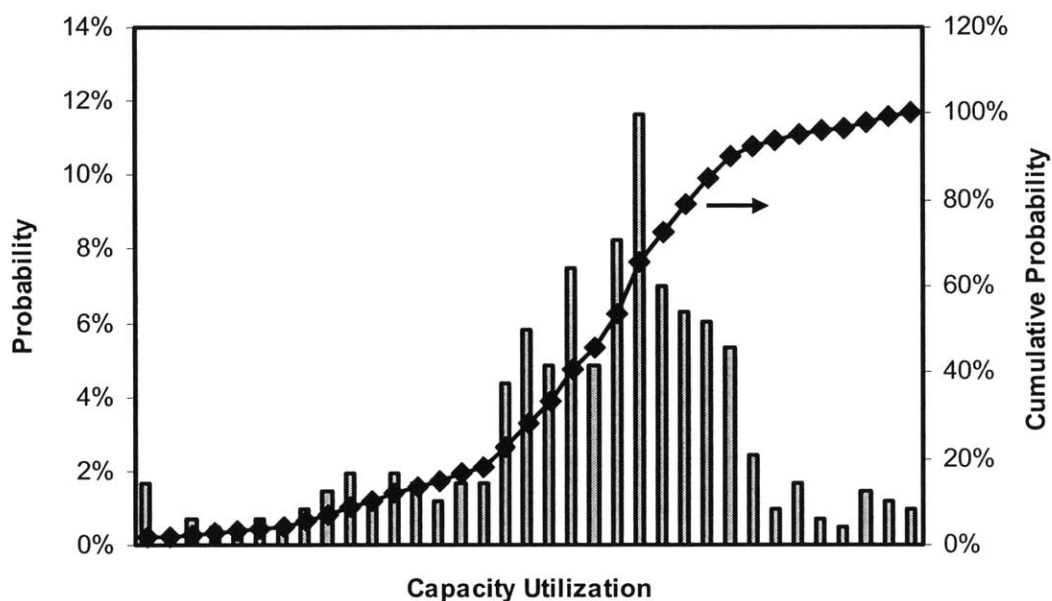


Figure 3.7. Distribution of capacity utilization in General Motors paint shops, derived by examining a five year history of eight different plants. The left axis is the probability distribution of capacity utilization (represented by the columns), while the right axis is the cumulative probability distribution of capacity utilization.

This figure shows that capacity utilization in paint shops appears to follow a normal distribution, though the distribution features an extended tail towards the low end of capacity utilization.

Because the normal distribution is easy to simulate in Monte Carlo simulations, the average capacity utilization histogram given in Figure 3.7(a) was approximated with a normal curve. Figure 3.8 shows the results of a least-squares fit to average capacity utilization, using the normal distribution as the fitting curve. While the probability distributions appear to match

reasonably well, the cumulative distribution shown in Figure 3.8(b) reveals that fitting the capacity utilization with a normal distribution severely underestimates the low end of the actual data.

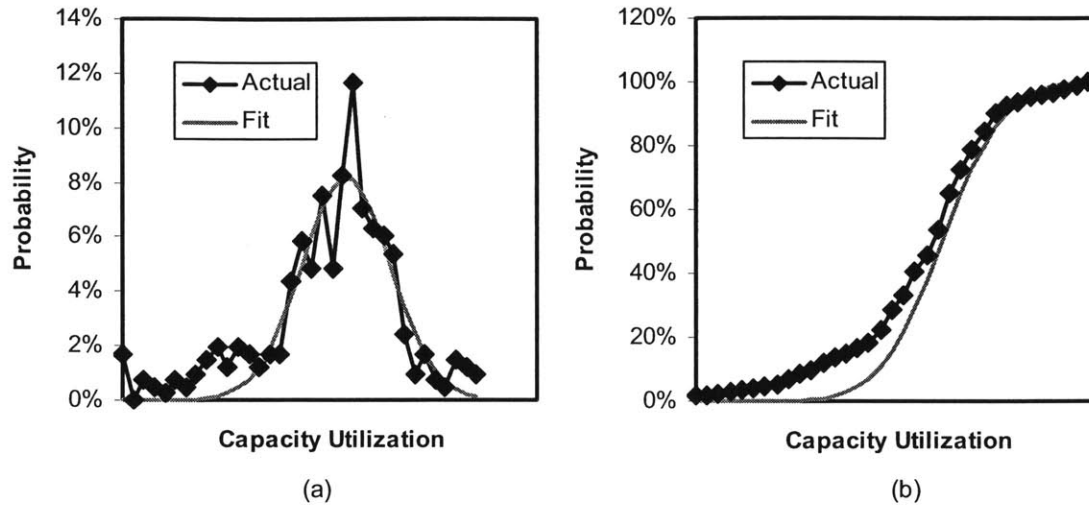


Figure 3.8. Fit to capacity utilization shown in Figure 3.7 using a normal distribution. (a) Probability distribution of capacity utilization. (b) Cumulative probability distribution of capacity utilization.

Since the normal distribution severely underestimates the probability of low levels of capacity utilization, a better fit was sought. In Figure 3.9, a hybrid distribution was used to match simulated and actual capacity utilization. Low values of capacity utilization are uniformly distributed, while high values are normally distributed. The distribution shown in this figure is the result of simulating 25,000 trials of capacity utilization using this hybrid distribution. The match to the actual capacity utilization is much better than when a normal distribution is used exclusively; hence, this hybrid distribution was used to simulate production volumes over the ten years of this analysis.

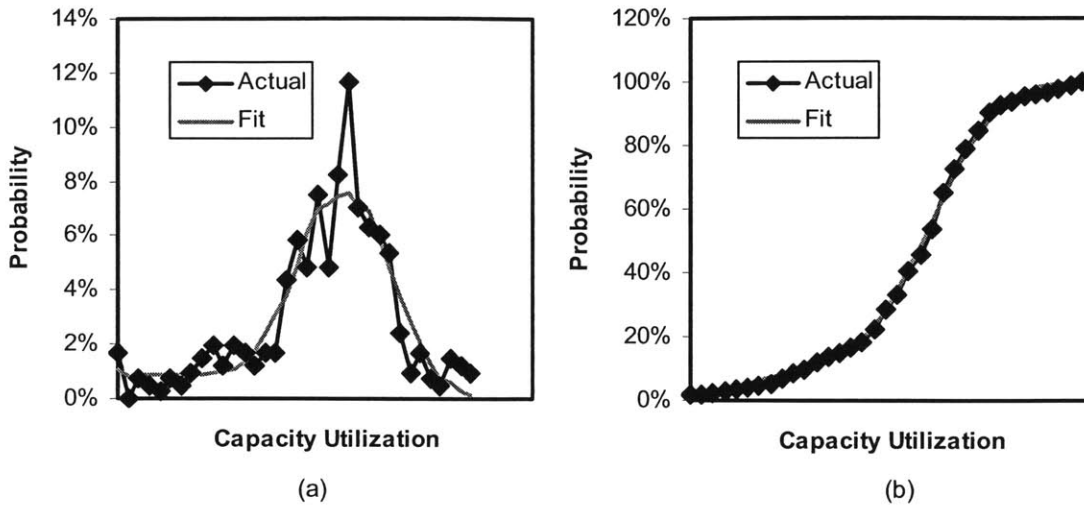


Figure 3.9. Fit to capacity utilization shown in Figure 3.7 using a hybrid distribution. (a) Probability distribution of capacity utilization. (b) Cumulative probability distribution of capacity utilization.

The distribution in Figure 3.9 also gives an average value of capacity utilization which can be used in the Monte Carlo simulations.

With the distribution that governs production volume defined, the next step is to relate investment and operating costs to these volumes. Figure 3.10 details the investment costs of selected General Motors North America paint shops versus capacity. Since the data for this figure spans approximately fifteen years, all investment costs were converted to 2006 dollars. This figure demonstrates that the investment in capacity has both a fixed and variable component and can be approximated with a linear curve fit ($R^2 = 0.77$).

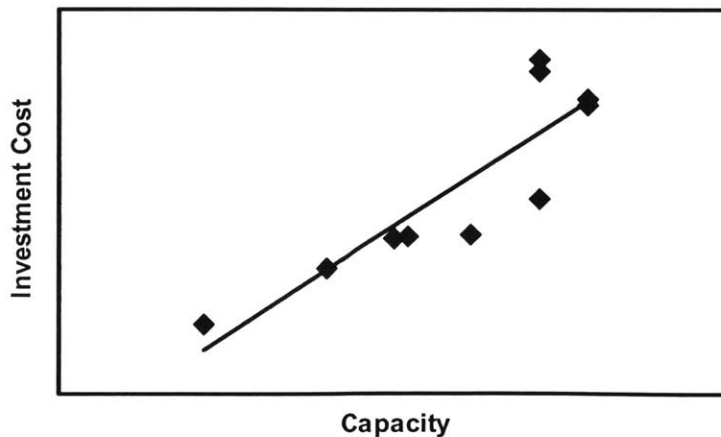


Figure 3.10. Investment costs of selected GM paint shops (in 2006 dollars) versus capacity.

Figure 3.11 details operating costs of General Motors North American paint shops in 2004 versus the capacity of each paint shop. As was the case with investment costs, operating costs have both a fixed and variable component and can be modeled with a simple linear curve fit ($R^2 = 0.75$).

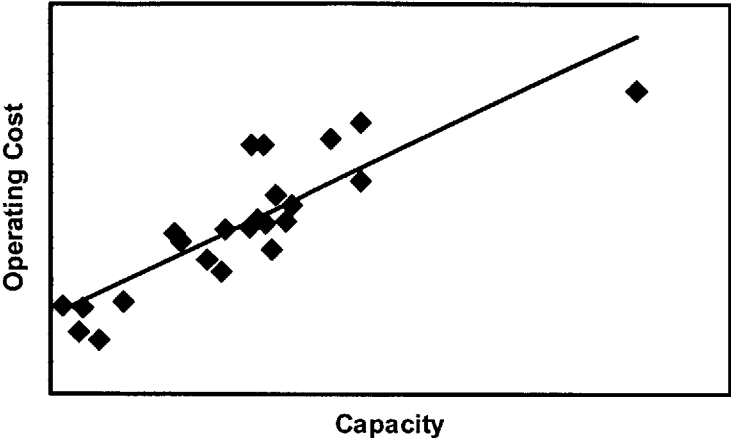
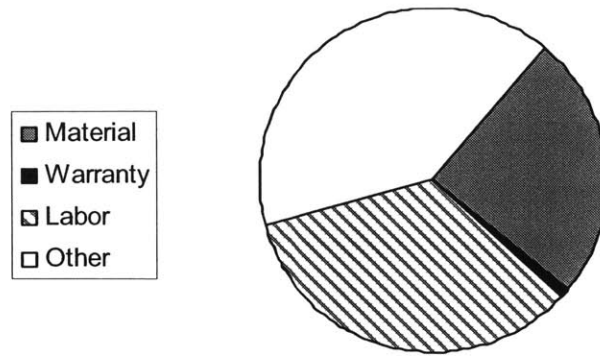


Figure 3.11. Operating costs (from 2004) of GM paint shops versus capacity.

The data presented in Figure 3.10 and Figure 3.11 enables calculation of investment and operating costs of a paint shop operating up to full capacity.

For times when a paint shop exceeds its capacity, labor costs should increase accordingly to account for overtime. To estimate the magnitude of this increase, a breakdown of operating cost components in General Motors North America paint shops was performed, using data taken from 2004. This breakdown is given in Figure 3.12, which reveals that approximately one third of operating costs are devoted to labor. Thus, to approximate the effect of overtime in this model, labor costs were doubled for each vehicle produced beyond the plant’s capacity, resulting in 66% higher operating costs for these vehicles. Note that this approximation neglects the possible additional operating costs associated with increased wear and tear on equipment or postponement of preventive maintenance procedures.



**Figure 3.12. Operating cost breakdown (from 2004) of GM paint shops.
Approximately 33% of operating costs are devoted to labor.**

Next, the operating cost premium for flexibility must be determined. After consultation with experts at General Motors, a simple model was proposed.⁴² Investment costs for a flexible plant exhibit a fixed operating cost premium over an inflexible plant (15%), while operating costs display an initial premium (again, usually 15%) that can decrease over time. The rate of operating cost reduction in a flexible plant is governed by an experience curve, which features an initial increase in operating cost and a constant experience curve factor b that describes the decrease over time.

Finally, the simulation can be run by simulating production volumes for each platform, and total cost for each scenario can be derived. The total cost of a given scenario is simply the net present value (NPV) of investment and operating costs, both of which are dictated by the simulated production volumes. The cost or value of flexibility is then simply the difference between the NPV for a flexible and inflexible plant. Using this model, a variety of scenarios were run, the results of which are outlined below. In all cases, 1,000 trials were run over a ten year horizon, and the discount rate was fixed at 15%.

First, the effect of capacity was examined, as shown in Figure 3.13. The total system capacity was fixed at the values indicated in this figure, and the model mix was fixed at three values (25%, 50%, or 75% of total capacity devoted to the new platform, on average). For the case where the new plant is flexible and the existing plant is closed, total system capacity is simply the capacity of this new plant. For the baseline case, where the new plant is inflexible

⁴² Claya, J., Personal Communication (2006).

and the existing plant is kept open, total system capacity is the sum of the capacities of the two individual plants. Average capacity utilization is given by the peak value given in Figure 3.9(a) and operating costs were determined for each year given the simulated demand at the time. In the scenario where a flexible plant was built, operating costs experienced an initial spike of 15% and declined with a constant experience curve factor b of 85%.

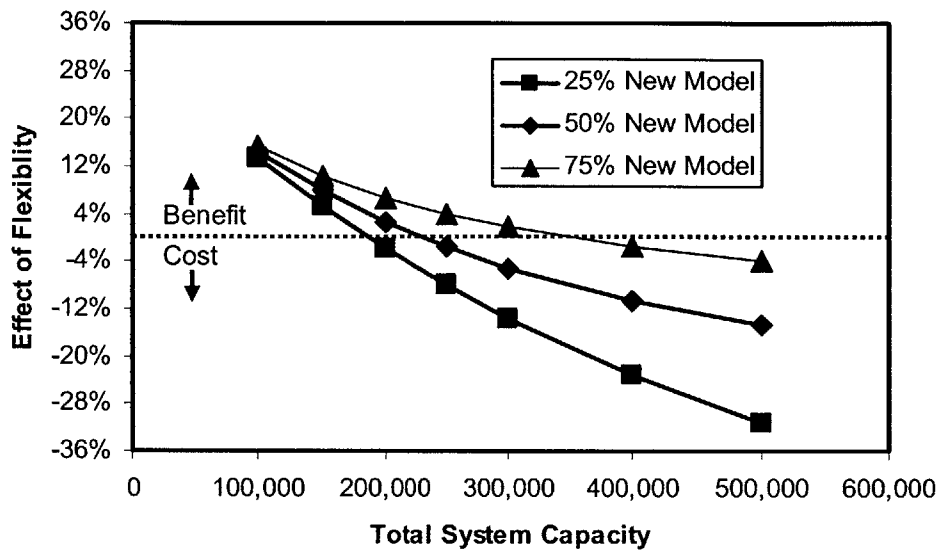


Figure 3.13. Effect of total system capacity on the cost or value of flexibility for three different product mixes. Flexibility adds value when the y-axis is positive. The amount of total capacity devoted to the new platform is given by the values in the legend. The initial premium in operating cost in the flexible plant was fixed at 15%, b was set to 85%, and average capacity utilization was fixed at the peak value in Figure 3.9(a).

This figure reveals that flexibility adds value when the total system capacity is low. In other words, when production volumes are low, economies of scale are weak and aggregating production into a single flexibility facility results in lower total cost despite the premium one has to pay for this flexibility. Furthermore, when the existing platform is low volume (that is, when most of the total system capacity is devoted to the new model), flexibility adds the most value. This effect is again due to economies of scale: the fixed component of operating costs means that the existing low volume platform cannot be processed inexpensively in a dedicated facility. To summarize, this figure shows that, for production volumes where economies of scale are weak, flexibility tends to add value.

Next, the effect of capacity utilization was examined, as shown in Figure 3.14. This figure shows the benefit or cost of flexibility versus the average capacity utilization for each plant over a ten year time span. In this figure, total system capacity was set at 200,000 units, half of the capacity was devoted to the new platform, the initial premium in operating costs in the flexible plant was set to 15%, and b was fixed at 85%. This figure demonstrates that changes in capacity utilization have a weak effect on the cost or benefit of flexibility. As the average capacity utilization drops, the benefit of flexibility increases, since only a single plant is being run at these low capacity levels. Thus, flexibility can actually serve as a buffer against low capacity utilization.

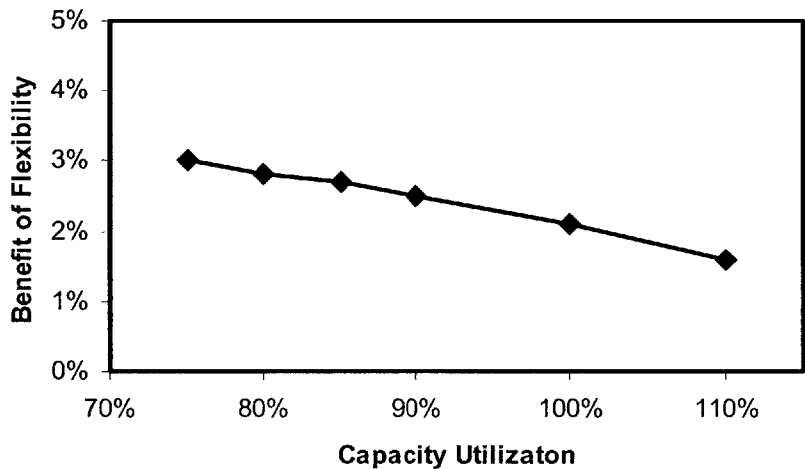


Figure 3.14. Effect of capacity utilization on the cost or benefit of flexibility. Total system capacity was fixed at 200,000 units, half of the total capacity was devoted to the new platform, the initial premium in operating cost in the flexible plant was fixed at 15%, and b was set to 85%.

Finally, experience effects were examined by varying the experience curve factor b , as shown in Figure 3.15. In these simulations, total system capacity was fixed at 200,000 units, average capacity utilization was set to the peak value in Figure 3.9(a), half of the total capacity was devoted to the new platform, and the initial premium in operating cost in the flexible plant was fixed at 15%. This figure shows that high learning rates (low values of b) enable a plant to maximize the value derived from flexibility by quickly reducing the operating cost premium.

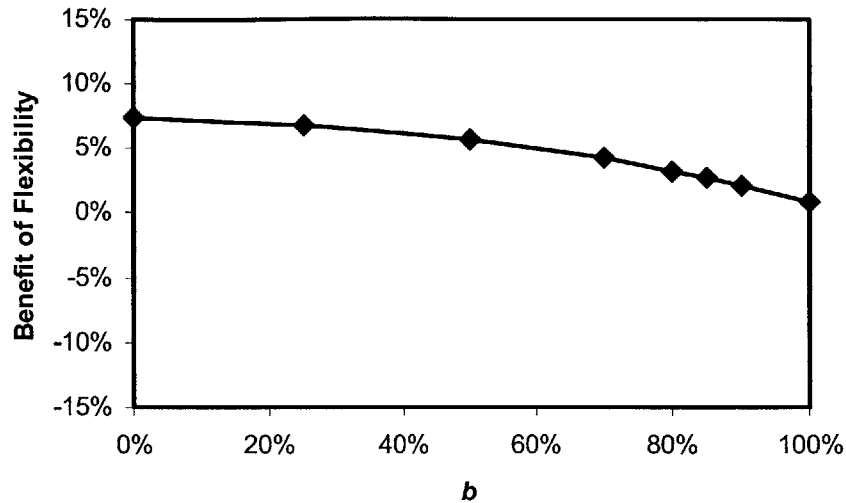


Figure 3.15. Effect of the experience curve factor b on the cost or benefit of flexibility. Total system capacity was fixed at 200,000 units, average capacity utilization was set to the peak value in Figure 3.9(a), half of the total capacity was devoted to the new platform, and the initial premium in operating cost in the flexible plant was fixed at 15%.

Taken together, these simulations reveal a relatively broad range of conditions where a new flexible facility can be used to accommodate both a new platform and existing platform, allowing an existing paint shop to close. While highly theoretical in nature, they can apply to real situations; e.g. the aggregation of existing low volume platforms into a paint shop designed for a new high volume platform. These simulations also suggest that since the investment and operating costs of paint shops are so high, significant benefits could be derived by having a common paint shop linking two different body and general assembly areas, as shown in Figure 3.16 below. The fabrication techniques used in the body shop and in general assembly could be completely different, but the inherent flexibility in paint shops allows the vehicles to share coating processes. In fact, this arrangement is currently in place at the General Motors plant in Oshawa, Ontario.

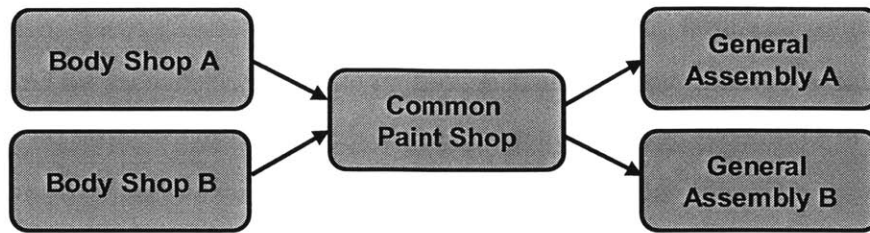


Figure 3.16. Schematic depicting the arrangement of body and general assembly facilities to take advantage of a single flexible paint shop.

The next set of simulations takes us from the high-level view of plant costs described above to the case of diffusion of a specific operating improvement throughout the plant network.

3.3.2 Case 2: Staging operating improvements in two different facilities

In this example, an improvement in plant operations that is expected to yield a reduction in per-vehicle operating costs is being considered at two different facilities. The improvement in per-vehicle operating cost comes at the expense of an initial investment. This improvement can be simultaneously introduced at both facilities, or the decision to introduce the improvement in the second facility can be contingent upon its performance in the first, with the assumption that learning can be effectively transmitted between the two facilities. If the decision to delay is made, the improvement cannot come online until the next year, as the upgrade requires an investment in time as well. While waiting to perform this upgrade enables the second facility to defer the implementation cost and avoid any potential implementation problems, deferment may cause the second plant to miss out on the operating cost reductions if implementation goes well in the first facility. In some cases in the simulations described below, the implementation of the improvement in the first facility could be so problematic that it actually results in an increase in operating costs there for some time, which is not an uncommon situation in manufacturing environments. Thus, these simulations also provide additional insight into the cost of disruption.

The Monte Carlo simulations below describe the extra value derived by waiting and the optimal implementation time for a range of assumptions. As in the previous case, the inputs to the simulations are production volumes, in this case for the second facility. In fact, an identical distribution to that used in Figure 3.9 is used to describe production volumes in the second plant, using a mean demand level of 100,000 vehicles per year. These stochastic production volumes are then multiplied by per-vehicle cost savings to arrive at the total operating cost savings for that year. Also, experience curves are again used to describe the rate of improvement in

operating cost savings; an initial decrease in savings (which may actually result in negative savings; i.e. increased operating cost) evolves according to the experience curve factor b towards the ideal per-vehicle savings. The final input is the time delay in implementing the improvement in the second plant; each trial in the simulation consists of time delays ranging from one to ten years, and the optimal delay time is recorded. The optimal delay time is not an artificial construct; in real life, plant management in the second facility would likely closely track the progress of implementation in the first and perform this calculation continuously. For each simulation, 1,000 trials were run over a ten year time horizon. The value of flexibility was determined by comparing the net present value of the operating improvement in the second plant with and without the implementation delay. Because there is always the option to not implement the improvement in the second plant, the value of flexibility is always greater than zero in the following discussion.

First, the trade-off between implementation cost and per-vehicle operating cost savings was examined. Figure 3.17 presents a three dimensional plot that displays the value of flexibility versus the initial implementation cost and the projected per-vehicle operating cost savings. The initial per-vehicle operating cost savings was set to zero (i.e. no cost savings in the first year), and b , which governs the rate at which actual cost savings approach the potential savings shown on this graph, was set to 85%. This plot reveals a wide area in which the value of flexibility is greater than zero. Within these areas, the optimal delay ranges from one to six years – essentially, the project is implemented when the discounted implementation cost is exceeded by the potential per-vehicle operating cost savings. In areas where the option value is zero, the improvement should never be implemented because the NPV of per-vehicle cost savings is not larger than the initial implementation cost.

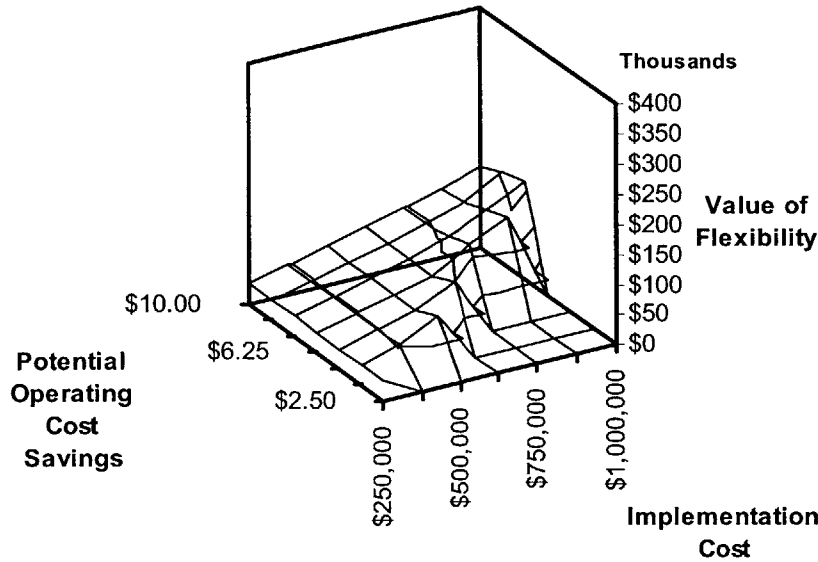
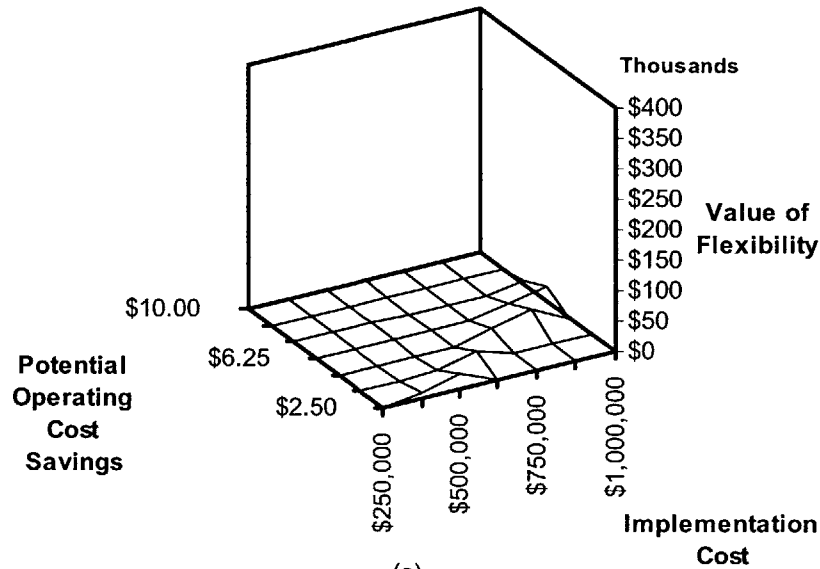


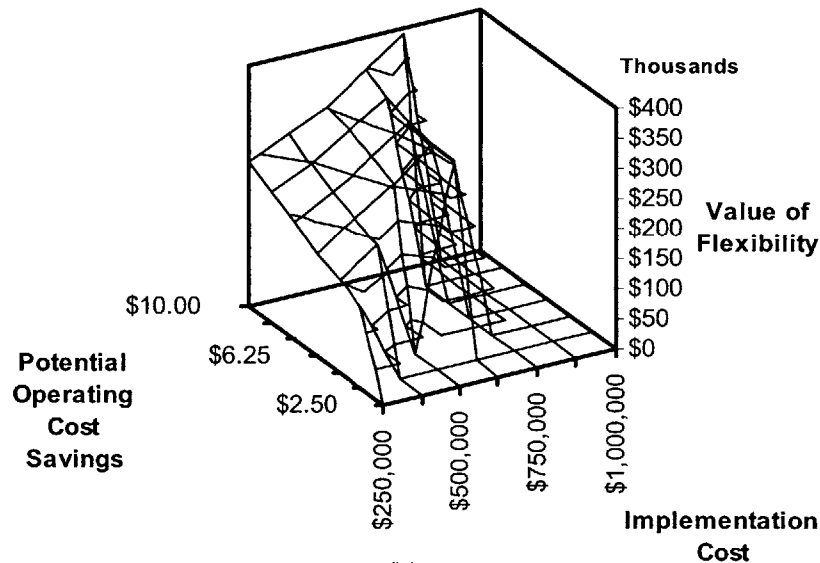
Figure 3.17. Value of flexibility for different implementation costs and potential per-vehicle operating cost savings. Initial per-vehicle operating cost savings was set to 0, and b was set to 85%.

Next, the effect of varying the initial per-vehicle operating cost savings is examined. Figure 3.18 presents two plots that display the value of flexibility versus the initial implementation cost and the projected per-vehicle operating cost savings. For clarity, these figures have identical vertical scales to each other and to Figure 3.17. In both plots, b was set to 85%. In Figure 3.18(a), the initial per-vehicle operating cost savings was set to 20% of the potential savings, while in Figure 3.18(b) operating costs were initially *increased* by 20%. Thus, for a potential per-vehicle operating cost savings of \$5.00, the initial per-vehicle savings is \$1.00 in Figure 3.18(a) while the initial per-vehicle *added* cost is \$1.00 in Figure 3.18(b). However, in both cases, they trend towards the same value. In general, the value of flexibility is generally non-zero when the implementation cost is low compared to the potential cost savings. In the right portion of Figure 3.18(a), the value of flexibility is zero because the improvement is never implemented, as potential savings are swamped by the implementation cost. In the left portion of this plot, the value of flexibility is zero because the improvement is immediately implemented to take advantage of the per-vehicle cost savings. In Figure 3.18(b), the value of flexibility is again zero when cost savings are significant compared to implementation costs. The areas where the value of flexibility is zero are regions in which the upgrade is never performed, largely because of the high implementation cost. Compared to Figure 3.17, the region of zero value is

larger because of the higher initial reduction in per-vehicle cost savings. Because of the initial increase in operating costs in Figure 3.18(b), the value of flexibility is highest in this scenario, as implementation is delayed until operating costs are reduced. In both of these plots, optimal delays ranged from one to five years.



(a)



(b)

**Figure 3.18. Value of flexibility for different implementation costs and potential per-vehicle operating cost savings. In both plots, b was set to 85%.
 (a) Initial operating cost savings compared to the projected was set to 20%.
 (b) Initial operating costs increase by 20%.**

Finally, the effect of the experience curve factor b and initial per-vehicle cost savings (expressed as a percent of the potential savings; negative values imply initial operating costs have increased) is examined in Figure 3.19 below, which is a plot of the value of flexibility versus these two factors. In this figure, implementation cost was fixed at \$500,000 and potential per-vehicle operating cost savings was \$5.00. Again, this plot reveals a broad range of values in which the value of flexibility is greater than zero. This plot reveals that the magnitude of initial cost savings has the strongest effect on the value of flexibility. Optimal implementation delays ranged from one to four years in this plot.

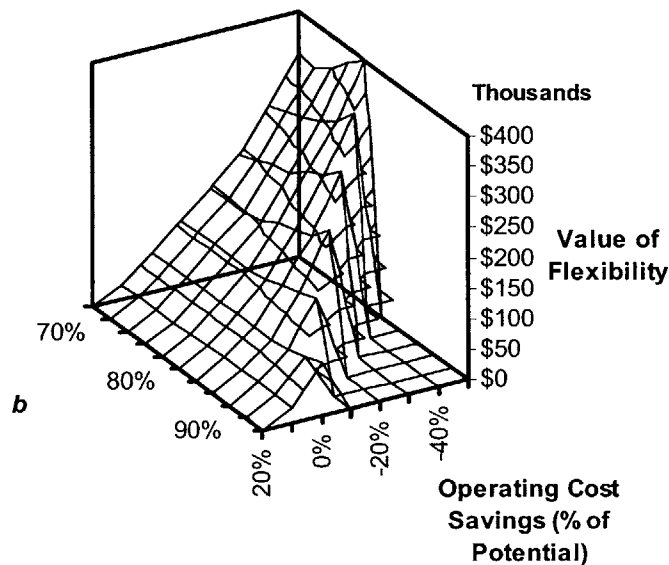


Figure 3.19. Value of flexibility for different experience curve factors (b) and initial per-vehicle operating cost savings. Implementation cost was fixed at \$500,000 and potential operation cost savings was fixed at \$5.00 per vehicle.

Taken together, these simulations demonstrate the value of efficiently transferring learning from one plant to another, rather than simultaneously rolling out process changes in each plant. The above figures indicate that this staged approach can result in substantial cost savings, depending on the nature of the process improvement.

3.4 Hidden Costs: A Broader Perspective

The three classes of hidden costs (variation, disruption, and flexibility) described above can potentially significantly impact the life cycle cost projections discussed in Chapter 2. However,

the importance of hidden costs goes beyond financial projections and touches upon issues as diverse as corporate culture, organizational design, and managerial incentives.

The semiconductor industry, and Intel in particular, provide a vivid case study of how hidden costs can impact these broader areas. Intel is the largest semiconductor manufacturer in the world and commands a dominant share in the microprocessor market. It is also a technological leader, defining the pace of innovation in the industry through Moore's Law. Moore's Law, first proposed by Gordon Moore (then a manager at Fairchild, later chairman of Intel), states that the density of transistors on a computer chip doubles every two years.⁴³ Moore's Law defines an incredible trajectory of change within the industry, ensuring a constant stream of challenges related to sustaining the pace of innovation necessary to meet this trend and ramping up each new generation of microprocessors realized through these innovations.

In essence, each generation of microprocessors represents a major disruption for the semiconductor industry, accompanied by major disruption costs as each chip fabrication plant (commonly denoted with the shorthand "fab" within the semiconductor industry; each fab is responsible for a family of product based on a given technology) struggles to implement the new process necessary for those products. In the past, each fab would experience initially low yields, which would take months or years to reach acceptable values, since learning was not being effectively transmitted between the fabs. In response to this major disruption cost, Intel developed its Copy Exactly! philosophy, where each fab copies the development fab down to the exact details.^{44,45} With this process in place, Intel was able to eliminate the cost of disruption, resulting in new chip fabs instantly achieving the yields established in other plants. The effect of the Copy Exactly! approach on yields is depicted schematically in Figure 3.20.

⁴³ Moore, G., "Cramming More Components Onto Integrated Circuits," *Electronics Magazine* 8 (1965) 567.

⁴⁴ Gasser, R.A., "Achieving High Microprocessor Manufacturing Output – The Copy Exactly! Method," *International Electron Devices Meeting Technical Digest* (2002) 318.

⁴⁵ Natarajan, S., *et al.*, "Process Development and Manufacturing of High-Performance Microprocessors on 300mm Wafers," *Intel Technology Journal* 6 (2002) 14.

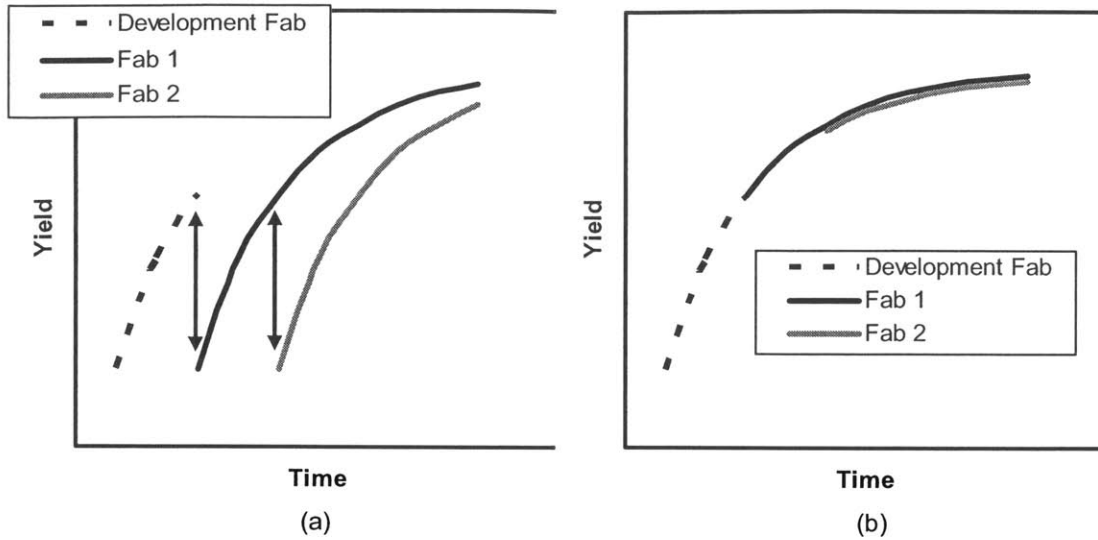


Figure 3.20. Schematic of yield curves before and after implementation of Copy Exactly!, modeled after Terwiesch and Yu.⁴⁶ Arrows point to yield loss at the time of technology transfer to the new fab.

This philosophy was a large cultural change in an organization full of technologists, and called upon extreme discipline in avoiding the urge to constantly implement process improvements (which often backfire) in each new facility.

The preceding example shows that when hidden costs are properly considered, their impact goes beyond cost estimation. The following chapter examines some of the broader issues of cost projections as they relate to the Global Paint and Polymers Center at GM.

⁴⁶ Terwiesch, C. and Xu, Y., "The Copy-Exactly Ramp-Up Strategy: Trading-Off Learning With Process Change," *IEEE Transactions on Engineering Management* **51** (2004) 71.

Chapter 4: Organizational Analysis: Linking Costs to Managerial Objectives

As described in Section 3.4, organizational structure and managerial incentives can determine which costs are emphasized and which are neglected. Before Copy Exactly! was implemented at Intel, each factory viewed itself as responsible for designing the optimal production process for their facility. Therefore, process improvements were uncoordinated and resulted in unintended hidden costs; individual facilities viewed the long ramp-up times as an inevitable cost associated with deployment of leading-edge production processes. When the cost of disruption became apparent, Copy Exactly! was adopted and process learning became coordinated across fabs. In short, Copy Exactly! was the managerial vehicle through which hidden costs could be reduced or eliminated.

In general, while the methods outlined in Chapter 3 allow us to determine what these hidden costs may be, they do not explain why they exist in the first place or how best to address them. Therefore, we cannot fully assess the impact of the techniques described in Chapters 2 and 3 of this work without understanding the dynamics that underlie the decision making processes in an organization. To this end, in the following discussion, the potential impact of the quantitative methods used in this work on the Global Paint and Polymers Center (GPPC) organization is considered. First, a description of the GPPC organization is given, and the internal and external forces that guide decision making are considered. Next, some recommendations for improving the organization's cost estimation procedures are provided.

4.1 Description of the Global Paint and Polymers Center (GPPC)

General Motors operates dozens of automotive assembly plants located throughout the world, used to manufacture a wide variety of vehicles across twelve brands (Buick, Cadillac, Chevrolet, GMC, GM Daewoo, Holden, HUMMER, Opel, Pontiac, Saab, Saturn and Vauxhall). These plants differ widely in the processes employed, partly due to local variations in labor costs and product requirements, and partly reflective of the various acquisitions made by General Motors throughout the years. Each region has its own regional manufacturing management, which is further divided into individual plant management. To link these regions together, global

manufacturing engineering organizations such as the GPPC are utilized. A schematic of the organizational structure for GM manufacturing is shown in Figure 4.1.

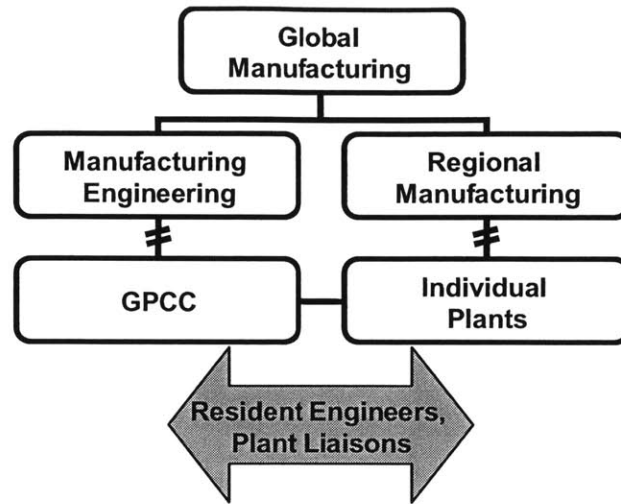


Figure 4.1. Schematic of GM global manufacturing organization. The parallel bars indicate there are multiple levels between the two levels depicted.

The GPPC exists to provide worldwide support to GM paint shops, serve as a centralized source of best practices, and provide a common avenue for process improvement validation; there are analogs to the GPPC in other areas of manufacturing as well. The entire GPPC consists of approximately 200 employees, specialized in such areas as paint facilities, materials, exterior polymers, and product design. Most GPPC personnel are located at GM’s Technical Center in Warren, MI, though the GPPC also has on-site resident engineers at plants and plant liaisons that travel between the central office and their assigned facilities. Though a similar organization has existed in GM North America for many years, the GPPC officially assumed its global role recently.

Because the GPPC functions in a support role, external forces significantly impact the nature of the work done there. The three most important influences on the GPPC are management at individual plants, the GM’s Worldwide Facilities Group, and suppliers or contractors to individual plants.

4.2 Relationship of GPPC with Manufacturing Plants

Plant management plays an important role in shaping the nature of the work done at the GPPC, particularly when GPPC is engaged in support or validation. Regarding plant support, plants tend request assistance from GPPC personnel, with plant liaisons functioning as pull signals for

this help. Thus, plants have a high degree of autonomy, as they can choose whether or not to utilize the GPPC to assist in their operations. Regarding new equipment validation, plant management must agree to any testing of process improvements developed by the GPPC. To deal with these coordination challenges effectively, members of the GPPC need to have close working relationships with individuals at different plants, underscoring the importance of the plant liaisons and resident engineers. This often requires GPPC engineers to be off-site for a significant fraction of their time, engaged in various long-term projects with different plants. The coordination challenge is magnified by the recent shift to a global organization, since regions had more autonomy in the past, and GPPC personnel must now build effective working relationships around the world.

Another area in which GPPC interests are intermingled with that of individual plants is in the budgeting process. For example, the GPPC budget includes material costs at all General Motors paint shops. Thus, individual plants are free to choose coating processes that maximize their metrics of interest without fear of being penalized for additional material costs. While this budgeting choice avoids the incentive for plants to try to cut operating costs by cutting back on coating thickness (and possibly paying a long term cost from reduced quality), it does create a situation in which the GPPC is not directly responsible for a component of its budget.

4.3 GPPC and the Worldwide Facilities Group

When a new paint shop is planned, a team composed of personnel from both the GPPC and Worldwide Facilities Group (WFG) is formed to evaluate the necessary investment to meet the projected product requirements. WFG is responsible for controlling investment costs and delivering the project on time, responsibilities shared with the GPPC. Because of the competitive dynamics of the automotive industry described in Chapter 1, the drive to reduce investment costs is incredibly strong. However, a built-in source of tension between WFG and GPPC centers on the additional metrics used by GPPC personnel when evaluating a project. Since the GPPC will have an ongoing support role with the plant, control of operating costs and minimization of hidden costs are also important criteria in their decision-making process. These sometimes competing metrics can set up situations in which investment cost is given precedence over life cycle cost, leading to sub-optimal decision where the long-term benefits are traded for short-term costs savings. Furthermore, the drive to reduce investment cost places enormous

pressure on suppliers to meet project budgets, which can potentially strain the relationship between GM and its suppliers.

4.4 GPPC and Suppliers

Finally, suppliers, particularly on the equipment side, play an important role in shaping the work done by the GPPC. These suppliers play an important role in the paint shop during the construction phase and continue to provide support after the plant goes online. In fact, as the automotive industry shifts to more collaborative OEM-supplier relationships, suppliers have steadily gained more of a voice in the design and operation of the paint shop. In the extreme case, a recent Daimler-Chrysler paint shop is actually being run by its suppliers, and Daimler-Chrysler pays a per-vehicle cost for each vehicle coated in that facility. The transition to this model has not been smooth; the original contractor (Haden) declared bankruptcy in early 2006 and another supplier (Magna Steyr) was brought in to execute the contract. While GM has not attempted this model to date, they still work closely with suppliers to the paint shop, and the future will likely bring closer collaboration between GM and its paint shop suppliers.

As suppliers have taken on a more active role in paint shop facility and process design, they have also increasingly taken on a leadership role in driving research and development activities. At General Motors, this enables organizations such as the GPPC to act as intermediaries between suppliers unveiling new processes and plants considering whether or not to utilize these processes. However, in this role, GPPC can only indirectly influence each party, complicating the diffusion of new technologies into the plant.

A recent change in industry dynamic has been the increased use of intellectual property by suppliers in an effort to build competitive advantage, a likely by-product of increased horizontal and vertical competition within the industry and reflective of the increased role that suppliers take in research and development. Figure 4.2 details the aggregate number of United States patents awarded and U.S. patent applications in the area of automotive paints for the equipment suppliers discussed in Section 1.5. The number of patent applications for 2007 was projected based on the number as of March 15, 2007. In this figure, the number of patent applications is fewer than the number of issued patents for two reasons: multiple patents can be issued from a single application, and some of these issued patents arose from applications filed outside of the U.S since many of these companies are headquartered elsewhere. This figure reveals a fairly

steady increase in patents over the recent years, particularly when viewed over the long term. For example, issued patents climbed by 45% in 2001-2006 compared to the previous five years. During this time, total U.S. patent issuances climbed by less than 9%, indicating that automotive paint shop equipment suppliers are seeking intellectual property protection at a rate far exceeding that of general industry.

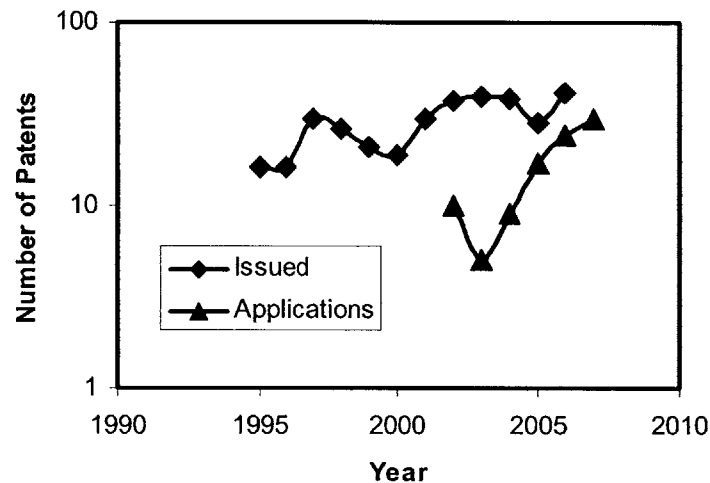


Figure 4.2. Total number of U.S. patents issued and patent applications by year, in the areas of automotive paints, for the equipment suppliers discussed in Section 1.5.

As mentioned above, the increased focus on intellectual property is an understandable outcome of the increasingly competitive automotive landscape described in Chapter 1, and firms naturally will try to protect their innovations in an extremely capital-intensive and mature industry. However, this dynamic potentially affects the collaborative relationships forged by GPPC with suppliers. As described by von Hippel,⁴⁷ many innovations may actually come from end-users of products, and not from product manufacturers. For example, in semiconductor equipment and scientific instruments – two areas that are at least broadly similar to automotive manufacturing equipment– von Hippel observed that the majority of innovations came from end-users and not from manufacturers.⁴⁸ The simple explanation for this phenomenon is that the end-

⁴⁷ von Hippel, E. *The Sources of Innovation*. Oxford University Press, New York (1988).

⁴⁸ *Ibid*, p. 44.

users were those most likely to benefit from their innovations, as they would be able to capture the benefits in the form of higher profits.⁴⁹

Extending von Hippel's theories to automotive vehicle coatings, GM employees likely contribute valuable product innovations in vehicle coating equipment and processes. Indeed, anecdotal information collected during this internship suggests that GPPC engineers (as well as other GM employees) routinely make improvements in these areas, not unexpected given the constant pressure to improve operations at plants. Suppliers' increased reliance on intellectual property may therefore complicate collaborative innovation in the paint shops, particularly when terms of joint development have not been clearly defined, as parties may focus on capturing innovations rather than creating them. Also, suppliers' reliance on patent license fees to OEMs may lead to double marginalization, eroding the cost competitiveness of all parties.

4.5 Closing the Loop: Life Cycle Cost and Incentives

To summarize the previous sections, some key observations emerge about the status of GPPC within General Motors.

1. The GPPC's role involves recommendation of best practices in manufacturing plants, but a single blueprint for all paint shops around the world does not currently exist due to variations in capacity requirements and labor rates and the infrastructure in place when the assets were acquired by GM.
2. GPPC operates in a highly collaborative fashion and must forge good working relationships with suppliers, plant personnel, and the facilities group to be successful. Often, the GPPC can only exert indirect control on these parties. In particular, development and validation, two responsibilities of the GPPC, call upon these relationships extensively.
3. There are sometimes competing metrics in the plant budgeting process, as investment costs are emphasized by WFG and life cycle costs are emphasized by the GPPC.
4. Suppliers are increasingly relying on intellectual property to fend off horizontal and vertical competition, at the possible cost of open collaboration with the GPPC.

⁴⁹ Harhoff, D., Henkel, J., and von Hippel, E., "Profiting from Voluntary Information Spillovers: How Users Benefit by Freely Revealing their Innovations," *Research Policy* 32 (2003) 1753.

Given this situation, the following paragraphs provide some recommendations for improving the effectiveness of the GPPC and creating mutually beneficial relationships for all stakeholders.

1. Adopt common metrics.

The first recommendation is to adopt a common set of metrics for project evaluation for all parties (GPPC, WFG, plant management, suppliers, and GM management) based upon life cycle cost minimization. There are many possible methods to link these metrics to incentives for each group; one suggestion is to link all stakeholders' compensation to operating cost targets in the plants. Admittedly, this is not a simple task, as all groups likely will have to rely on mutually negotiated standards for cost projection to arrive at the most accurate projections of life cycle cost. Additionally, incentives and rewards will depend on costs that may be incurred years from now, possibly leading to "gaming" of the system over the long term in exchange for short-term gains. However, this problem is not so different from the current incentive to postpone investment in projects to maintain the appearance of cost control. Furthermore, this suggestion could enable all groups to negotiate mutually agreeable standards for a project, avoid potential conflict down the road by creating linked incentives, and streamline the decision-making process.

2. Consider hidden costs and strive to increase commonality.

In a related fashion, all parties should recognize the role of hidden costs in driving life cycle cost, particularly experience effects and the cost of disruption. At this point, it is instructive to examine the applicability of Intel's Copy Exactly! philosophy to automotive paint shops. To this end, Terwiesch and Xu⁵⁰ have developed a mathematical model describing process change dynamics within manufacturing organizations, which enabled them to outline conditions in which Copy Exactly! is an advantageous approach for manufacturing process transfer. Generally, they determined that Copy Exactly! is best suited to processes with low initial levels of process knowledge, where production ramps are conducted quickly, and where processes are extremely sensitive to slight variations. This theoretical framework provides some insight into the suitability of Copy Exactly! to the automotive industry. Compared to semiconductor manufacturing, automotive process knowledge is high – there is no equivalent of Moore's Law driving exponential advances in the automotive industry, so change tends to be evolutionary and

⁵⁰ Terwiesch, C. and Xu, Y., "The Copy-Exactly Ramp-Up Strategy: Trading-Off Learning With Process Change," *IEEE Transactions on Engineering Management* 51 (2004) 71.

the rate of process change is relatively low. For example, automotive manufacturing has not changed radically over the past decade, while ten year old semiconductor processes are essentially obsolete. However, the rate of process ramps is similar between the two industries; in both cases, changeovers must be accomplished in weeks or months. Finally, the highly integrated and complex nature of modern automotive design, coupled with a broad supply base, means that manufacturing processes are relatively sensitive to variation, though of course not on the atomic scale of semiconductors.

Given this theoretical framework, we can begin to see why GM's paint shops do not employ a Copy Exactly! strategy. In fact, there are several reasons why it would be impractical to fully shift to this approach. First, different labor rates throughout the world give rise to different levels of automation, as plants need not rely as much on automation in regions where labor rates are low. Second, different plants have different production capacities, which again call upon different levels of automation and equipment types. Third, differences in product requirements may call upon different coating processes, such as an added focus on anticorrosion coatings in environments with long winters. Finally, unlike microelectronics plants (which face obsolescence after only a few years), automotive manufacturing plants operate for decades, and not every system can be cutting edge. In fact, in areas with low labor rates, vehicle manufacturers routinely choose manufacturing processes with higher labor requirements, which are also inherently more flexible. To accommodate these differences, rather than utilize a strict Copy Exactly! methodology, GM employs a set of guidelines for process and facilities requirements given the projected needs of the product to be served. The GPPC is actively involved in creating and interpreting these guidelines.

However, while Copy Exactly! is not literally applicable to the paint shop, many of the main lessons hold. OEMs and suppliers should pay careful attention to process changes and be sure to consider the possible disruption cost that accompanies these changes. In short, no process improvement is free. Furthermore, when the cost of disruption is explicitly part of life cycle cost estimates, all parties recognize the true potential value of factory investments.

3. Effectively share risk between OEMs and suppliers.

The next set of recommendations involves the nature of supplier relationships. Here, OEMs and suppliers share the same fate; not only are they financially interdependent, but continuous innovation and process improvements rely on strong bonds between the parties. While this is a

well-documented fact, the continued struggles between both parties suggest that while risk is shared, it is not shared effectively.⁵¹

Zielke *et al.* point out two major categories of shared risk between OEMs and suppliers: quality risk and volume risk.⁵² The former arises when the indirectly responsible OEM must bear the cost of poor supplier quality, while the latter arises when the supplier must bear the risk of reduced sales volume by the OEM. For purposes of this work, we can expand these definitions to the paint shop by stating that OEMs endure quality risk when suppliers cannot meet their cost targets without compromising on another design parameter, and suppliers endure volume risk when poor business conditions at the OEM force current and future paint shop investments to be scaled back and supplier's margins to shrink.

With these expanded definitions in place, the following suggestions, broadly following those outlined by Zielke *et al.*,⁵³ can help facilitate better supplier-OEM relationships in the paint shop. First, both sides must credibly commit to each other's success. In particular, in exchange for suppliers' contribution of process development resources, OEMs can commit to future business with these suppliers to mitigate their volume risk. Also, as discussed above, linked incentives to reduce operating costs in plants can help ensure that all parties make the correct long-term decisions for GM, mitigating the OEM's quality risk. Finally, both sides should invest in open-source innovations, through such mechanisms as industrial consortia or joint development partnerships. This helps mitigate intellectual property risks on both side of the relationship. Admittedly, many of these recommendations have been implemented in some form in the past; the key to making them sustainable is to build long-term commitments from all parties at the highest level.

⁵¹ Zielke, A., *et al.*, "Race 2015: Refueling Automotive Companies' Economics." Germany, McKinsey & Company (2005) p. 73.

⁵² *Ibid.*

⁵³ Zielke, A., *et al.*, "Race 2015: Refueling Automotive Companies' Economics." Germany, McKinsey & Company (2005) p. 73-85.

Chapter 5: Conclusions and Future Work

5.1 Summary

A simple and flexible life cycle cost estimation tool has been developed for use in the Global Paint and Polymers Center (GPPC) at General Motors. This tool enables users to build estimates of life cycle cost over arbitrary time periods by entering separate line items into pre-defined user forms. Powerful built-in sensitivity analysis tools allow users to test the sensitivity of life cycle cost to fluctuations in inputs. Finally, the estimates of life cycle cost generated in this tool can then be compared, using a separate analysis tool, to determine net present value, internal rate of return, and payback of one project with respect to another. Taken together, these tools allow engineers at the GPPC to quickly generate estimates for investment and operating costs for a given project over its life.

While the cost estimation tool provides insight into investment and operating costs, separate estimates of hidden costs must be determined on a case-by-case basis. In this work, three classes of hidden costs are defined – variation, disruption, and flexibility – and frameworks for evaluating each of these classes are given. The cost of variation can be estimated using statistical analysis on historical data that is analogous to the situation of interest. The cost of disruption can be estimated by integrating experience curves over the time period of the disruption. The cost or benefit of flexibility can be simulated using Monte Carlo techniques. Taken together, these classes of cost can potentially represent a significant component of life cycle cost and therefore must be considered when making projections.

Finally, this work has been placed in a broader context by considering the impact that accurate cost estimation methods will have on the relationships between GPPC personnel and other stakeholders in the cost estimation process. By considering life cycle cost over investment cost, the needs of all stakeholders can be met and management can ensure that employees make optimal decisions over the long term.

5.2 Suggestions for Future Work

The first set of suggestions for future work involves integration of the life cycle cost estimation tool described in Chapter 2 with additional tools and models at General Motors. First,

while the life cycle cost estimation tool developed in this work has limited ability to link process parameters to cost (in particular, for material usage), a fully integrated process-based cost model could be developed that uses mathematical and logical relations to link inputs to cost. For example, instead of manually entering in required process equipment based on projected capacity, an integrated model would have logic that describes the equipment necessary for a given capacity, and seamlessly switch between different configurations as capacity is varied. That is, in its current state, the tool cannot automatically vary the assumptions that describe the changes in equipment requirements that accompany changes in capacity – the user must build separate scenarios to describe this behavior. A fully integrated tool would thus help the user make the correct choices in input and allow more accurate sensitivity analysis when inputs are varied over a wide range. This integration could follow the guidelines set forth in the bill of engineering (BOE) and bill of process (BOP) developed for paint facilities at General Motors. Further up the chain, the output of the cost estimation tool could also be integrated seamlessly into the streamlined project proposals viewed by upper management, which compare project cost to future revenue streams. Currently, the output is rather detailed, and automatically user-friendly graphs and tables could cut down on the time required to package the model output.

Regarding hidden costs, recommended future work centers on analysis of historical data. General Motors has a wealth of manufacturing data, at all levels of detail, which could be used to generate more examples of hidden cost at General Motors. In the best case, these examples could then be used to generate simple decision rules, equations, or models that would enable end-users to quickly estimate the magnitude of hidden costs. For example, the cost of disruption could be estimated with a simple questionnaire that links the type of disruption event (e.g. new part, system, or plant) to the likely effect on output and cost of disruption typically associated with that event.

Finally, this work could be expanded by considering the possible impact of long-term future trends – e.g. technological developments, changes in the competitive landscape, or new regulations – on the decisions that one would make when choosing between various scenarios. Many of the decisions made during the paint shops design phase are not easily reversed, as the facilities are built to operate over several decades and are very costly to alter. However, large-scale changes in the outside world during that time could drastically alter the recommendations provided by a cost model. For example, carbon dioxide emissions may be capped at some point

in the future, with emissions credits available for trade on the free market. This would dramatically alter the economics of carbon emissions and place a high value on energy conservation, despite the likely higher initial investment required. Additionally, abrupt changes in the marketplace, such as shifts in consumer demand or introduction of disruptive technologies, would vastly devalue inflexible plants incapable of responding to these shifts. In short, while life cycle cost estimates provide valuable guidance to managers, they must be used to supplement a comprehensive long-term strategy and vision regarding the future of automotive manufacturing.

Appendix A: Implementing Monte Carlo Analysis

The following four steps describes the basic implementation of Monte Carlo Analysis in a spreadsheet program such as Microsoft Excel.

1. Choose a statistical distribution over which to vary the input. The three most common distributions are the uniform distribution, triangular distribution, and normal distribution. The shapes of these distributions and relevant statistical parameters required for Monte Carlo simulation using these distributions are shown in Appendix Figure 1 below.
2. Generate a uniformly distributed random variable (RV) on the range [0,1]. This can be done using the RAND function in Microsoft Excel.
3. Transform this random variable to a random input (RI) for the simulation. In this step, the uniformly distributed random variable on [0,1] is converted to a randomly distributed input according to the distribution of choice.

- a. For a uniform distribution, the relation between the RV and RI is:

$$RI = \text{Minimum} + RV \times (\text{Maximum} - \text{Minimum})$$

- b. For a triangular distribution, the relation is given by:

If $RV \leq (\text{Peak} - \text{Minimum}) / \text{Maximum} - \text{Minimum}$ Then




$$RI = \text{Minimum} + [RV \times (\text{Peak} - \text{Minimum}) \times (\text{Maximum} - \text{Minimum})]^{0.5}$$

If $RV \geq (\text{Peak} - \text{Minimum}) / \text{Maximum} - \text{Minimum}$ then

$$RI = \text{Maximum} - [(1-RV) \times (\text{Maximum} - \text{Peak}) \times (\text{Maximum} - \text{Minimum})]^{0.5}$$

- c. Finally, for a normal distribution, the random input is the inverse of the cumulative normal distribution curve, for the given mean and standard deviation, that yields the random variable. In Microsoft Excel, this calculation is accomplished with the NORMINV function.
4. Calculate the resulting output.

The results of Monte Carlo analysis are usually recorded as a histogram of output values, such as cost. The shape of the histogram is determined by the statistical distributions that defined the inputs and the mathematical relations between inputs and output.

Distribution	Uniform	Triangular	Normal
Shape of Probability Density Function			
Parameters	Minimum, Maximum	Minimum, Peak, Maximum	Mean, Standard Deviation

Appendix Figure 1. Common statistical distributions used in Monte Carlo analysis.

Appendix B: Screenshots of Life Cycle Cost Estimator

In the following section, the life cycle cost estimator interface is described and several screenshots are presented through generation of life cycle costs for a purely hypothetical scenario. In this scenario, we seek to estimate the twenty-year life cycle cost for system described in the table below, operating at a volume of 250,000 vehicles per year (divided into 50 jobs per hour processed over 5000 hours in each year).

Appendix Table 1. Description of hypothetical system to be modeled in this appendix.

Input	Class	Description
Robots	Investment	Two robots at \$250,000 each, 10 year replacement cycle
Conveyors	Investment	100 feet of conveyor at \$100/foot, 7 year replacement cycle
Paint Booth	Investment	100 feet of booth at \$600/foot, twenty year replacement cycle
HVAC Equipment	Investment	\$500,000 of air handling equipment, twenty year replacement cycle
Building Space	Investment	Floor space and overhead to handle 50 ft. wide booth at \$100 per square foot
Labor	Operating	Two operators at \$50/hour
Utilities	Operating	\$5/job
Paint Material	Operating	\$10/job
Miscellaneous	Operating	\$100,000 per year to cover maintenance material and labor costs

When generating cost estimates, the first step is to define basic inputs, as shown in Appendix Figure 2 below.

Field	Value
Yearly Production Hours	5000
Jobs per Hour (Net Net)	50
Annual Work Days	225
Discount Rate (%)	15 %
Corporate Tax Rate (%)	37.5 %
Time Horizon (years)	20

Appendix Figure 2. Basic inputs for the system being modeled in this appendix.

Next, the user must input each line item into the menu shown in Appendix Figure 3 below. The fields on this menu automatically update to fit the class of cost (operating or investment), and most fields are checked to ensure that they fall within reasonable limits, which helps ensure that users cannot make simple mistakes that compromise the model (such as depreciating labor costs). As described in Chapter 2, each instance of investment must be entered separately to enable depreciation; thus, each equipment replacement occurrence is entered as a separate line item in this model. For investment costs, the initial cost is assumed to be incurred in the years given in the table above, while depreciation begins one year later. All investments were depreciated over a ten year straight line schedule; actual schedules used by General Motors vary.

Add, Edit, or Delete Line Items [X]

Line item class: Operating

Line item category: Labor

Line item: Add New Edit/Delete Existing

Item Name: Operators Unit Cost (\$): 50 No. Units: 2 Unit Type: lot

Frequency of Occurrence: Every 1 Hour(s) Year of First Use or Occurrence: 1 Annual Inflation Rate: 0 %

Depreciation Class: No Depreciation

Comment: |

Material Unit Calculator

Add to Model Update Model Delete Close

Appendix Figure 3. Sample input screen for a line item, with the inputs for labor defined according to the system described in this appendix.

In the next step, the user compiles life cycle costs and arrives at the output shown in Appendix Figure 4 (only the first three years are shown). During this step, each line item input above is annualized and annual depreciation costs are calculated. These annual costs are then converted to net cash flows and summed to yield life cycle cost.

Lifecycle Cost
\$17,990,775.71

Item Costs by Year	0	1	2	3
HVAC Equipment	\$500,000.00	\$0.00	\$0.00	\$0.00
Paint Booth	\$60,000.00	\$0.00	\$0.00	\$0.00
Conveyors, Fourteen Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Conveyors, Seven Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Conveyors	\$10,000.00	\$0.00	\$0.00	\$0.00
Robots, 10 Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Robots	\$500,000.00	\$0.00	\$0.00	\$0.00
Operators	\$0.00	\$500,000.00	\$500,000.00	\$500,000.00
Paint Material	\$0.00	\$2,500,000.00	\$2,500,000.00	\$2,500,000.00
Utilities	\$0.00	\$1,250,000.00	\$1,250,000.00	\$1,250,000.00
Miscellaneous	\$0.00	\$100,000.00	\$100,000.00	\$100,000.00
Depreciation Costs by Year	0	1	2	3
HVAC Equipment	\$0.00	\$50,000.00	\$50,000.00	\$50,000.00
Paint Booth	\$0.00	\$6,000.00	\$6,000.00	\$6,000.00
Conveyors, Fourteen Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Conveyors, Seven Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Conveyors	\$0.00	\$1,000.00	\$1,000.00	\$1,000.00
Robots, 10 Year Replacement	\$0.00	\$0.00	\$0.00	\$0.00
Robots	\$0.00	\$50,000.00	\$50,000.00	\$50,000.00
Undiscounted Net Cost	0	1	2	3
Investment	\$1,070,000.00	\$0.00	\$0.00	\$0.00
Operating	\$0.00	\$4,350,000.00	\$4,350,000.00	\$4,350,000.00
Depreciation	\$0.00	\$107,000.00	\$107,000.00	\$107,000.00
Net Cost	\$1,070,000.00	\$2,678,625.00	\$2,678,625.00	\$2,678,625.00
Discounted Net Cost	0	1	2	3
Investment	\$1,070,000.00	\$0.00	\$0.00	\$0.00
Operating	\$0.00	\$3,782,608.70	\$3,289,224.95	\$2,860,195.61
Depreciation	\$0.00	\$93,043.48	\$80,907.37	\$70,354.24
Net Cost	\$1,070,000.00	\$2,329,239.13	\$2,025,425.33	\$1,761,239.42

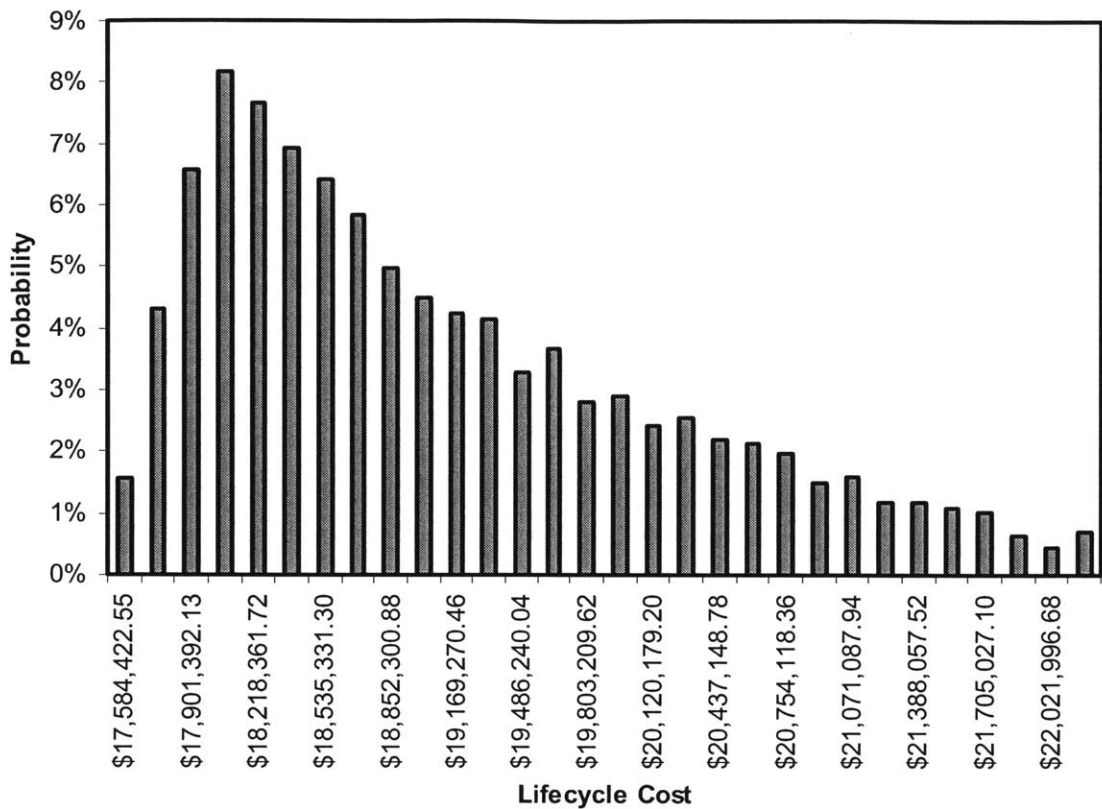
Appendix Figure 4. Sample life cycle cost output for the system described in this appendix. Because of formatting constraints, only the first three years are given.

Finally, the user can perform sensitivity analysis. Two different routines are described below. First, the input leverage routine allows the user to quickly determine which inputs drive life cycle cost, enabling quick determination of where cost cuts may be most effective and where slight errors in projections can have the largest impact on life cycle cost. A sample input leverage table is given below. Paint material and utility costs have the highest leverage, indicating that they dominate life cycle cost. On the other hand, investment costs do not exhibit high input leverage, since they are depreciated over ten years and their replacement costs are incurred far in the future.

Input	Leverage
Paint Material	0.54362%
Utilities	0.27181%
Operators	0.10872%
HVAC Equipment	0.02256%
Robots	0.02256%
Miscellaneous	0.02174%
Robots, 10 Year Replacement	0.00558%
Paint Booth	0.00271%
Conveyors	0.00045%
Conveyors, Seven Year Replacement	0.00017%
Conveyors, Fourteen Year Replacement	0.00007%

Appendix Figure 5. Input leverage for the system described in this appendix, showing that paint material and utility costs are the most significant drivers of life cycle cost.

Second, the user can perform Monte Carlo analysis. In this example, the annual inflation rate of energy costs is varied from -2% to 10% according to a triangular distribution (with peak value of 0%) and conveyor and robot replacement frequencies are uniformly varied one year from their nominal values. Life cycle cost is then determined from 10,000 trials using these assumptions. The resulting histogram is shown below. Because utility costs exhibit high leverage, this shape of the histogram is largely determined by the triangular shape of the utility cost variation assumed in this analysis.



Appendix Figure 6. Histogram that results from Monte Carlo analysis on the system described in this appendix. The annual inflation rate of energy costs is varied according to a triangular distribution from -2% to 10% (with peak value of 0%) and conveyor and robot replacement frequencies are uniformly varied plus or minus one year from their nominal values.

Bibliography

1. Andrews, D., Nieuwenhuis, P., and Ewing, P.D., "Black and Beyond – Colour and the Mass-Produced Motor Car," *Optics & Laser Technology* **38** (2006) 377.
2. Argote, L. *Organizational Learning: Creating, Retaining, and Transferring Knowledge*, Boston, Kluwer Academic (1999).
3. Barberich, B., "Application of Color Powder Paint in the Automotive Industry." Master's Thesis, Massachusetts Institute of Technology (2004).
4. Beuerle, J.E., "A Study of Electrostatically Applied Powder Paint in the Automotive Industry," Master's Thesis, Massachusetts Institute of Technology (1996).
5. "BMW to Operate World's First Green Paint Shop," *Business Wire*, May 5, 2006.
6. *CIA World FactBook*, <https://www.odci.gov/cia/publications/factbook/geos/xx.html>.
7. Claya, J., Personal Communication (2006).
8. Data Monitor, *Global Paints & Coatings Industry Profile*, www.datamonitor.com (2005).
9. DeWitt, C.M., "A Holistic Approach to Automotive Powder Coating." Master's Thesis, Massachusetts Institute of Technology (1995).
10. Dobson, I.D., "Life Cycle Assessment for Painting Processes: Putting the VOC Issue in Perspective," *Progress in Organic Coatings* **27** (1996) 55.
11. Gaines, L., and Stodolsky, F., "Lifecycle Analysis for Automobiles: Uses and Limitations," *Society of Automotive Engineers International Congress & Exhibition* (1997).
12. Gasser, R.A., "Achieving High Microprocessor Manufacturing Output – The Copy Exactly! Method," *International Electron Devices Meeting Technical Digest* (2002) 318.
13. Goldratt, E. *The Goal*, Third Revised Edition. Great Barrington, MA, North River Press (2004).
14. Halberstam, D. *The Reckoning*. New York, William Morrow and Company (1986).
15. Harhoff, D., Henkel, J., and von Hippel, E., "Profiting from Voluntary Information Spillovers: How Users Benefit by Freely Revealing Their Innovations," *Research Policy* **32** (2003) 1753.
16. Henderson, B., "Perspectives on Experience," Boston, MA, Boston Consulting Group (1972).
17. Howard, M. and Graves, A., "Painting the 3Daycar: Developing a New Approach to Automotive Coatings and Lean Manufacture," *Society of Automotive Engineers Automotive and Transportation Technology Congress and Exhibition* (2001).
18. Johnson, J.C., Joyce, J.R., and Kolarik, W., "Multidimensional Design, Multicolor Powder Primer," *Metal Finishing* **98** (2000) 10.
19. Jordan, W.C. and Graves, S.C., "Principles on the Benefits of Manufacturing Process Flexibility," *Management Science* **41** (1995) 577.
20. Kalligeros, K., "Platforms and Real Options in Large-Scale Engineering Systems." Ph.D. Thesis, Massachusetts Institute of Technology, 2006.
21. Keoleian, G., *et al.*, "LCI Modeling Challenges and Solutions for a Complex Product System: A Mid-Sized Automobile," SAE Paper 982169, 1988.
22. Kirchain, R., and Field, F., "Process Based Cost Modeling: Understanding the Economic Impact of Technical Decisions," *Encyclopedia of Materials Science & Engineering*, Elsevier Science Pubs, Oxford, 2001.
23. Matson, E. and Prusak, L., "The Performance Variability Dilemma," *MIT Sloan Management Review* (Fall 2003) 39.

24. Migliore, P., "Ford Makes Electricity from Paint Fumes," *Automotive News*, September 12, 2005.
25. Montgomery, D.C., *Introduction to Statistical Process Control*, Fourth Edition. United States, John Wiley & Sons (2004).
26. Moore, G., "Cramming More Components Onto Integrated Circuits," *Electronics Magazine* **8** (1965) 567.
27. Nallicheri, R.A., "Automotive Painting: An Economic and Strategic Analysis." Master's Thesis, Massachusetts Institute of Technology (1993).
28. Natarajan, S., *et al.*, "Process Development and Manufacturing of High-Performance Microprocessors on 300mm Wafers," *Intel Technology Journal* **6** (2002) 14.
29. Papasavva, S., *et al.*, "Characterization of Automotive Paints: An Environmental Impact Analysis," *Progress in Organic Coatings* **43** (2001) 193.
30. Papasavva, S., "Addressing Environmental Concerns in the Automotive Industry," *Materials Research Society Symposium Proceedings* **895** (2006) 27.
31. Schoff, C.K., "Organic Coatings: The Paradoxical Materials," *Progress in Organic Coatings* **52** (2005) 21.
32. Schoening, P., and Leddy, L., Personal Communication (2006).
33. Storey, J., *The World's Car Manufacturers: A Strategic Review of Finance and Operations*. Automotive World, <http://www.awresearcher.com>, (2006).
34. Terwiesch, C. and Xu, Y., "The Copy-Exactly Ramp-Up Strategy: Trading-Off Learning With Process Change," *IEEE Transactions on Engineering Management* **51** (2004) 71.
35. Tong, E.H. and Loch, T.A., "Paint Usage Reduction in Automotive Paint Booths," *Society of Automotive Engineers World Congress Proceedings* (2000).
36. Truett, R., "Automakers Struggle to Wipe Out Paint Shops," *Automotive News*, August 7, 2006.
37. von Hippel, E. *The Sources of Innovation*. Oxford University Press, New York (1988).
38. Wright, T., "Factors Affecting the Costs of Airplanes," *Journal of the Aeronautical Sciences* **3** (1936), 122.
39. Wimmer, W., "Powder Clear Coat – A Quantum Leap in Automotive Paint Technology," *Society of Automotive Engineers World Congress Proceedings* (2000).
40. Womack, J.P., Jones, D.T., and Roos, D., *The Machine that Changed the World*. New York, Harper Perennial (1990).
41. Yamane, T., *et al.*, "Development of Eco-Friendly Coating Technology Paints and Coating System for Primer / Top Coat Wet-on Coating," *Review of Automotive Engineering* **25** (2004) 1999.
42. Zielke, A., *et al.*, "Race 2015: Refueling Automotive Companies' Economics." Germany, McKinsey & Company (2005).