1-1-2011

Methodological study on technology integration for sustainable manufacturing in the surface finishing industry

Tamer Girgis
Wayne State University,

Recommended Citation

Girgis, Tamer, "Methodological study on technology integration for sustainable manufacturing in the surface finishing industry" (2011). *Wayne State University Dissertations.* Paper 309.

METHODOLOGICAL STUDY ON TECHNOLOGY INTEGRATION FOR SUSTAINABLE MANUFACTURING IN THE SURFACE FINISHING INDUSTRY

by

TAMER GIRGIS

DISSERTATION

Submitted to the Graduate School

of Wayne State University,

Detroit, Michigan

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

2011

MAJOR: CHEMICAL ENGINEERING

Approved by:

____
Advisor Date

____

____

____

____

DEDICATION

To my family

ACKNOWLEDGMENTS

I would like to express my sincere appreciation and immense gratitude to my advisor, Dr. Yinlun Huang, for his invaluable assistance, support and guidance throughout my graduate study at Wayne State University. His knowledge, advice, encouragement, and dedication for his students have been essential to my success and will follow me throughout my future endeavors.

I would like to thank my dissertation committee members, Drs. Charles Manke, Joesph Louvar, Xin Wu and Cristina Piluso, for their valuable time serving on my dissertation and providing constructive suggestions that helped me improve the dissertation contents. Additionally, I am very grateful for the advice offered by my members: Jie Xiao, Zheng Liu, Rohan Uttarwar, Halit Akgun and Hao Song. I greatly appreciate the partial support from The Graduate School at Wayne State University for the Summer Dissertation Fellowship Award.

Finally, and most importantly, I would like to thank my Lord Jesus Christ for being with me and blessing my life with great people. I also greatly appreciate the financial support fully from The Girgis Family that made this doctorate degree possible. I want to express my infinite gratitude to my parents, Dr. Ozoris M. Girgis, D.D.S. and Mrs. Jannette G. Ghali, J.D., for their unconditional love, patience, encouragement, support, and many sacrifices throughout every stage of my educational path to help me build a strong foundation, achieve the highest education, and strive to become the best I can be. I would also like to thank my siblings, Mariham and Sameh for their continuous love, support, and encouragement their entire life. Finally, yet importantly, I owe my beloved fiancée Madonna the utmost heartfelt happiness, joy, and pleasure she brought to my life in the past year as well as her great motivation, encouragement and patience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Chemical and many other manufacturing industries are implementing sustainability as a crucial pillar in their business plan. It is certainly clear that the interest among chemical engineers for industrial sustainability research and education has been growing in the past decade. There are further accomplishments and discussions on sustainability and development of sustainability metrics to assist chemical industries in their global system operations. Chemical engineering is an integrative discipline in nature. In other words, it utilizes various system approaches to process a variety of optimized designs. Nowadays, chemical industries are seeking new approaches and basis for decision-making methodologies to overcome the challenges of industrial globalization, cost of operations, alternative resources and energies, and advancements in technological innovations.

Traditionally, chemical engineers design and operate complex processes in industry that manage and control specific chemical operations and systems. However, there are many constraints that chemical engineers face during design and operation, such as raw material usage, technological investments, and environmental and health safety in the work place. There are various potential impacts on industrial sustainable development, such as economic performance, environmental regulations, and social policies, to permit the industry to reach a successful degree of sustainability in the future. This requires the industry to adopt new approaches and decision-making framework without compromising their current level of sustainability. In order to manage process and product design from a sustainability perspective, this requires advanced reliable metrics to quantify the progress towards a specific sustainability level. There are two kinds of metrics used to indicate the state and the current performance of an industrial system. The first metric indicates the state of an industrial system and known as content indicators. The second metric indicates the operational behavior of an industrial system and known as performance indicators (Sikdar, 2003).

Chemical engineers attempt to measure industrial systems process improvements with regards to the three pillars of sustainability corresponding to a qualitative measure and assessment of industrial sustainability from economic, environmental and social aspects. A reliable sustainability metrics is the one that could be obtained from the intersection of all three aspects. At this intersection where sustainable development exists, a balance between economic, environmental and social aspects is simultaneously achieved. Traditionally, process design and optimization is performed based on a single sustainability bottom line, mainly economic aspects without major consideration to the other two sustainable aspects. This process design and optimization will be susceptible to an unsustainable state as a result of not considering sustainability triple bottom lines as an integral part of industrial systems. Sustainability analysis and assessment is conducted using advanced process simulations, which are readily available for approximate calculations and estimations. On the other hand, current methodologies need to be more systematic to incorporate all triple bottom lines of sustainability to present a complete sustainable state that will improve the industries sustainability performance systems.

In this research, technological base methodology is utilized to provide an integrated approach towards an industrial sustainable development for the electroplating industry. Technological network modeling is a tool to help in the development of electroplating systems and deliver a state of sustainable operation. Optimization-based decision-making modeling is a powerful methodology to help in selecting the appropriate technologies necessary to achieve sustainability in electroplating systems. The research presented deal with technological framework that would be constructive in incorporating sustainability by utilizing appropriate quantitative metrics and indices. The optimization-based decision-making methodology for system sustainability should provide clear comprehensive information to the decision-maker to confidently achieve proper accurate results to support their decisions. The combination of technological network modeling and optimization-based decision-making methodology will be tools for successful quantification, evaluation and assessment of electroplating system sustainability. The following section will discuss the current status and historic trends of the metal finishing industry sustainability crisis.

1.1 Surface Finishing Sustainable Manufacturing Problem

The metal finishing industry is an uneven service industry that is comprised of many small job shops that are typically located near large manufacturer industries. Large capital cost expenditures and increasing material costs as well as tighter environmental regulations has affected the number of metal finishing industries. On the other hand, foreign competition and offshore manufacturing hindered the success of the industry profitability. The metal finishing industry is suffering from business losses however; Asia is experiencing a huge growth. There is a need for technological development to increase the metal industry profitability and to gain visibility and competitiveness by implementing process control and monitoring to minimize production cost as well as improving product quality and eliminate use of toxic materials.

1.1.1 Industry Current Status

The metal finishing industries encompass a wide variety of processes, which provide the surface of products with various desirable physical and chemical properties as well as appearance qualities. The US Census Bureau uses the North America Industry Classification System (NAICS) 332813 number as an industrial identification code for electroplating, plating polishing, anodizing, and coloring, which is replacing the US Standard Industrial Classification (SIC) 3471 number to accommodate sectors and allows more flexibility in designating subsectors. An establishment is a single physical location at which business is conducted and/or services are provided. It is not necessarily identical with a company or enterprise, which may consist of one establishment or more. (U.S. DOC, 2007)

According to the 2007 US Census Bureau, the number of establishments and companies are 2,720 and 2,611 respectively. Compared to the 2002 US Census Bureau the number of establishments and companies were 3,066 and 2,932 respectively (U.S. DOC, 2007). From 2002 to 2007, the statistics shows a reduction in the number of total establishments and companies in the United States metal finishing industry of about 10.9 % and 11.3 % respectively, see Figure 1.1.

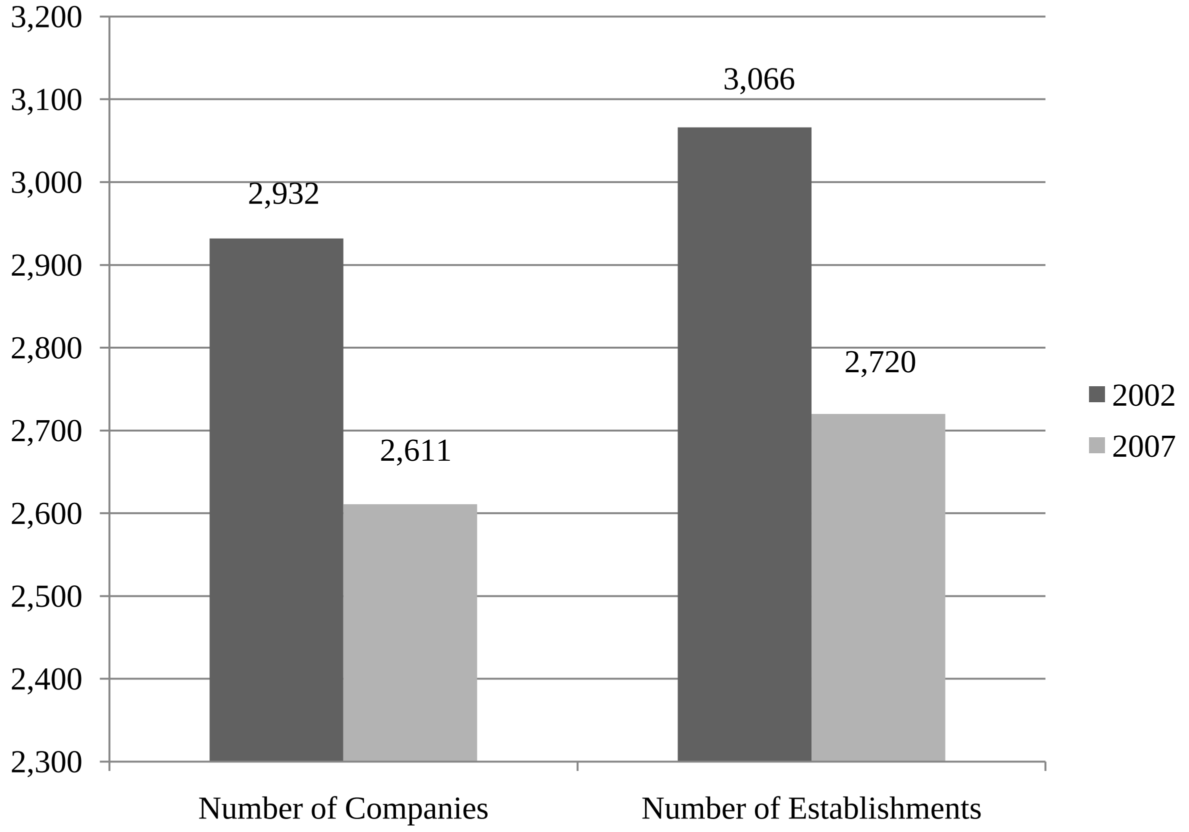


Figure 1.1. Comparison of metal finishing companies and establishments in 2002 and 2007 (U.S. Census Bureau, 2007).

This resulted in a decrease in the work force especially in production workers by 5% and overall industry's employment by 3.2%. This is also reflected in a decrease in the production hours of about 4.7% during those five years see Figure 1.2. On the other hand, the metal finishing total capital expenditures and material cost increased significantly to be 15.3% and 35.8 % respectively. There has been a 7% increase in the production workers wages and 8.6% increases in all employees payroll during this period, see Figure 1.3.

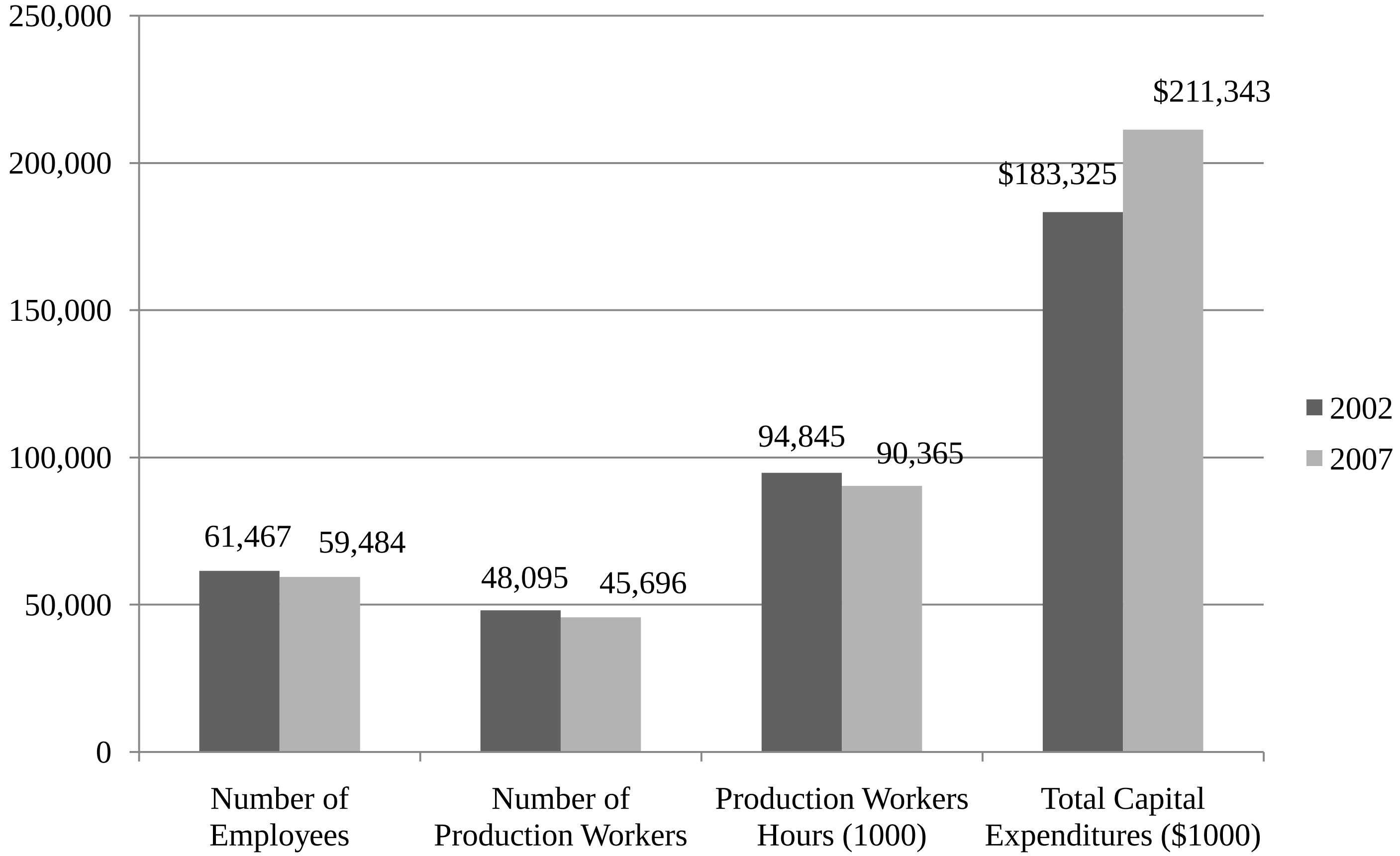


Figure 1.2. Comparison of number of employees, production workers, production workers hours, and total capital expenditures in 2002 and 2007 (U.S. Census Bureau, 2007)

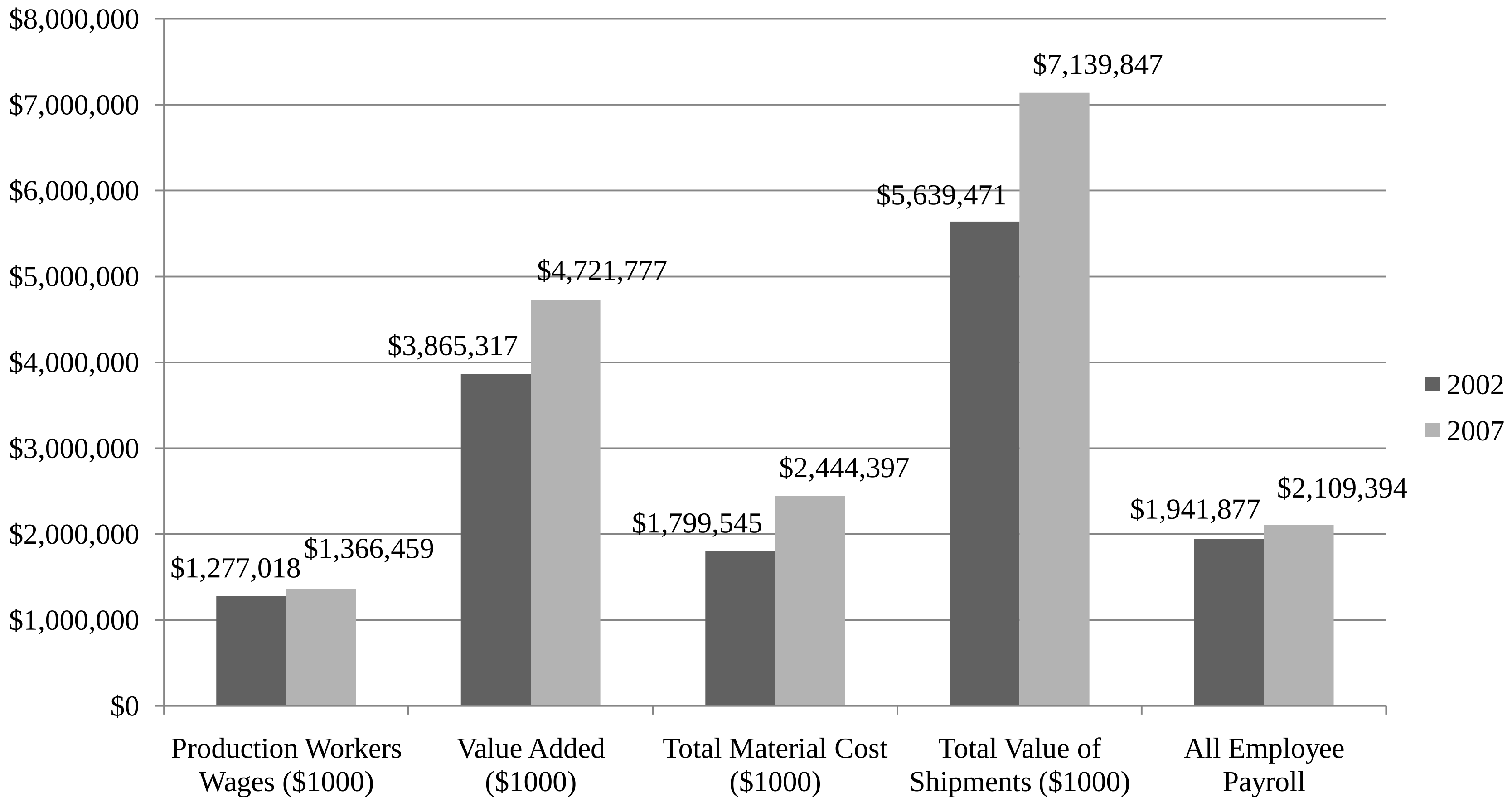


Figure 1.3. Comparison of amount of production workers wages, value added, total material cost, total value of shipments, and employee payroll in 2002 and 2007 (U.S. Census Bureau, 2007)

Table 1.1 summarizes the percentage change in number of companies and establishments, number of employees and their payroll, number of production workers and hours worked, total capital expenditures and material costs, value added, and total value of shipments for 2002 and 2007 according to the statistics collected by US Census Bureau see Figure 1.4.

Table 1.1. US Census Bureau Electroplating Statistics (U.S. DOC, 2002; 2007)

Statistics Criteria	YEAR		% Change
	2002	2007	
Number of Companies	2,932	2,611	-10.9
Number of Establishments	3,066	2,720	-11.3
Number of Employee	61,467	59,484	-3.2
Number of Production Workers	48,095	45,696	-5.0
Number of Production Workers Hours (1000)	94,845	90,365	-4.7
Total Capital Expenditures ($1000)	$183,325	$211,343	15.3
Production Workers Wages ($1000)	$1,277,018	$1,366,459	7.0
Value Added ($1000)	$3,865,317	$4,721,777	22.2
Total Material Cost ($1000)	$1,799,545	$2,444,397	35.8
Total Value of Shipments ($1000)	$5,639,471	$7,139,847	26.6
Employee Payroll	$1,941,877	$2,109,394	8.6

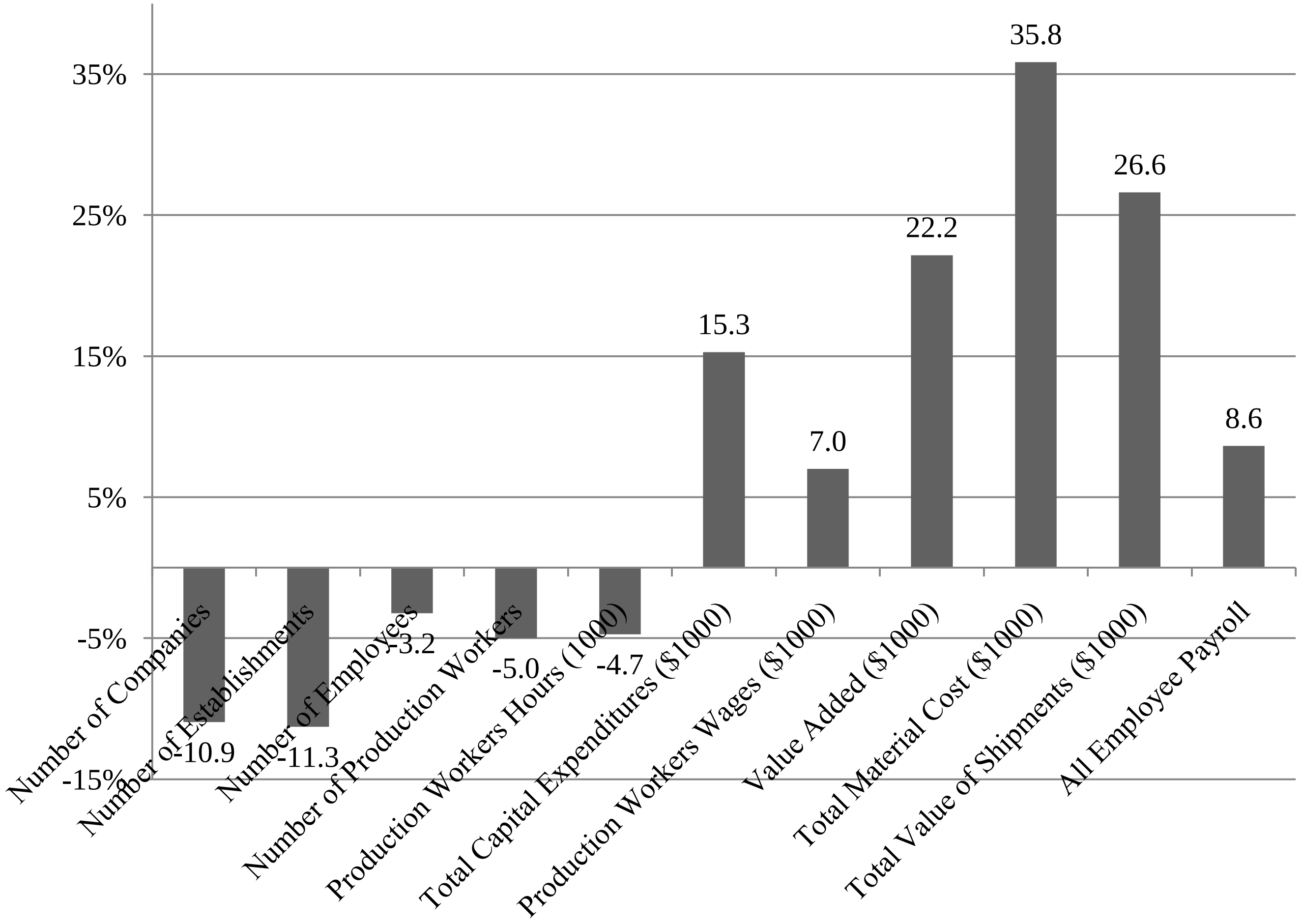


Figure 1.4. Percentage change of metal finishing industry statistical comparisons in 2002 and 2007 (U.S. Census Bureau, 2007)

The aforementioned statistics depicts that the metal finishing industry in the United States has been facing dramatic economic, environmental, and social challenges that is reflected on the industries performance and hindering its future prosperity (SFMRB, 2004). The metal finishing industry under such challenges needs technological innovations to guide its progress in a sustainable manner. A technological development will aid the metal finishing industry and its supply chain to make better decisions through sustainable assessment methodology that will provide the industry with detailed statistical information for their business development in the future.

1.1.2 Industry Historic Trends

The metal finishing industry can be categorized into two sections depending on their size and nature of their operations. First category, captive operations meaning establishments that conduct metal finishing within larger manufacturing operations. Second category, job shops meaning independently owed establishments that contract with manufacturing industries for their finishing needs. According to the US Environmental Protection Agency (EPA), the metal finishing industry is composed of small independently owned facilities that employ 50 or fewer employees. The industry is highly concentrated in industrialized areas such as the great lakes states, California, Texas, and Florida (U.S. EPA). A geographical illustration of the number of establishments for the metal finishing industry is illustrated in Figure 1.5 (U.S. DOC, 2007).

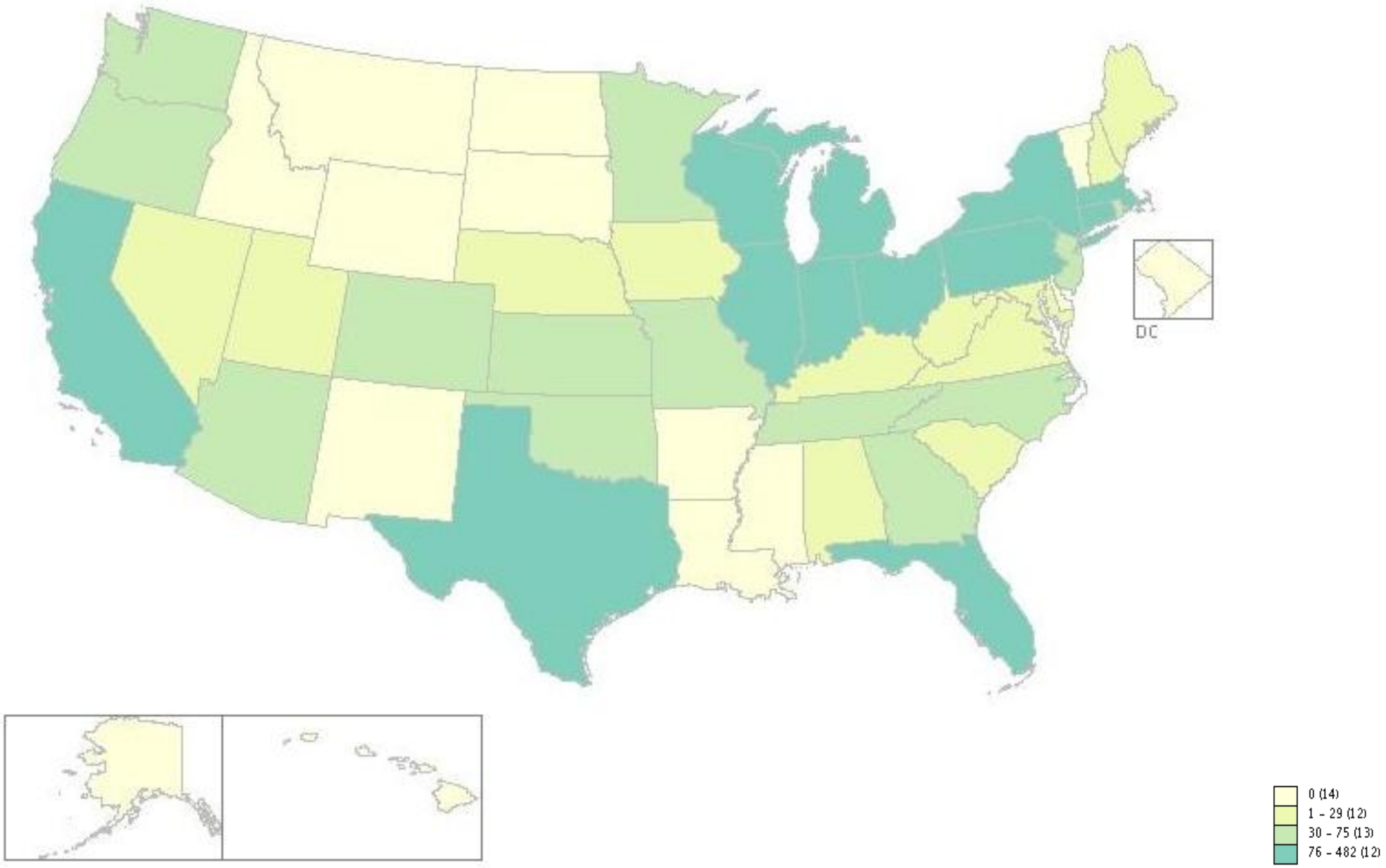


Figure 1.5. U.S. geographical distribution of number of electroplating establishments. (U.S. Census Bureau, 2007)

This industry is facing major economic pressures from foreign competition and declines in the US automotive industries which lead to continuous decline in the number of establishments and reduction in the number of employees. Metal finishing job shops have limited financial resources at their disposal due to small profit margins. Capital investments are highly dependent on the economy and driven by customer demands. The industry has been affected by high production costs, environmental compliance and strict regulations. The existence of job shops is related to the cost structure of captive operations and the nature of metal finishing operations in relation to the manufacturing process supply chain. This requires intensive capital investment and loss of valuable floor space that will only have minor financial benefit to the larger manufacturer facility value-added of their products. From a large manufacturing industry business view, it is more desirable to outsource the finishing process to a job shop operations to avoid undesirable costs and regulations. The metal finishing industry has a growing trend of moving overseas specifically to Asia (SFMRB, 2005).

1.2 Challenges Facing the Surface Finishing Industry

The metal finishing industry has been influenced by modern science and technology advancements. Profitable Pollution Prevention (P3) technologies have been directed to improve plant operations, alternative materials and solvents, in-process modification, and utilizing renewable energy. Pollution prevention focuses mainly on toxic industrial wastes and methods of controlling their use in metal finishing facilities. In 1992, the U.S. EPA launched the "design for the environment" (DfE) program to aid in chemical process designs by publishing information on industrial toxic wastes and comparative risk and performance of chemicals in order to assist in an optimum environmental design. This will create a mind set of substituting toxic chemicals by less toxic ones and ensure proper handling and operator exposure risk for toxic chemicals that cannot be replaced (U.S. EPA).

1.2.1 Economic Challenges

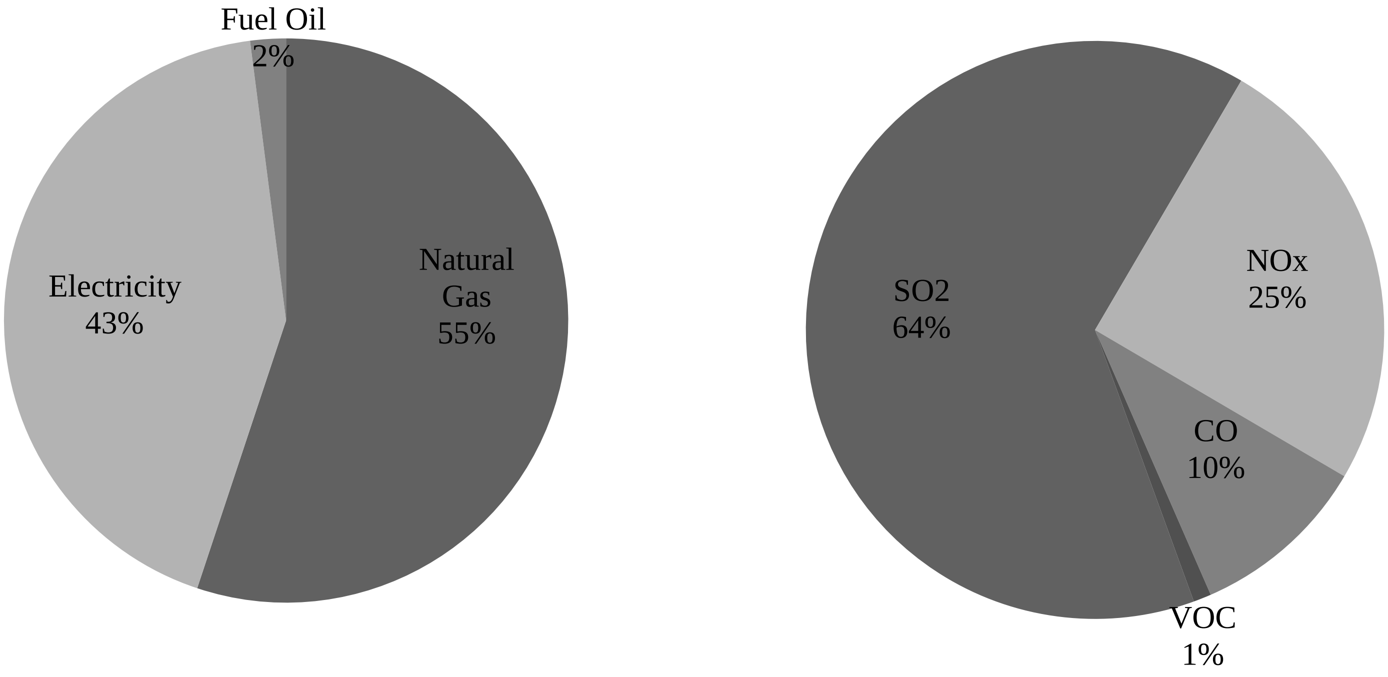
The metal finishing industry depends on electricity and natural gas as their source of energy for their daily operations. Approximately half of the energy cost is split between electricity and natural gas as primary energy inputs of the total energy supply to the industry. Figure 6 illustrates that electricity and natural gas is about 43% and 55% respectively of the total energy supply to the metal finishing industry (U.S. EPA, 2007). It is very crucial to find alternative clean energy sources and more efficient to enable the industry to be more profitable and environmentally friendly. There are many energy efficiency opportunities available to the metal finishing industry; however, the economic challenges the industry faces forces that improvements to be from retrofitting existing technologies with other more efficient equipment instead of changing the entire process.

1.2.2 Environmental Challenges

Metal finishing facilities are required to obtain an air pollution permit and to file for a new permit according to requirements based on federal and/or state regulations. Also, many regional and local governments have their own requirements which make the metal finishing industry challenging to become profitable and compliance at the same time. Many energy efficient technologies offer improvement opportunities for the metal finishing industry focus on waste reduction in existing processes and substitution to conventional electroplating processes. Figure 1.6 depicts that according to the 2002 National Emission Inventory (NEI) 90% of energy related emissions are composed of sulfur dioxide and nitrogen oxides. An increase in energy consumption will affect energy related Criteria Air Pollutant (CAP) emissions by pollutant. Implementation of new technologies to replace conventional heat and power equipments by generating energy in a clean and efficient approach (U.S. EPA, 2007).

1.2.3 Social Challenges

Metal finishing facilities are complex systems that are integrated to perform specific operations. It is of great importance to conduct such operations in a safe state free from hazard or danger to the operators and employees in this dynamic chemical environment. The condition of the industrial facility to operate according to federal and state standards is of utmost significance to the plant in order to avoid legal actions filed against it if proven that the employees are at high risk being exposed to hazardous chemical compounds, chemical reactions, unit operations and equipment condition. There is a strong demand to follow stringent rules and regulations to fulfill government and customers requirements to create a safe working environment. The industry's safety performance during operation depends on the system complexity and the operators training capabilities to run the equipment and overall process according to common safety standards. Safety is a challenging issue for the metal finishing industry to maintain and guarantee for operators and other surrounding industrial zones.



(a) (b)

Figure 1.6. (a) Electroplating total energy supply (b) Electroplating CAP emissions by pollutant (U.S. EPA, 2007)

1.3 Technology Development Need

Technological advancements in the metal finishing industry focus on process chemistries and optimization processes to recover metals and treat wastewaters. Process control techniques require critical understanding of metal finishing operation parameters in order to effectively implement chemical recovery technologies, solution maintenance technologies, material and process substitutions, and waste reduction optimization practices at the same time pay attention to environmental, economic and social tradeoffs associated with the technologies implementation (Haveman, 1995).

The survival of the metal finishing industry depends on implementing new technologies or optimization of existing technology that will facilitate market competitiveness which will lead to operating cost reduction, product quality improvement, increase productivity rate, waste generation minimization and expand process capability. Commercially available process control technologies improved metal finishing process performance and resulted in significant profitability for the metal finishing industry. Although automation technologies have been developed for metal finishing process lines, a large number of process lines and lab analysis in metal finishing plants are manually operated and controlled. Automation of manual process lines is a step in the right direction to ensure consistent production quality and provide essential production data for troubleshooting, monitoring, and evaluating process improvement. Optimization of current surface finishing process lines with the purpose to reduce chemical usage, waste generation and operator exposure to harmful chemicals, without compromising production rate and quality (Steward, 1993). Some of the existing technology trends in the metal finishing industry are pursuing sustainable manufacturing; improve in energy efficiency and process monitoring and control systems, and optimizing wet processes to achieve near zero discharge. Pursuing sustainable manufacturing indicates utilizing processes and systems that possess energy conserving, economically efficient, environmentally friendly, and safe for operators and customers. This trend will lead to improvement in the performance of traditional surface finishing processes; however, there is a new technology trend that is being implemented by larger metal finishing industries or during new construction of production lines. They are adopting newly developed technologies such as changing from wet process chemistries to dry process chemistries, using green environmentally friendly chemistries, changing substrate material from metal finishing to non-metals, and incorporating nanotechnology metal coating processes.

A proficient transition in technology trends will start by optimization of existing technologies then implementing new advanced ones which is driven by environmental regulations and economic restrictions. Since there is a continuous pressure to reduce environmental impact and liabilities, the metal finishing industry will implement a long term plan to modify traditional metal finishing processes to maximize material utilization and recovery or converting to green chemistries and dry processes for new processes. The optimum cost effective time to implement process optimization technologies is during new or renovated processes are being designed and installed. Many surface finishing facilities implemented process optimization to achieve near zero discharge and exposure risk. Those implementations lead to significant cost savings due to better process performance by utilizing fewer raw materials and minimizing waste generation (Cushnie, 1994).

From a sustainability point of view, production using processes that are energy conserving, environmentally friendly, economically efficient, and socially safe requires a systematic approach to view the life cycle of the product. Sustainability requires that production and consumption be preserved for future generations. Using green chemistry will reduce or eliminate generation of toxic hazardous wastes. Over the past decade, there have been various green technologies developed to replace or eliminate existing harmful chemistries such as replacement for cyanide and cadmium plating chemistries, development of trivalent passivation to eliminate hexvalent chemistries, and organic stabilized electroless nickel. Proper implementation of sustainable technologies requires strategic planning and process support system for the new chemistry and infrastructure.

Recently, many metal finishing industries are implementing new specialized products and advanced processing technologies that are sustainable and provide competitive market share. This advantage in promoting sustainable alternatives to conventional processes and products will have a positive influence on other manufacturers to take the opportunity to pursue sustainability goals. This will involve decisions to change production strategies and processes such that customers will accept more sustainable products which will result in great business and continuous sustainability improvement. Technological advancements in both process energy efficiency and in process design as well as proper management for reducing energy consumption is a major technology trend in the metal finishing industry due to high and potentially increasing in energy costs and environmental regulations to reduce pollution and conserve resources.

1.4 Objective, Significance, and Scope

The main goal of this research is to develop an industrial sustainability assessment of electroplating systems and optimization-based decision-making methodology that utilizes technology to evaluate the performance and effectiveness of the new process design for achieving a positive sustainability state.

There are many problems and hazards facing the electroplating and metal finishing industries that require a new technological approach with optimization based decision making modules to intelligently select the optimum technological path that is suitable for attaining a sustainable state and improving the overall sustainability performance. Various problems are classified as economic, environmental, and social challenges. A number of major economic challenges on a plant level are increasing in chemical costs, waste generation and operations costs; moreover, a decrease in the amount of recycling operations for water or chemicals due to lack of technologies or ineffective technological selection. All of this will have a negative effect on the plant profitability and the overall industrial sustainability. Several environmental challenges the electroplating industry are facing, such as toxic waste generation from spent plating solutions, chemical additives, and pre-treatment chemistries, continuous chemical addition due to drag in/drag out, spent acids and bases during stripping and cleaning operations that causes major gassing and tank over flowing into waste treatment facilities, lead sulfates sludge due to anode decomposition, waste water during rinsing parts and cleaning process line filters, and finally, top coats contamination from waxes, seals, and paints. All of the aforementioned challenges will impact the plant environmental sustainability, if it is not properly controlled and monitored using an integrated technological approach. Social challenges include plant safety and security, number of reported accidents per year. This could be as a result of direct human contact and exposure to harmful toxic fumes generated from electroplating bath reactions and poor ventilation system for gaseous emissions. Another direct human contact is during transferring or addition of harmful chemicals to the process lines.

Objectives and scope. This research is to develop a holistic methodology for sustainability assessment and decision-making that will assist in improving the sustainability level through implementing sustainable technologies in manufacturing systems through case studies, particularly on the electroplating industry. The scope of this methodology is general but our intent is to apply it on electroplating metal substrate processes. There are many other issues the electroplating industry is facing, such as supply chain challenges. Our focus is specifically concentrated on the electroplated product and process lines, such as in process environmental issues rather than post or offsite environmental issues.

Significance. To the best of our knowledge, this optimization based technological network development approach is the first systematic approach that provides a comprehensive methodology to determine how to integrate the optimum technologies together with an expectation that the group of selected technologies will seek the most benefits and profitability as a result of industrial sustainability enhancement. This work argues that technological network modeling combined with optimization-based decision-making methodologies will provide an integrated holistic approach to assist industry not only to achieve a sustainable degree but also to improve their sustainability performance.

1.5 Thesis Organization

This dissertation will first present an industrial sustainability assessment approach specifically for the metal finishing industry in Chapter 2. Then the remainder of the thesis is structured to associate each of the selected industrial sustainability triple bottom lines metrics introduced in Chapter 2 to aid in the technological assessment methodology. In Chapter 3, technology-based sustainability modeling and analysis is discussed. Furthermore, an optimization-based decision-making approach for industrial sustainability is being introduced in Chapter 4, in which three optimization models are evaluated based on investment-constraint, sustainable-goal-oriented, economic-development-focused model, and a solution strategy discussion for optimal industrial sustainability. Chapter 5 discusses applied studies on electroplating industrial sustainable development decision making using technology integration for overall system improvement and optimization. Finally, Chapter 6 presents concluding remarks and future work.

CHAPTER 2

SURFACE FINISHING SUSTAINABILITY ASSESSMENT

2.1 Sustainability Metrics and Indicator Selection

Developing metrics for sustainable manufacturing is critical to enable industries to quantitatively measure their sustainability performance in specific processes. Currently, there is a focus towards achieving overall sustainability in the metal finishing industry that is arising due to various emerging challenges which are diminishing non-renewable energy and natural resources, devastating global environment deterioration, stricter regulations related to environment, human pursuing higher occupational health and safety quality, and increasing consumer preference for environmentally-friendly products. In particular, the metal finishing sector, which is the core of many industrial manufacturing processes, must achieve a sustainable level in order to preserve the high quality and standards of living sustainably. Further, the industrial sustainability improvement effort is analyzed by the benefits at three dimensional perspectives: environmental, economic, and societal. The most widely accepted common definition of sustainable development is provided by the United Nations' Brundtland Commission and defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED, 1987). In general, the phrase "three-pillar" or "triple-bottom-line" concept has become common to describe sustainable development. There are many attempts to measure and analyze the performance of the three aspects of sustainability by developing quantitative or qualitative sustainable indicators.

The main purpose of these indicators is to evaluate each aspect of sustainability which are environmental performance, social responsibility and economic contribution.

2.1.1 Triple Bottom Line Requirement

There is no doubt that sustainability metrics are increasingly sophisticated in content and methodology; in addition to providing meaningful measurements from data collected for suitable decision-making activities. Proper metrics selection will assist in supporting and evaluating technical alternatives, comparing different technologies and processes, identifying environmental aspects and impacts of industrial unit operations, tracking overall performance of industrial sector (Tanzil and Beloff, 2006). Figure 2.1 illustrates how sustainability triple bottom line interlink to achieve sustainable development. At the intersection of the three circles economic, environmental and social sustainability is achieved depending on the relationship between each triple bottom line aspects. This multi-dimensional sustainability is very challenging to achieve due to the complexity of their interrelation between each other. Socio-economic, socio-environmental, and eco-efficiency exist at the intersections of two aspects of sustainable metrics. Socio-economic criteria depends on the relationship between the economy and the societal well being such as investments and job availability. Socio-environmental criteria depend on the relationship between the environment and the social aspects such as the effect of natural resource depletion and the environmental impact on people health and safety. Eco-efficiency criteria depends on the relationship between the economy and the environment such as using less natural resources with less environmental impact of toxics and wastes.

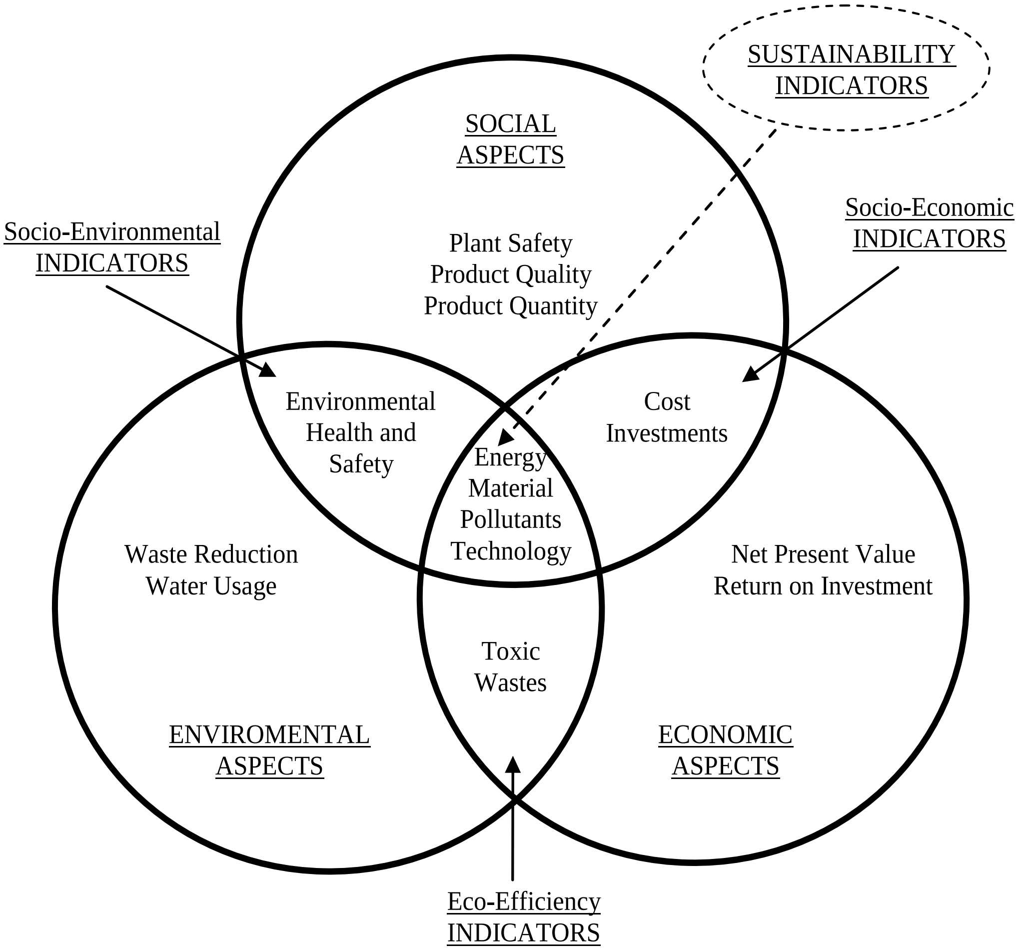


Figure 2.1. Sustainability Triple Bottom Line Metrics and Indicators Intersecting Circles.

2.1.2 Criteria for Sustainability Metrics Selection

There are many sustainable indicators that cover a wide spectrum from being general to sector specific depending on the industry of interest. Sustainability indicators could be categorized in various ways depending on the metrics selection as shown in table 2.1 (Feng and Joung, 2009b). In general indicators should have some characteristics to satisfy the following criteria: a) measurable quantitatively or qualitatively according to sustainability triple bottom line; b) cost effective from a data collection and availability stand point; c) relevant and useful for the entity under evaluation to fit the purpose of measuring its current and future performance for decision making; d) simple and understandable to a variety of users other than the experts; e) complement and compatible with existing regulatory programs; f) scalable for multiple boundaries of analysis; g) protective of proprietary information; h) robust to illustrate better sustainable performance; and h) reproducible and consistent in comparing different time periods and decision alternatives.

Table 2.1. Common Sustainability Indicators and Metrics.[1]

Indicator Name	Components	Reference
Global Reporting Initiative (GRI)	70 indicators	http://www.globalreporting.org/ReportingFramework/ReportingFrameworkDownloads/
Dow Jones Sustainability Index (DJSI)	12 criteria based single indicator	http://www.sustainability-index.com/07_htmle/publications/guidebooks.html
2005 Environmental Sustainability Indicators	76 building blocks	http://www.sustainability-index.com/07_htmle/publications/guidebooks.html
2006 Environmental Performance Indicators	19 indicators	http://sedac.ciesin.columbia.edu/es/epi/downloads/2006EPI_Report_Full.pdf
United Nations Committee on Sustainable Development Indicators	50 indicators	http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf
OECD Core Indicators	46 indicators	http://www.oecdbookshop.org/oecd/display.asp?sf1=identifiers&st1=972000111E1
Indicator Database	409 indicators	http://www.Sustainablemeasures.com
Ford Product Sustainability Index	8 indicators	http://www.ford.com/doc/sr07-ford-psi.pdf
GM Metrics for Sustainable Manufacturing	46 Metrics	http://actionlearning.mit.edu/s-lab/files/slab_files/Projects/2009/GM,%20report.pdf
ISO 14031 Environmental Performance Evaluation	155 example indicators	http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_ics_browse.htm?ICS1=13&ICS2=20&ICS3=10
Wal-mart Sustainability Product Index	15 questions	http://walmartstores.com/download/3863.pdf
Environmental Indicators for European Union	60 indicators	http://biogov.cpdr.ucl.ac.be/communication/papers/tepi99rp_EN105.pdf
Eco-Indicators 1999	3 main factors based single indicator	http://www.pre.nl/eco-indicator99/ei99-reports.htm
IChemE Sustainability Metrics	49 indicators	http://www.icheme.org/sustainability/metrics.pdf

---

[1] Modified from Feng and Joung, 2009b.

Using proper sustainability metrics and indicators will assist in measuring and evaluating the sustainability performance of the industry. According to the sustainability performance results, decisions could be made to determine the trend of sustainability and how to achieve the goal within a specified time frame (Tanzil and Beloff, 2006). There are a vast number of different sustainability indices developed; however, most of them incorporate similar data because of the small number of available global sustainability data collected by various international organizations using similar methods to collect and aggregate the desired data. Since sustainability indices are made measurable, the results and decisions are given more weight by scientists and experts in the field; however, it is very important to consider all the factors that influence each indicator (Mayer, 2008). Figure 2.2 depicts that recent sustainability research depend simultaneously on quantitative data and include more metrics dimensions. It is important to determine system sustainability by taking in consideration both the path of the system and its position with respect to multidimensional sustainable boundaries. Mayer modified Cabezas *et al.* trajectory of a system perspective figure to illustrate that a system which is unstable in one metrics dimension is not generally sustainable because multiple indicators are used to measure each metrics dimension and aggregated into an index which will identify the overall position and trajectory of the system (Mayer, 2008).

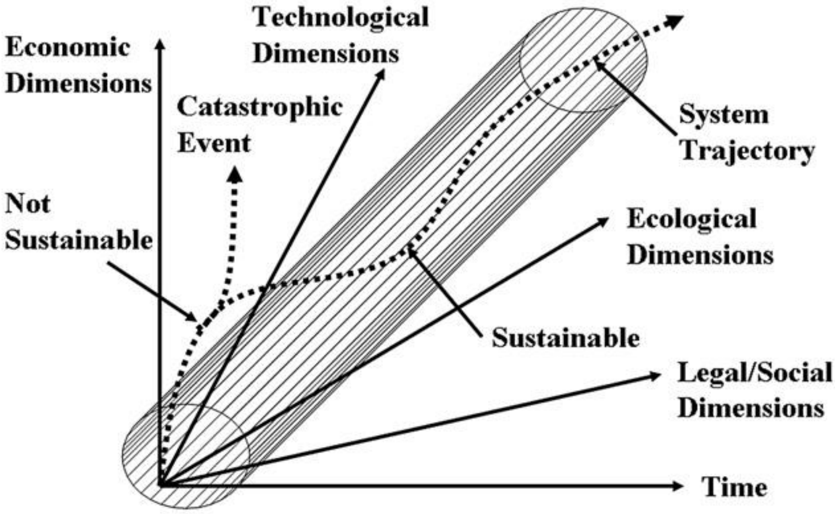


Figure 2.2. System trajectory and its position with respect to multidimensional sustainability boundaries (Mayer, 2008).

2.1.3 Common Sustainability Metrics

There have been many attempts and initiatives to develop robust guidelines for indicator selection and their recommended utilization related to sustainability performance and applications for various entities starting from unit operations within companies to regions and industrial zones; moreover, expanding to the national and global level. A summary of most commonly publicly available sustainability metrics and indicators are summarized in table 2.1. Feng *et al.* summarized some of the available sustainability indicator sets with a brief explanation to clarify the current state of metrics development.

Institute of Chemical Engineers (IChemE). In 2002, the institute of Chemical Engineers (IChemE) published a set of sustainability indicators to measure the sustainability of operations within the process industry see Figure 2.3. It is important to note that not all IChemE metrics will be applicable to every industrial operation. Engineers should select the most relevant metrics that is suitable for each specified unit operation. However, selecting relevant metrics is a challenge in order to properly quantify the sustainability performance for each of the three areas environmental, economic, and social (IChemE, 2002).

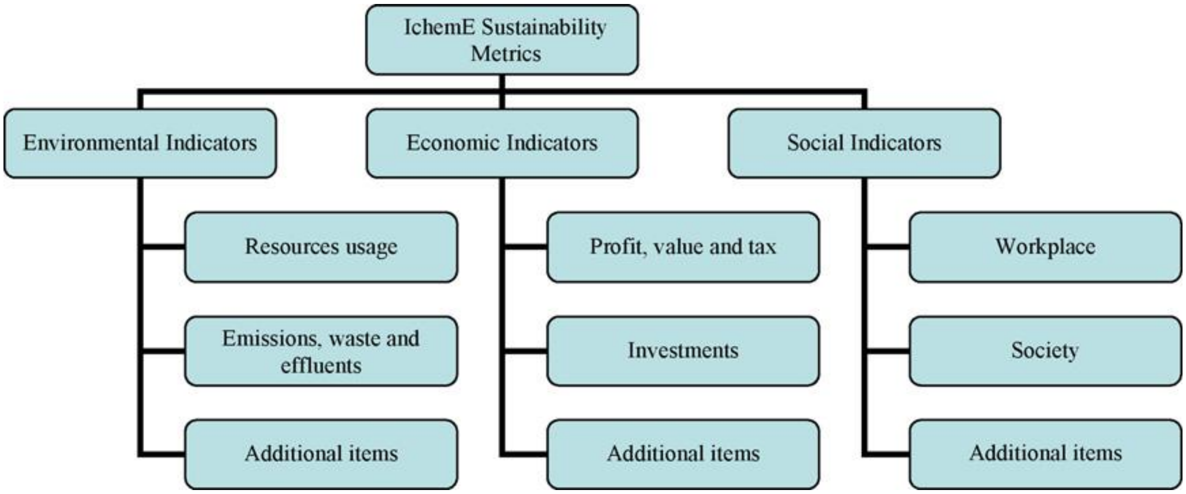


Figure 2.3. The Institute of Chemical Engineers (IChemE) Sustainability Metrics, 2002.

With respect to the metal finishing industry, a precise selection of the metrics are chosen to properly quantify each aspect of the process operations in all three areas. Tables 2.2 - 2.4 describes the selected IChemE metrics and indicators with their units that is suitable for quantifying the metal finishing industry sustainability performance environmentally, economically and socially. On the left hand side, vertical column, are first listed the sustainability metrics: environmental, economic, and social. Those indicators will help to describe the collected data in quantifiable terms to be used to assist decision making in determining the current sustainability status and future sustainability performance for the industrial sector.

Table 2.2. IChemE Environmental Sustainability Metrics (IChemE, 2002).

Metrics		Indicators	Value
ENVIRONMENTAL	Energy (Electricity and Gas)	Total Net Primary Energy Usage Rate = Imports - Exports	GJ/y
		Total Net Primary Energy Usage/Kg Product	KJ/Kg
		Total Net Primary Energy Usage/Unit Value Added	KJ/$
	Material (excluding fuel and water)	Total Raw Materials used/Kg Product	Kg/Kg
		Total Raw Materials used/Unit Value Added	Kg/$
		Fraction of raw materials recycled within company	Kg/Kg
		Hazardous Raw Mateiral/Kg Product	Kg/Kg
	Water	Net water consumed/Unit mass of product	Kg/Kg
		Net water consumed/Unit value added	Kg/$
	Land	Total land occupied + affected for value added	$\mathrm{m}^2/(\$/\mathrm{y})$
	Atmospheric Impacts	Atmospheric acidification burden/Unit value added	te/$
		Global warming burden/Unit value added	te/$
		Human health burden/Unit value added	te/$
		Ozone depletion burden/Unit value added	te/$
		Photochemical ozone burden/Unit value added	te/$
	Aquatic Impact	Ecotoxicity to aquatic life/Unit value added	te/$
	Waste	Hazardous solid waste/Unit value added	te/$
		Non-hazardous solid waste/Unit value added	te/$

Table 2.3. IChemE Economic Sustainability Metrics (IChemE, 2002).

Metrics		Indicators	Value
ECONOMIC	Profit / Value / Tax	Value Added = Sales - Cost (goods, raw materials, services)	$/y
		Value Added/Unit value of sales	$/$
		Value Added/Direct employee	$/y
		Cost Margin/Direct employee	$/y
		Return on Average Capital Employed	%/y
		Taxes paid (% of Net Income Before Tax)	%
	Investments	% increase (decrease) in capital employed	%/y
		R&D expenditure as % sales	%
		Employees with post-school qualification	%
		New appointments/Number of direct employees	%/y
		Training expense as % of payroll expense	%
		Ratio of indirect jobs/Number of direct employees	
		Educational investment/Employee traininng expense	$/$
		Charitable gifts as % of NIBT	%

Table 2.4. IChemE Social Sustainability Metrics (IChemE, 2002).

Metrics		Indicators	Value
SOCIAL	Workplace	Benefits as % of payroll expense	%
		Employee turnover (resigned+redundant/number employed)	%
		Promotion rate (number of promotions/number employed)	%
		Working hours lost as % of total hours worked	%
		Income+benefit ration (top10%/bottom 10%)	
	Society	Number of stakeholders meetings/Unit value added	/$
		Indirect community benefit/Unit value added	$/$
		Number of complaints/Unit value added	/$
		Number of legal action/Unit value added	/$
	Safety	Lost time accident frequency (#/million hours worked)	
		Expenditure on illness and accident prevention/payroll expense	$/$

Global Reporting Initiative (GRI). Global Reporting Initiative (GRI) framework uses a hierarchical framework in sustainability triple bottom lines which are economic, environmental, and social as shown in Figure 2.4. The GRI initiative gives a standard report for sustainability performance which is composed of 70 indicators in order to assist manufacturers to benchmark their process performance to achieve a sustainable level (Feng and Joung, 2009b).

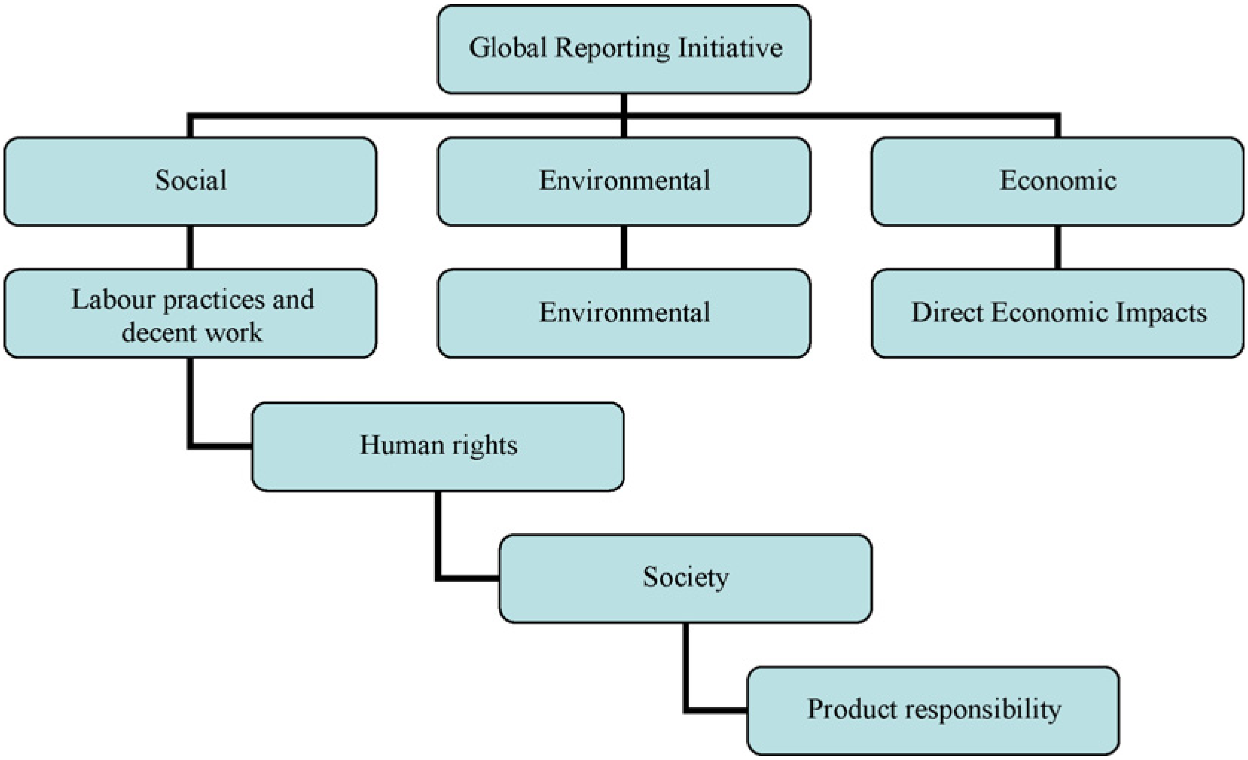


Figure 2.4. Global Reporting Initiative (GRI) framework (Source: GRI, 2002)

United Nations Commission for Sustainability Development (UNCSD). The United Nations Commission for Sustainability Development (UNCSD) constructed a sustainability indicator framework for the evaluation of governmental progress towards sustainable development goals. A hierarchical framework groups indicators into 38 subthemes and 15 main themes, that are divided between the four aspects of sustainable development as shown in Figure 2.5. This provides guidance on applying their defined indicators for the development of national indicator sets (Feng *et al.*, 2009a).

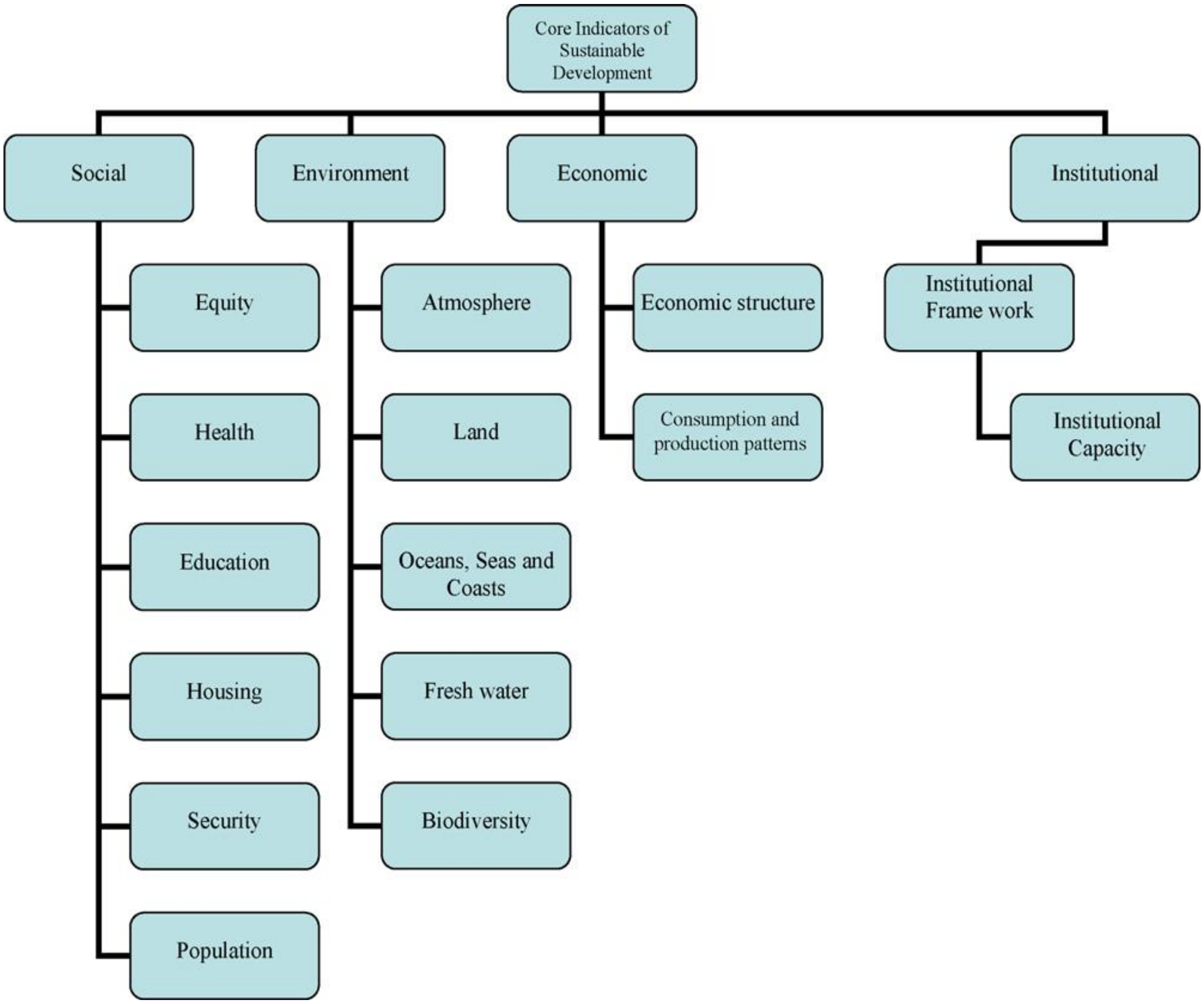


Figure 2.5. United Nations Commission for Sustainability Development (UNCSD) Indicator Framework (Feng *et al.*, 2009a)

Dow Jones Sustainability Index (DJSI). The Dow Jones Sustainability Indexes are utilized to assist in the financial assessment and measure sustainability performance of the top 10% of the companies that are part of the Dow Jones Global Total Stock Market Index. As summarized in table 2.1, the assessment is divided into three sections with 12 criteria that covers sustainability triple bottom lines (economic, environmental, and social) aspects in addition to results from stakeholders and media analysis (Feng *et al.*, 2009a).

Ford Product Sustainability Index (FORD's PSI). Ford's product sustainability index takes into consideration sustainability triple bottom line environmentally, economically, and socially. Those three aspects of sustainability are based on external environmental and cost reviews such as Life Cycle Assessment (LCA) and Life Cycle Cost Analysis which incorporate the use of sustainable materials, safety, mobility and nose. As explained in table 2.1, Ford's Product Sustainable Index is composed of 8 indicators (Feng *et al.*, 2009a).

General Motors Metrics for Sustainable Manufacturing (GM M4SM). General Motors Metrics for Sustainable Manufacturing has a more precise review of state-of-the-art metrics for sustainable manufacturing. There are 46 metrics grouped under 6 categories which are: environmental impact, energy consumption, personal health, occupational safety, waste management, and manufacturing costs. GM M4SM goal is to recommend and determine which metrics for sustainable manufacturing is suitable for implementation (Feng *et al.*, 2009a).

Environmental Pressure Indicators for the European Union (EPI-EU). Environmental Pressure Indicators for the European Union goal is to provide a comprehensive description of the most important human activities that have a negative impact on the environment. As summarized in table 2.1, the EPI-EU contains 60 indicators summarizing various pressures of human activities on the environment under 10 policy fields, which cover air pollution, climate change, bio-diversity, and dispersion of toxic substances (Feng *et al.*, 2009a).

Walmart Sustainability Product Index Questions (Walmart Qs). Walmart Sustainability Product Index Questions aims to develop a worldwide sustainable product index composed of 15 questions to suppliers. Walmart expects to assist customers to make purchase decisions while encouraging suppliers to meet sustainability requirements, on the other hand, there are no further details about the sustainability requirements (Feng *et al.*, 2009a).

Feng *et al.* extended Bordt's work on reviewing currently available sustainable indicator metrics by including the effectiveness of major global initiatives on various technical domains and levels. In Figure 2.6, most indicator metrics and indices are for reporting sustainability of a company such as, GRI, DJSI, and UNCSD. On the other hand, other indicators and metrics focus on reporting and measuring environmental aspects of sustainability such as EPI-EU, and OECD. It is clear that only two indicators and indices are related to products which are OECD and Ford's PSI. Figure 2.6 illustrates the level of technical details required for each indicator and indices to conduct sustainability analysis.

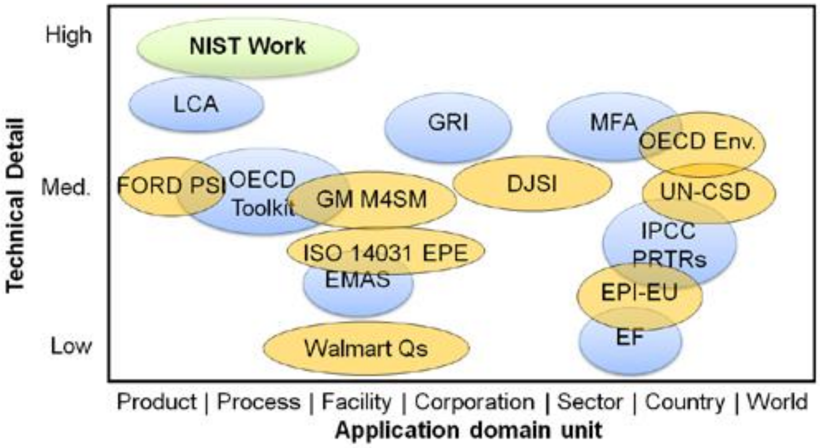


Figure 2.6. Common Metrics and their Application Domains (Bordt, 2009)

2.2 Assessment Methodology

Preliminary assessment of sustainability three triple bottom lines is based on evaluating sustainability's indicator criteria. Recent researchers (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008) are focusing on combining sustainability assessments with suitable indicators for industrial chemical process design to achieve a successful sustainable development and to determine industrial process sustainability performance.

There is no consistent reasonable methodology assessment in integrating all three aspects of sustainability triple bottom lines into the electroplating industrial systems. The most common methodology that is being adopted by industries is driven by economics. Industrial economics could be micro-economics or macro-economics depending on the industry's globalization, impact, and contribution to the society's economy. However, this is not sufficient to satisfy industrial profitability and success in the future from a sustainability stand point. Industry should adapt a methodology to consider and integrate all three aspects of sustainability economic, environmental and social criteria into their processes and systems. Many researchers are focusing their work on integrating and applying sustainability methodologies to many industrial processes in order to develop a variety of sustainable process alternatives. (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008; Halim and Srinivasan, 2008).

This work argues that technological network modeling combined with optimization-based decision-making methodologies will provide an integrated holistic approach to assist industry not only to achieve a sustainable degree but also to improve their sustainability performance.

2.3 Summary

Many assessment techniques associated with sustainability exists in the literature; however, which assessment technique(s) to utilize in evaluating technology integration in an industrial process is not clear. Even knowing the selected technology to be integrated in the system or process, it is difficult to quantitatively assess the overall sustainability triple-bottom-line due to the lack of data or knowledge of the technology being implemented. This research emphasized the assessment of the sustainability status for the metal finishing industry after integrating technology in its design or operation by utilizing appropriate quantitative metrics and indices. This technological framework development approach is the first systematic approach that provides a comprehensive methodology to determine how to integrate the optimum technologies together with an expectation that the group of selected technologies will seek the most benefits and profitability as a result of industrial sustainability enhancement. A thorough review of literature dealing with sustainability metrics and indices selection was made to select the appropriate indicators that will assist in assessing technology in the metal finishing industry. The scope of this methodology is general but our aim is to apply it on electroplating metal substrate processes as a decision making tool for industrial analysts and policy makers. There are many other issues the electroplating industry is facing, such as supply chain challenges. Our focus is specifically concentrated on the electroplated product and process lines, such as in process environmental issues rather than post or offsite environmental issues.

CHAPTER 3

TECHNOLOGY-BASED SUSTAINABILITY MODELING AND ANALYSIS

The metal finishing industry consists of a variety of chemical processes featuring a diverse group of technologies related to specific operational units. Due to the wide variety of surface finishing as well as substrate selection, this adds complexity to the industry's technological network classification and analysis of its sustainability status. The metal finishing industry utilizes specialized process technologies to enhance the substrates properties; however, a broad range of waste can be generated in all of its unit operations. Owing to strict environmental regulations, the industry waste treatment and disposal expenses could be economically detrimental to the overall industry's profitability.

The electroplating industry has been implementing various pollution prevention (P2) technologies developed by the USEPA in order to target end-of-pipe waste generation such as, waste water, solid waste, and air emissions. The USEPA has been working closely with the metal finishing industry in order to create a cleaner environment. However, in an economic globalization industry, electroplaters and metal finishers are seeking advanced cost-effective pollution prevention (P2) technologies to increase their profitability (USEPA 1999; Barnett and Harten, 2003). In recent years, a novel concept profitable P2 (P3) was introduced that extends traditional P2 technologies by adding economic aspects as a third dimension. This P3 theory enhances both economic and environmental aspects for the metal finishing process applications (Lou and Huang, 2000).

The metal finishing processes are divided into four major groups - organic finishing, metal deposition, conversion, and removal processes (Haveman, 1995). Organic finishing process is coating the surface of the metal substrate with paint which could be applied either in liquid or powder state. The selection of coating technology depends on the desired properties of the final finish. Metal deposition process is the deposit of metal coating onto the surface of a metal substrate which could be aqueous based application via electroplating (electric current), electroless plating (chemical reaction), and mechanical plating (direct contact with metal bearing solution) or dry based application via vapor phase technologies (Haveman, 1995).

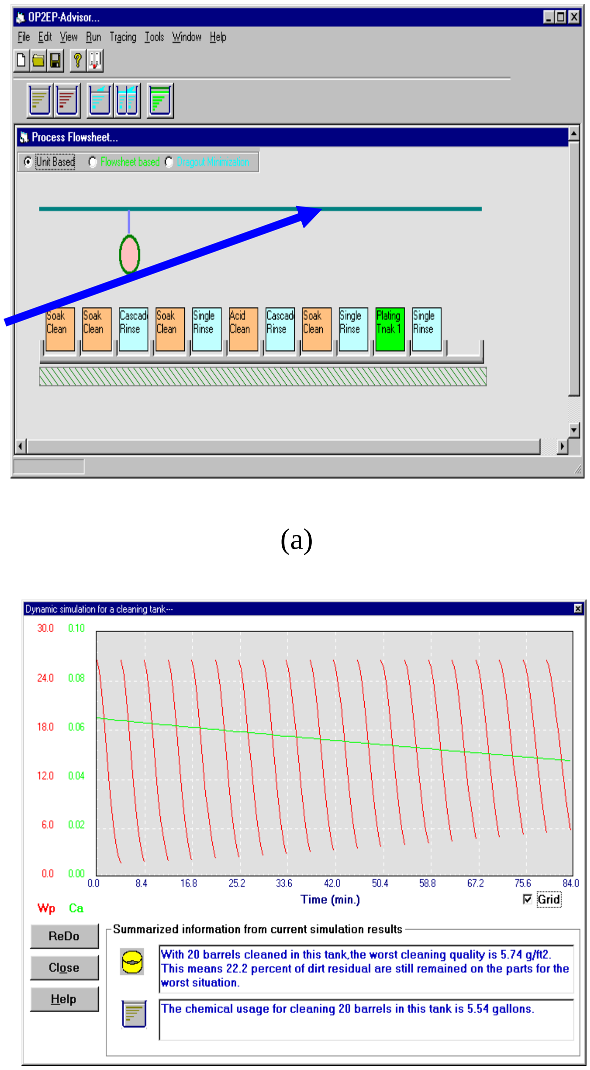
3.1 Classification of Manufacturing Technology

Over the years, the basic principles of metal finishing processes chemical applications have not been changed. Thus, a generic metal finishing process flow diagram of a recent electroplating process will be very similar to the initial process operation. This is because most of the technological innovations focused on meeting environmental regulations by controlling end-of-pipe wastes. Most recently, metal finishing industry have several technological opportunities available to assist in their overall sustainable development. Technological innovation in the metal finishing industry can be grouped into five general categories in order to provide economic prosperity, environmental cleanliness and social satisfaction. A decrease in waste generation and its treatment expenditures is accomplished by implementing technologies that are (a) process design and equipment oriented, (b) product oriented, (c) materials oriented, (d) energy efficient, and (e) waste treatment proficient. This section will put emphasis on key economic, environmental and social tradeoffs associated with technological implementation.

3.1.1 Process Design and Equipment Oriented Technologies

The metal finishing industry processes have been influenced by modern science and technology advancements. In addition to, proficient operating practices and process management techniques for process control and optimization. Profitable Preventive technologies have been directed to improve plant operations by process retrofit design for improving product quality, energy and material efficiency, and source waste reduction. Furthermore, new processes such as alternative materials and solvents, in-process modification, and process monitoring and control are a few examples for process oriented technologies that will assist in developing the metal finishing industry sustainability. Comprehensive understanding of critical process parameters such as, temperature, chemical concentration, pH, flow rates, contamination control, etc. are fundamental knowledge to reduce waste and minimize economic, environmental and social effects from plating operations. One of the most successful process oriented technologies is P3 technologies that have been developed by Huang and associates over the past years. Adequate utilization of P3 technologies techniques will assist the industry to achieve optimum economic profitability and environmentally benign processes. Due to environmental regulations and social demands placed on the metal finishers, technological innovation was a necessity rather than an option for the metal finishing industry to attain a balanced sustainable development. Following is a list of six P3 technologies effectively proven and utilized in the metal finishing processes.

Dynamic simulation technology. There is a need for a well defined electroplating process for both qualitative and quantitative analysis to ensure comprehensive understanding of the operation of each unit as well as the entire plating line. The basic principle of simulating cleaning and/or rinsing tanks predict the chemical and water consumption, cleaning and rinsing qualities, and waste generation in each unit and waste transfer among units (Gong *et al.*, 1997; Lou and Huang, 2001). Another advantage of this dynamic unit simulation is to perform process optimization to minimize chemical consumption and to achieve uniform cleaning among all barrels in process (Gong *et al.*, 1997). A well defined profitable pollution prevention technology depends on precise information regarding the process operation parameters. This accurate information could be acquired from dynamic process modeling simulation. This technology provides a thorough analysis of cleaning and rinsing processes. Figures 3.1 illustrates a platform of process simulation where a user can build an electroplating process of his interest by clicking unit icons on the tool bar and then input process data for each unit. The analytical results from simulation allows the metal finishing industry with opportunities for minimizing process wastes and maximizing process efficiency in an organized controlled manner. The main goal of dynamic simulation is to assist the industry control their waste while achieving maximum economic profitability simultaneously.



● Unit Based ○ Flowsheet based ○ Dragout Minimization

(a)

☑ Grid

Summarized information from current simulation results

With 20 barrels cleaned in this tank,the worst cleaning quality is 5.74 g/ft2. This means 22.2 percent of dirt residual are still remained on the parts for the worst situation.

The chemical usage for cleaning 20 barrels in this tank is 5.54 gallons.

(b)

Figure 3.1. (a) Process configuration window of P3 Technology.
(b) Cleaning simulation windows of P3 Technology.
(Lou and Huang 2001).

Table 3.1 illustrates some advantages and incentives of electroplating process simulation from a process oriented point of view based on an evaluation of sustainability triple-bottom-line. There are some restrictions and risks to utilize this technology due to some simulation limitations.

Table 3.1. Electroplating Process Simulation Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Dynamic Simulator (DYSIM)[1]	Functionality	• Simulate dynamically user-defined electroplating process	• Predict the waste and water consumption per unit operation • Calculate the chemical consumption automatically • Achieve uniform cleaning for all processed work pieces	• Track waste generation in each unit • Determine waste transfer between unit operation • Optimize processes to minimize chemical consumption	• Determine cleaning and rinsing qualities
	Incentive	• Effective source reduction tool by having a comprehensive understanding of each unit operation and the entire process			
	Application	• Graphic configuration capability of up to 10 plating units • Simulation for cleaning and/or rinsing unit operations			
	Restriction	• Cannot be used for more than 10 unit operations			
	Risk	• Depends on user-defined operation parameters			

---

[1] Technology 1: See Gong *et al.*, 1997.

Cleaning and rinsing optimization technology. The pretreatment process operation before the plating process is very crucial to ensure product quality and minimize chemical loss and waste generation. There is at least one rinsing operation after any cleaner unit operation that will require identifying optimum chemical additions, water flow rates, and cleaning and rinsing times (Zhou and Huang, 2002). Figure 3.2 shows a case study of a three-step cleaning and rinsing system, chemical concentration ranges of the three cleaning tanks. Having the knowledge and tools to optimize the pretreatment process will have a positive impact on the overall process economically, environmentally and socially through cost associated with chemical usage and waste generation.

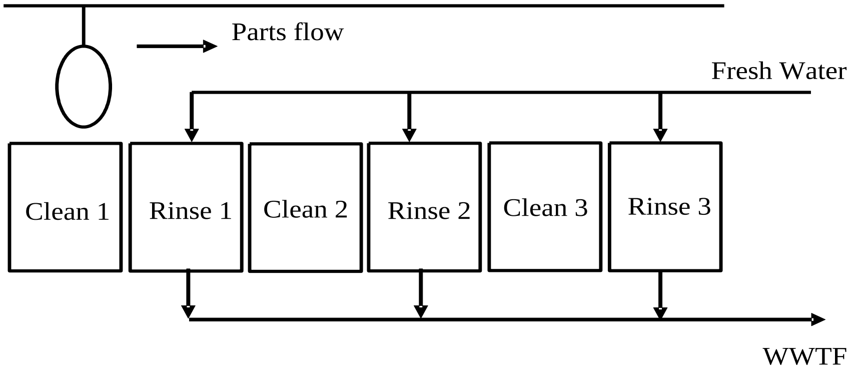


Figure 3.2. Application of P3 Technology for a three-step cleaning and rinsing system Optimization (Zhou and Huang 2002).

Table 3.2 illustrates a comparison between the original system cleaning and rinsing results and the improved optimized system after implementing P3 technology with significant savings in both chemical and operation costs.

Table 3.2. Cleaning and rinsing optimization technology results (Zhou and Huang 2002).

	Original system	Optimized system
Cleaning 1	4.5 min	4.35 min
Cleaning 2	4.5 min	4.35 min
Cleaning 3	4.5 min	5.22 min
Total chemical cost	$ 89,916	$ 82,975
Rinse 1	1 min	0.72 min
Rinse 2	1 min	0.72 min
Rinse 3	1 min	1.14 min
Total rinsing cost	$ 20,724	$ 19,956
Total operating cost	$ 110,640	$ 102,931

A process oriented evaluation of sustainability triple-bottom-line based on cleaning and rinsing optimization technology is summarized in table 3.3. Some incentives for this application and its restrictions from a process oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters. Recently, Gong *et al.* successfully implemented controlled changes to implement new technologies for dynamic modeling and simulation for cleaning and rinsing process applications. Below are some general dynamic models for cleaning and rinsing systems.

Cleaning Tank Dirt Removal Model:

——— (3.1)

(3.2)

(3.3)

where

A_p = total surface area of parts in barrel (cm^2)

$C_a(t)$ = chemical concentration in the cleaning tank at time t (cm^3-chem/cm^3-sol)

r_{pc} (t) = dirt removal rate in cleaning tank at time t (cm^3/min)

W_{pc} (t) = amount of dirt on parts at time t (g-dirt/cm^2)

γ_c (t) = looseness of dirt on parts at time t (cm^2.cm^3-sol/cm^3-chem.min)

γ_0 = kinetic constant (cm^2.cm^3-sol/cm^3-chem.min)

α = constant

t = time function

Chemical Concentration Model:

—— —— (3.4)

where

V_c = capacity of cleaning tank (cm^3-sol)

$W_c(t)$ = flow rate of chemical addition in cleaning tank at time t (cm^3-chem/min)

η = chemical capacity for dirt removal (g-dirt/cm^3-chem)

$D_o(t)$ = drag-out flow rate (cm^3-chem/min)

Amount of chemicals in cleaning tank:

—— —— (3.5)

where

$C_0(t)$ = chemical concentration in preceeding cleaning tank at time t (cm^3-chem/cm^3-sol)

k_d = drag-out coefficient determined by temperature, drainage time, shape of parts, and surface tension

Chemical Consumption Estimation:

$i = 1, \ldots, N$; $H = 1, \ldots, N$ (3.6)

where

C_i = chemical consumption in cleaning tank *i* during cleaning time

H = number of hours worked per shift (hr/shift)

Rinsing Tank Dirt Removal Model:

(3.7)

(3.8)

(3.9)

where

$F_w(t)$ = flow rate of rinse water at time t (cm^3-water/min)

k_r = mass transfer coefficient (cm^3-chem.cm^3-water/cm^3-sol.cm^2)

$r_{ri}(t)$ = dirt removal rate in rinsing tank at time t (cm^3/min)

V_r = capacity of rinsing tank (cm^3-water)

$W_{ri}(t)$ = amount of dirt on parts in rinsing tank at time t (g-dirt/cm^2)

$W_{ci}(t_e)$ = amount of dirt on parts leaving cleaning tank at time t_e (g-dirt/cm^2)

$x_r(t)$ = pollutant composition in rinse water at time t (g/cm^3-water)

$z_r(t)$ = pollutant concentration in influent rinse water at time t (g/cm^3-water)

$\gamma_r(t_e)$ = looseness of dirt on parts at time t_e (cm^2.cm^3-sol/cm^3-chem.min)

θ = unit conversion factor (cm^2/cm^3-water)

Assumptions. Water in the rinsing tank is well mixed, the pollutant composition in rinsing tank is the same as the effluent water. The quantity of pollutants is directly related to the rinsing efficiency, water flow rate, initial part dirtiness, and influent rinse water purity. Initial amount of dirt on parts $W_{ri}(t_0)$ can be estimated from cleaning tank models computations. The influent rinse water $z_r(t)$ dirtiness can be easily measured.

Water consumption in rinsing tanks:

—— (3.10)

where

$F_w(t)$ = flow rate of rinse water at time t (cm^3-water/min)

$x_r(t)$ = pollutant composition in rinse water at time t (g/cm^3-water)

$R_r(t)$ = recycle flow rate at time t (cm^3-water/min)

$z_r(t)$ = pollutant concentration in influent rinse water at time t (g/cm^3-water)

$D_{ri}(t)$ = drag-in flow rate at time t (cm^3-water/min)

$z_i(t)$ = pollutant concentration in drag-in at time t (g/cm^3-water)

Assumption. Uniform chemical concentration in rinse tank, no chemical reaction in rinse tank, this model can be applied to multiple rinsing tanks, and the water flow rate variables are determined based on the rinsing system configuration.

Water Consumption Estimation:

$$i = 1, \ldots, N \qquad (3.11)$$

where

W_i = amount of water consumed in rinse tank *i* during rinsing time

H = number of hours worked per shift (hr/shift)

Table 3.3. Electroplating Cleaning and Rinsing Optimization Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Cleaning and Rinsing Optimizer (CROP)[2]	Functionality	• Simulate dynamically and identify optimal values of cleaning and rinsing settings	• Optimization can give a reduction in operating cost by 6.9% compared to the original operations • Adjust processing time distributions for all cleaning and rinsing operations • Explore global opportunities to minimize the overall operating cost and waste generation	• Identify optimal settings for chemical concentration and rinse water flow rate for each unit based minimum consumption	• Determine cleaning and rinsing qualities
	Incentive	• Effective source reduction tool by having a comprehensive understanding of each cleaning and rinsing unit operation and the entire process			
	Application	• Simulation for cleaning and/or rinsing unit operations			
	Restriction	• Based on hierarchical optimization strategy			
	Risk	• Depends on user-defined operation parameters			

---

[2] Technology 2: See Zhou and Huang, 2002.

Switchable water allocation network technology. This is an important technology for the electroplating industry since freshwater is sent to different rinsing units for rinsing off the dirt and solution residues on parts; however, some used rinse water can be either partially or entirely reused in other rinse steps. Figure 3.3a shows a schematic flow sheet of a complete SWAN designed by the P3 SWAN technology. In each operation cycle of 10 min, the primary WAN runs for the first 7.5 min and the secondary WAN for the next 2.5 min as shown in figure 3.3b operational scheme of valves control strategies. The ability of designing an optimal water allocation network for any plating line, and developing optimal operation strategy based on rinse network dynamics has significant economic and environmental incentives (Zhou *et al.*, 2001; Yang *et al.*, 2000).

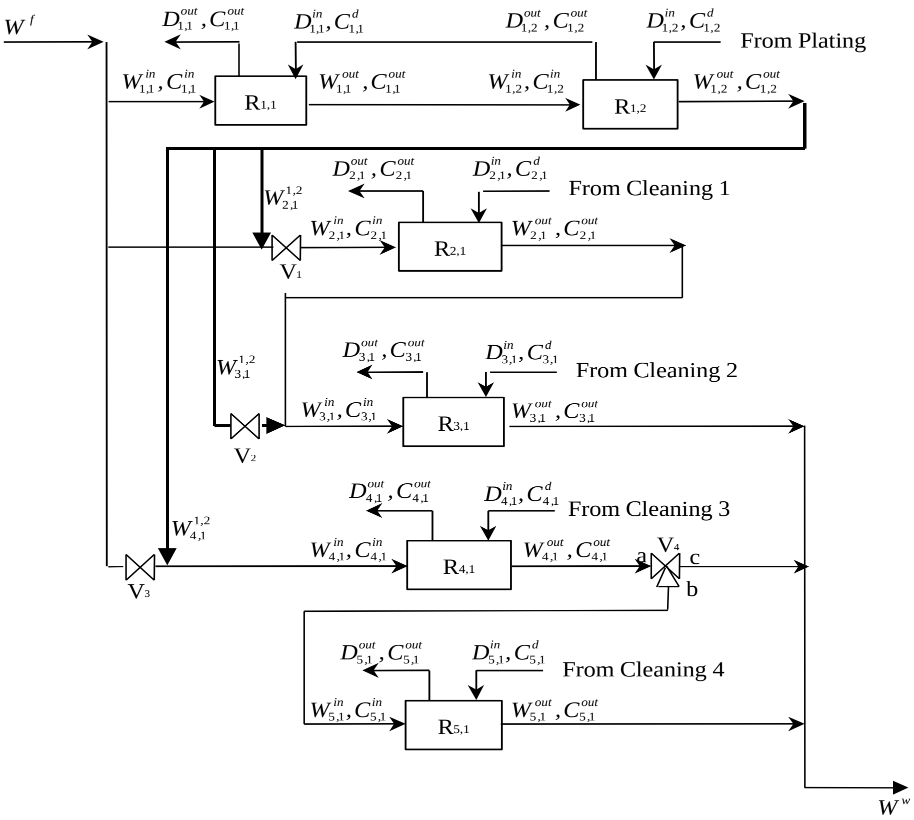


Figure 3.3a. Flow sheet of a SWAN technology (Zhou *et al.* 2001).

SWAN	Valve Control Strategies				
	V_1	V_2	V_3	V_4	
				a→b	a→c
Primary WAN	Open	Close	Open	Open	Close
Secondary WAN	Close	Open	Close	Close	Open

Figure 3.3b. Operational scheme of a SWAN technology (Zhou *et al*. 2001).

A process oriented evaluation of sustainability triple-bottom-line based on switchable water allocation network technology is summarized in table 3.4. Some incentives for this application and its restrictions from a process oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters. Zhou *et al.* introduced some general dynamic optimization models for rinse water allocation based on process system dynamics. Below is a general optimization model based on overall characteristics of rinsing dynamics.

Rinse Tank Water Allocation and Reuse Modeling:

Water cleanliness dynamics:

—— —————— —— ——— ;

(3.12)

Rinse tank inlet of fresh and reused water mix:

(3.13)

Rinse tank inlet water contaminants:

(3.14)

Rinse tank water mass balance:

(3.15)

where

= fresh water flow rate into rinse tank

= total water flow rate into rinse tank

= total amount of pollutions in inlet rinse tank

= total water flow rate out of rinsing tank

= total recycled water flow rate from other rinsing tanks

= binary variable integer (0 or 1) determining the existing of recycling streams into rinsing tanks

= drag in flow rate into rinsing tank

= drag out flow rate out of rinsing tank

= pollutant concentration in rinsing tank

= pollutant concentration of drag in into rinsing tank

= volume of rinsing tank

= pulse function

= time instant when a barrel enters rinsing tank

= time instant when drag in into rinsing tank ends

The drag-in is modeled according to an intermittent volumetric flow rate instead of a discrete volume which means a continuous flow( ) times a pulse function( ).

Table 3.4. Electroplating Switchable Water Allocation Networking Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Switchable Water Allocation Networking (CROP)[3]	Functionality	• An optimal water allocation network design for any plating line	• Water allocation networks Optimization can reduce 39.3% of the total annualized cost compared to the original operations set up • Adjust water consumption processing time distributions for all unit operations • Exploring opportunities to minimize the overall operating cost and waste water generation	• Identify optimal settings for rinse water flow rates for each unit based on minimum consumption and reuse in proper unit operations	• Determine unit operation rinsing qualities
	Incentive	• Optimal operation strategy development based on rinse network dynamics			
	Application	• Provide control policies for switching water flow patterns during process operations			
	Restriction	• Not all rinse water could be utilized entirely in other critical			
	Risk	• Depends on user-defined operation parameters			

---

[3] Technology 3: See Zhou *et al.*, 2001; Yang *et al.*, 2000.

Sludge reduction technology. In the metal finishing industry sludge could be dry or wet depending on the type of treatment methods and chemicals utilized. Sludge is formed in the pretreatment process mainly in cleaning and rinsing steps. Sludge is generated from dirt and oils on the surface of the work piece being processed. Sludge reduction technology classifies sludge as avoidable and unavoidable. The avoidable sludge is related to excessive and improper use of chemicals, high rinse water flow rate, and excessive drag-out into rinsing unit operations (Luo *et al.* 1998). Figure 3 shows a case study of sludge reduction for 70 barrels processing that is investigated by Luo *et al.* Based on the optimization of the P3 Technology SLUE, the total amount of sludge generated is reduced by 15% as shown in figure 3.4. The sludge could be reduced by optimizing the pretreatment process to reduce the chemical consumption and determine the optimum amount of chemicals and water necessary for maintaining the work piece pretreatment quality requirements.

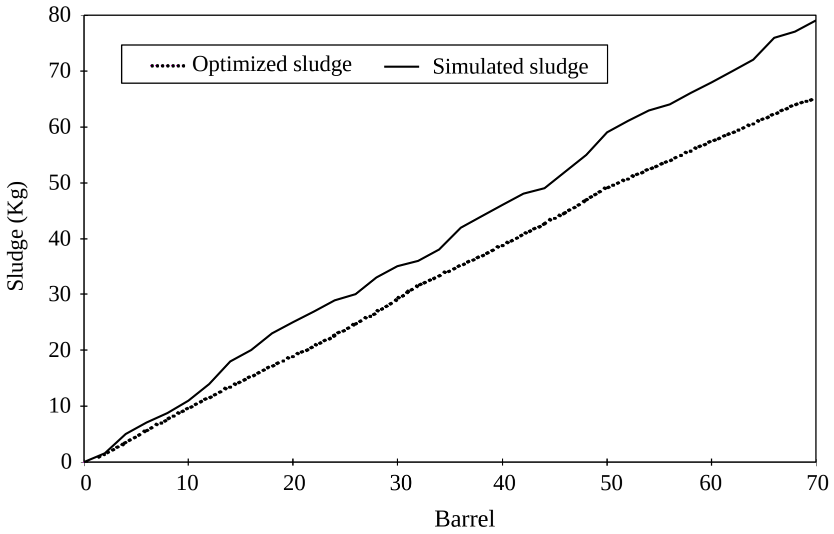


Figure 3.4. Comparison of the sludge accumulations before and after process optimization (Luo *et al.*, 1998).

Luo *et al.* developed some mathematical models for estimating sludge from cleaning and rinsing process tank operations. Below are some general model based strategies for sludge estimation.

Sludge Modeling:

(3.16)

(3.17)

(3.18)

(3.19)

(3.20)

where

S_T = total sludge (g-sludge)

S_d = sludge from dirt removed from surface of parts (g-sludge)

S_c = sludge from chemicals used to remove dirt from surface of parts (g-sludge)

S_g = sludge from drag out from cleaning tanks (g-sludge)

S_w = sludge from natural contaminants in make-up water or rinse water (g-sludge)

A_i = total surface area of parts in *i*th barrel (cm^2)

k_{cj} = precipitation constant for the *j*th chemical (g-sludge/cm^3-chem)

N_b = number of barrels of parts processed per day (bbl/day)

N_d = number of types of dirt on surface of parts

$W_{ci,j}$ = amount of *j*th dirt type removed from the surface of parts (g-dirt/cm^2)

μ_j = *j*th chemical capacity for dirt removal (g-dirt/cm^3-chem)

D_g = drag out rate from cleaning tanks to rinsing tanks (g-dirt-chem/cm^2)

k_{pw} = precipitation constant for rinse water (g-sludge/g-contaminant)

k_w = rinse water hardness (g-contaminant/cm^3)

F_w = flow rate of make-up and fresh water into rinsing system (cm^3/day)

Assumptions. Base sludge source is found in cleaning and rinsing tanks that include dirt and soils present on the surface of the parts being processed, chemicals used to treat it, and natural contaminants in the make-up water or rinse water including drag-out from previous cleaning tanks.

A process oriented evaluation of sustainability triple-bottom-line based on sludge elimination technology is summarized in table 3.5. Some incentives for this application and its restrictions from a process oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.

Table 3.5. Electroplating Sludge Eliminator Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Sludge Eliminator Technology (SLUE)[4]	Functionality	• Technology for reducing avoidable sludge generated from cleaning dirt on the surface of parts that is removed by chemicals	• Sludge elimination technology optimization can reduce total amount of sludge generated by 15% compared to process optimization before implementing technology • Opportunities to minimize the overall operating cost and waste water generation	• Identify optimal settings for cleaning conditions depending on cleaner type, concentration, and processing time • Suggesting strategies for reducing the avoidable sludge	• Determine unit operation cleaning qualities
	Incentive	• Classifying sludge into 2 categories: avoidable and unavoidable • Reducing avoidable sludge due to excessive use of chemicals, insufficient parts surface pretreatment, and improper cleaning time			
	Application	• Calculating amount of sludge generated			
	Restriction	• Cleaner type, concentration, and processing time			
	Risk	• Depends on user-defined operation parameters			

---

[4] Technology 4: See Luo *et al*. 1998.

Plating solution recovery technology. The metal finishing industry consumes high volume of chemicals to run their daily process operations; however, a high percentage of their chemical usage is lost by drag-out. The chemistries being lost are not economically or environmentally beneficial due to increasing in overall operating and waste treatment costs. This technology is based on a unique reverse drag-out process approach (Xu and Huang 2004, 2005), which can assist in identifying critical operational parameters based on comprehensive economic and environmental analysis. Figure 3.5 illustrates a general superstructure of solution recovery scheme. Based on user-defined requirements, P3 electroplating chemistry recovery technology can identify the optimal design and operating policy for a cost-effective solution recovery system.

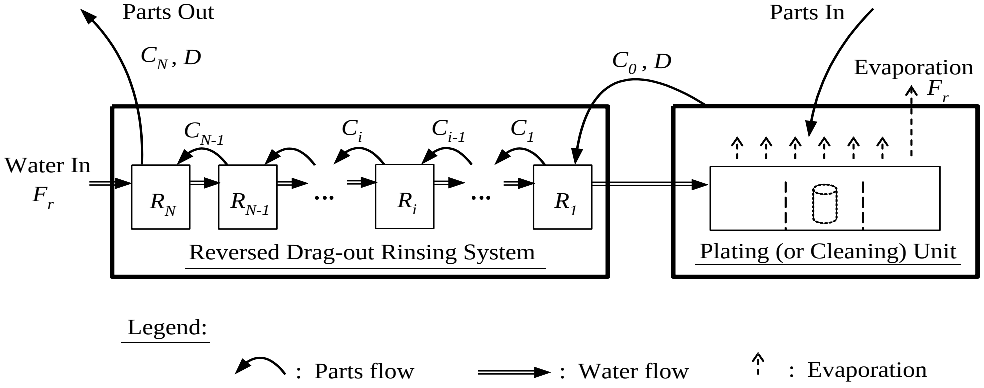


Figure 3.5. A general superstructure of electroplating chemistry recovery scheme synthesized by the P3 Technology (Xu and Huang 2005).

Qiang *et al.* introduced a general model based simulation methodology for characterizing an electroplating system unit with a solution recovery subsystem. Below are some general mathematical modeling for the aforementioned system for identifying optimal chemical recovery.

Plating Solution Recovery:

Chemical dynamic model:

(3.22)

Solution recovery model from rinsing tanks:

$-$, (3.23)

(3.24)

(3.25)

where

= concentration of chemical *j* in plating tank (mol/L)

= concentration of chemical *j* in the *k*th rinsing tank (mol/L)

= reaction rate function of chemical *j* (mol/C)

= current efficiency of the anode

= current efficiency of the cathode

= volume of the electroplating tank (L)

= total surface area of parts (m^2)

= current density (A/m^2)

= chemical species index

= rinse tank index

= flow rate of recovery (L/min)

= flow rate of drag-in or drag-out (L/min)

= binary variable integer (0 or 1) determining the existing of rinsing tanks after or before plating tank

= unit step function at time instant

= initial starting time of drag-out from the *k*th rinsing tank (min)

= starting time of drag-in into the plating tank (min)

= ending time of drag-in into the plating tank (min)

= starting time of drag-out from the plating tank (min)

= ending time of drag-out from the plating tank (min)

= number of rinsing tanks

= volume of rinse tank (L)

= starting time of drag-in into the *k*th rinsing tank (min)

= ending time of drag-in into the *k*th rinsing tank (min)

= starting time of drag-out from the *k*th rinsing tank (min)

= ending time of drag-out from the *k*th rinsing tank (min)

= starting time of initial drag-out from the *k*th rinsing tank (min)

= ending time of initial drag-out from the *k*th rinsing tank (min)

Assumption. Equation 23 can be utilized to construct a system model for any number of rinsing tanks. Equation 24 assumes that the drag-in solution to first rinsing tank after plating is from the plating tank (E). Equation 25 means the solution flowing into the first rinsing tank after plating comes from fresh water free from any chemicals or metals.

Table 3.6. Electroplating Solution Loss Prevention Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Solution Loss Preventer Technology (SLOP)[5]	Functionality	• Design scheme based on reverse drag-out technique for any specific requirement of solution recoveries	• Technology can reduce overall amount of chemical solvents and plating solutions loss which will dramatically decrease operating cost • Opportunities to identify optimal design and operating policies for cost-effective solution recovery systems	• Identify optimal settings (evaporation rate, drag-out rate, rinse cycle time) for replenishing cleaners, plating solutions, fresh water and waste treatment efforts • Suggesting strategies for reducing solution loss during process operations	• Determine unit operation qualities on operators health and safety
	Incentive	• Identify critical operational variables settings			
	Application	• Calculating evaporation rate, drag-out rate, rinse cycle time based on environmental and economic analysis			
	Restriction	• Difficult and expensive recovery of some valuable chemicals and metal ions			
	Risk	• Depends on user-defined operation parameters			

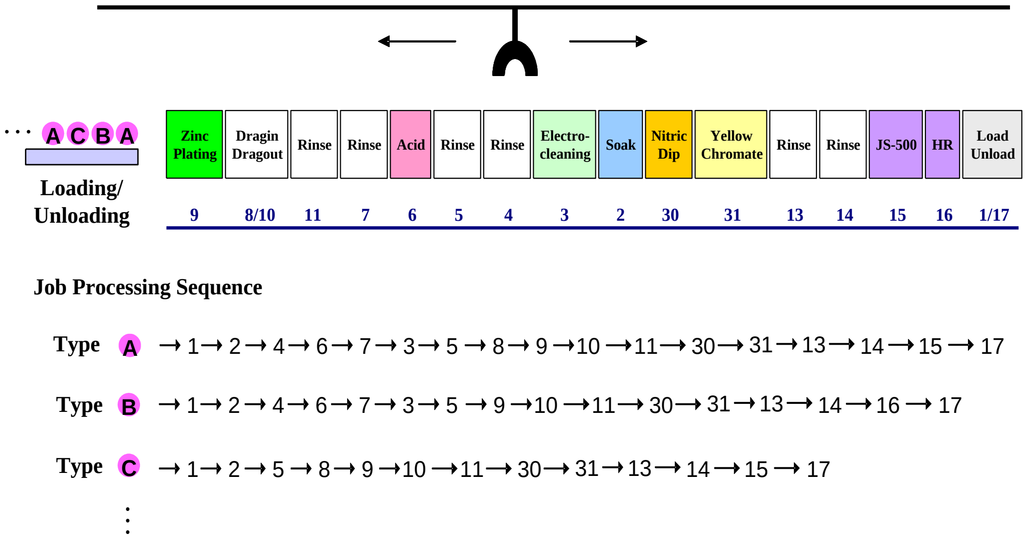
---

[5] Technology 5: See Xu and Huang 2004, 2005.

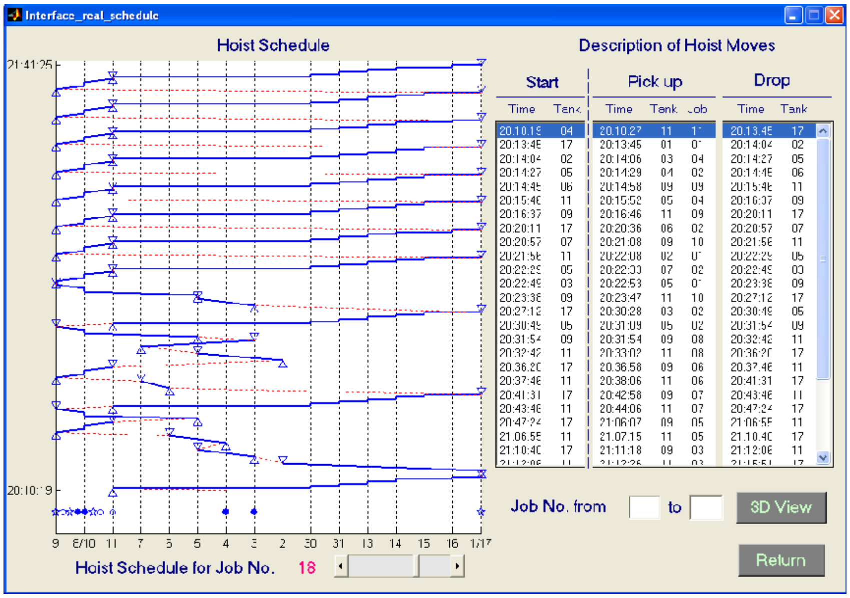
A process oriented evaluation of sustainability triple-bottom-line based on electroplating solution loss prevention technology is summarized in Table 3.6. Some incentives for this application and its restrictions from a process oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.

Plating line hoist scheduling technology. One of the main factors for the success of the metal finishing industry is improving their production rate. Hoist scheduling technology can play an important role in waste minimization as well as managing production rate (Kuntay *et al.*, 2005). This technology is utilized to illustrate optimum real time production schedules that address any changes to production demands in addition to improving the overall process efficiency economically and environmentally (Xu and Huang, 2004). Figure 3.6a illustrate an example where one hoist is employed in a line to process three different types of jobs continuously, and the plating unit can accommodate eight jobs at the same time. With help of P3 technology HOST, a real-time scheduling strategy is developed. A snapshot of the hoist schedules is shown in Figure 3.6b.

A process oriented evaluation of sustainability triple-bottom-line based on electroplating hoist schedule technology is summarized in Table 3.7. Some incentives for this application and its restrictions from a process oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.



(a)



Description of Hoist Moves

Start		Pick up			Drop	
Time	Tank	Time	Tank	Job	Time	Tank
20.10.19	04	20.10.27	11	11	20.13.45	17
20:13:45	17	20:13:45	01	01	20:14:04	02
20:14:04	02	20:14:06	03	04	20:14:27	05
20:14:27	05	20:14:29	04	02	20:14:45	06
20:14:45	06	20:14:58	09	09	20:15:46	11
20:15:46	11	20:15:52	05	04	20:16:37	09
20:16:37	09	20:16:46	11	09	20:20:11	17
20:20:11	17	20:20:36	06	02	20:20:57	07
20:20:57	07	20:21:08	09	10	20:21:56	11
20:21:56	11	20:22:08	02	01	20:22:29	05
20:22:29	05	20:22:33	07	02	20:22:49	03
20:22:49	03	20:22:53	05	01	20:23:38	09
20:23:38	09	20:23:47	11	10	20:27:12	17
20:27:12	17	20:30:28	03	02	20:30:49	05
20:30:49	05	20:31:09	05	02	20:31:54	09
20:31:54	09	20:31:54	09	08	20:32:42	11
20:32:42	11	20:33:02	11	08	20:36:20	17
20.36.20	17	20.36.58	09	06	20.37.46	11
20:37:46	11	20:38:06	11	06	20:41:31	17
20:41:31	17	20:42:58	09	07	20:43:46	11
20:43:46	11	20:44:06	11	07	20:47:24	17
20:47:24	17	21:06:07	09	05	21:06:55	11
21.06.55	11	21.07.15	11	05	21.10.40	17
21:10:40	17	21:11:18	09	03	21:12:06	11
21:12:06	11	21:12:26	11	03	21:15:51	17

(b)

Figure 3.6. (a) Flow sheet of an electroplating line. (b)Plating line hoist movements responding to a new job load (Xu and Huang, 2004).

Table 3.7. Electroplating Hoist Schedule Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Hoist Schedule Teller Technology (HOST)[6]	Functionality	• Optimize schedules to meet the changing requests from production	• Optimal hoist scheduling improves production rate which will dramatically decrease operating cost • Opportunities to identify optimal design and operating policies for cost-effective operating process systems total savings are approximately $15,000/yr with negligible capital investment	• Identify optimal settings for replenishing cleaners, plating solutions, fresh water and waste treatment efforts • Suggesting strategies for reducing solution loss during process operations	• Determine unit operation qualities on operators health and safety
	Incentive	• Hoist scheduling improve productivity and minimize waste generation from processes			
	Application	• Real time scheduling strategy for processing various jobs			
	Restriction	• Taking in consideration production uncertainties			
	Risk	• Depends on user-defined operation parameters			

---

[6] Technology 6: See Xu and Huang, 2004; Kuntay *et al.*, 2005.

From the aforementioned Profitable Pollution Prevention (P3) technologies that the main purpose is to focus on improving the metal finishing industry from a process oriented technology to achieve, economic and environmental manufacturing optimization. P3 technologies could be integrated and networked for a comprehensive profitable and environmentally benign industrial manufacturing process. There is approximately 15% reduction in chemical consumption using cleaning technology for determining optimal chemical concentration. Also, there is approximately 20% reduction in fresh water consumption used for process rinsing operations by implementing rinsing technologies for determining optimal rinse water flow rates. Moreover, advanced design technology for developing an optimal water use and reuse network reduced water consumption by 10% and an additional 25% reduction utilizing design and processing technology for rinsing water neutralization. Furthermore, major reductions in metal finishing process material consumption and waste generation from implementing reversed drag-out technologies lead to reduction in chemicals, water and sludge by approximately 20%, 15%, and 10% respectively. Plating solution recovery technologies caused more than 86% in direct recovery of plating chemistries. Hoist scheduling optimization technology determines not only the production rate but also improves economic and environmental performance of the metal finishing process. Environmentally conscious dynamic hoist scheduling technology reduced chemical consumption approximately by 5% and water consumption by 10%.

3.1.2 Product Oriented Technologies

Potential product oriented technology changes will affect the metal finishing industry. Change from conventional surface finishing product to alternative technologies such as Physical

Vapor Deposition (PVD), High velocity oxygen fuel (HVOF), and High-Frequency Short-Pulsed Plasma-Immersion Ion Implantation and Deposition (HFSP^{2}I^{3}D) will reduce worker hazardous exposure, air emissions, chemical handling, and waste generation. Transitioning from wet processes to dry processes technologies improves product direction towards optimum sustainability. Dry technologies are implemented and evaluated to replace some hazardous toxic materials such as hard chrome plating which is a primary wear resistance coating for steel substrates.

Physical Vapor Deposition (PVD) Technology. According to Navinsek *et al.*, PVD technology is a proven dry coating process that provides harder, durable, and more corrosion resistant coatings than electroplated ones. PVD encompass a variety of methods used for deposition and film growth on desired substrates. This conducted by vaporization of coating material via evaporation, arc vaporization, sputtering, and chemical vapor and gases; in addition to, transferring from vapor phase to the desired substrate by molecular flow, line-of-sight, and plasma induced vaporization (Navinsek *et al.*, 1999). PVD technology is utilized for decorative surface finishing creating anti-tarnish surface properties that will prevent parts from tarnishing, corroding or any discoloring occurring due to harsh environmental conditions. Another variation of PVD dry technology that is used to replace cadmium plating is Ion Vapor Deposition (IVD) which is a low vacuum plasma induced vapor ionization of Aluminum. IVD Aluminum technology has exceptional material properties than cadmium plating in corrosion resistance and galvanic reactions between dissimilar metals that causes galvanic corrosion challenges. On the other hand, there is a high capital cost associated with implementing such advanced dry technology. Achieving high coating quality and superior performance comes at a very high cost and specialized operating requirements. PVD technology proved to replace traditional electroplating technology (wet processes) while providing better coating properties to replace hazardous chemicals such as cadmium and chromium in the metal finishing operations. PVD dry technology achieves sustainability by minimizing environmental and safety issues that can be related to the capital investment required to achieving sustainability goals. Table 3.8 illustrates an example of a product oriented PVD technology evaluation of sustainability triple bottom lines. Some incentives for this application and its restrictions from a product oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.

Table 3.8. Product Oriented PVD Technology Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
Physical Vapor Deposition (PVD)[1]	Functionality	• Vacuum coating technology • Dry coating technology	Coating time: • Traditional Chrome plating: 2 - 8 hours for a stack of 100 rings • PVD 4 hours for coating 8 stacks of 100 rings simultaneously	• Clean dry coating • Lighter surface grinding than traditional coatings (approximate waste mass = 0.1 Kg compared to 0.3 Kg traditional coating process) • Approximate aqueous waste mass = 4 Kg compared to 348 Kg traditional coating process waste	• Process efficiency depends on application
	Incentive	• Electrolytic coating replacement • Clean technology • No refinishing required			
	Application	• Coating for wear, erosion, corrosion, and decorative applications			
	Restriction	• Cannot be used to rebuild worn components			
	Risk	• More careful surface preparation • Plasma nitriding is required for soft steel surfaces to enhance wear and rolling-sliding contact fatigue performance			

---

[1] Technology 1: See Navinsek *et al.*, 1999.

High Velocity Oxygen Fuel (HVOF) Technology. Another dry technology is high velocity oxygen fuel (HVOF) thermal spray technology. This technology is utilized in order to replace conventional hard chrome plating processes. A HVOF thermal spray gun has a variety of applications in order to achieve specific coating properties. Applying high velocity spraying of specified gas mixture consisting of propylene, propane, or hydrogen at supersonic velocity over 7,000 fps (Legg *et al.*, 1996) exiting the nozzle and being ignited externally. HVOF process is conducted in a booth or room enclosure due to the high combustion temperature range from 5,000 to 6,000 ^{0}F in addition to the noise generated from process operation. Due to superior operating conditions a relatively high density coating could be achieved with performance similar to or better than traditional hard chrome plating. HVOF has bond strengths of 12,000 psi that improves wear, impact and corrosion resistance due to exposure to harsh environmental conditions. Some of the limitations of HVOF technology is that it is a line-of-sight coating application which means it cannot be utilized for coating inner diameter or other objects customized physical structures. Another limitation for HVOF technology is that stripping steps for metal deposits on objects is a wet process which means it is not totally dry technology for this stage of the process and sometimes the coating is very difficult to remove due to superior bond strengths (Chalmer, 2008). From a sustainability point of view, HVOF technology has high economic investment, strict environmental regulations, and social impacts for operators health and safety risks. High economic impact because of the expensive equipment capital cost such as thermal spraying systems, robotics, noise control systems, and air emission equipment. Another potential economic barrier as well as an environmental impact is that HVOF line-of-sight technology will require the use of traditional hard chrome plating processes which is a wet process in order to satisfy and meet customer requirements and demands. This means not only implementing a dual process (wet and dry) which is very a costly investment but also did not eliminate a more hazardous process from an environmental aspect. From a social point of view, due to the high operating parameters and the nature of the process has major concerns on operators health and safety. Table 3.9 illustrates an example of a product oriented HVOF technology evaluation of sustainability triple bottom lines. Some incentives for this application and its restrictions from a product oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.

Table 3.9. Product Oriented HVOF Technology Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
High Velocity Oxy-Fuel (HVOF)[2]	Functionality	• Thermally Sprayed Coating • Dry coating technology	Coating time: • Traditional Chrome plating: 2 - 8 hours for a stack of 100 rings • HVOF 15 minutes for a stack of 100 rings	• Clean dry coating • Lighter surface grinding than traditional coatings (approximate waste mass = 0.2 Kg compared to 0.3 Kg traditional coating process) • Approximate aqueous waste mass = 2 - 3 Kg compared to 348 Kg traditional coating process waste	• Process efficiency depends on application • Occupies 20% of the floor space needed for equivalent hard chrome production volume • HVOF coatings will last 3 - 4 times longer than traditional coatings
	Incentive	• Electrolytic coating replacement • Clean technology • No refinishing required • Suitable for rebuilding operations, finishing is easier and cheaper than traditional coating (hard chrome)			
	Application	• Coating for wear, erosion, corrosion, and hot oxidation applications, used to rebuild worn components			
	Restriction	• Limited residence time for powder particles in flame			
	Risk	• Cannot be used for high melting temperature ceramics			

---

[2] Technology 2: See Legg *et al.*, 1996.

High Frequency Short-Pulsed Plasma-Immersion Ion Implantation and Deposition ($HFSP^2I^3D$) Technology. An alternative dry technology is high velocity oxygen fuel High-Frequency Short-Pulsed Plasma-Immersion Ion Implantation and Deposition ($HFSP^2I^3D$) that will reduce worker hazardous exposure, air emissions, chemical handling, and waste generation. According to Ryabchikov and Stepanov, this technology is utilized to replace conventional hard chrome process applications. $HFSP^2I^3D$ uses vacuum arc generators of gaseous and metal plasma that passes through micro-particles filtration devices in conjunction with medium frequency dual magnetron, high current ion, plasma source, and high voltage generator equipment to produce a multilayer nano structured coating treatment of dielectric materials. There are many advantages to utilize this technology in the near future since it is a replacement to electrolytic coatings. Moreover, it is a clean hybrid technology that combines ion beam and plasma material applications. $HFSP^2I^3D$ exceeds traditional PVD technology in the quality and physical properties of coatings. Its application is extensively utilized to produce coatings for wear, erosion, corrosion, and forming deep modified layers with high concentration of dopant. On the other hand, $HFSP^2I^3D$ is very limited to be applied in many applications due to its expensive and complex installation of system equipment and material treatments. Although of its many incentives and advantages, there are risk factors due to compatibility of forming monolayer coatings with different inter-metallic alloys.

Table 3.10 illustrates an example of a product oriented $HFSP^2I^3D$ technology evaluation of sustainability triple bottom lines. Some incentives for this application and its restrictions from a product oriented point of view based on an evaluation of sustainability triple-bottom-line is due to hierarchical optimization strategies limitations and user-defined operation parameters.

Table 3.10. Product Oriented HFSP^{2}I^{3}D Technology Evaluation of Sustainability Triple Bottom Line.

Technology Base					
Technology (T_i)	Evaluation	Description	Quantification		
			Economic	Environmental	Social
High-Frequency Short-Pulsed Plasma-Immersion Ion Implantation and Deposition (HFSP^{2}I^{3}D)[3]	Functionality	• Vacuum-Arc generators of gaseous and metal plasma with Micro-particles Filtration Devices, Medium Frequency dual Magnetron, High Current Ion and Plasma Source, and High voltage generator for HFSP^{2}I^{3}D coating treatment of dielectric materials for the formation of a multilayer nano structured coating	• Increase in sample strength under cyclic loading by 2 orders of magnitude • Increase in coating density resulted in 20 fold increase in samples corrosion resistance to salt spray under thermal cycling • Forming more than 300 separate double layers of nanomaterial alloys in a total thickness of 4 µm coating	• Clean dry coating • Coating delamination requires a 7 N load on indenter for destruction of a 4 mm thick multilayer nanomaterial alloy coating while only 5 N load for destruction of a 4 mm thick monolayer alloy • No Cracks across the coating surface due to the formation of a structure with layers compensating inner tensions	• Process efficiency depends on application • Improvement of physical and mechanical coating properties in comparison with traditional PVD technologies
	Incentive	• Electrolytic coating replacement • Clean hybrid technology of Ion Beam and Plasma material • Improve physical properties of coatings in comparison with traditional PVD technology			
	Application	• Coating for wear, erosion, corrosion, and forming deep modified layers with high concentration of dopant			
	Restriction	• Expensive and Complex Installation system equipment and material treatment			
	Risk	• Coatings compatibility of forming monolayers with different inter-metallic alloys			

---

[3] Technology 3: See Ryabchikov and Stepanov, 2009.

3.1.3 Materials Oriented Technologies

In recent years there has been a trend to find alternative advanced materials to enhance or replace finished metal substrates. Advanced materials can provide sufficient corrosion resistance without using toxic surface finishing chemical processes on substrate surfaces. Advanced materials can be categorized into compatible alloys on molecular or nanocrystalline scale materials.

Advanced metal alloys technology. Developing advanced metal alloys that will eliminate the need for toxic surface finishing chemicals is another promising technology that will provide better product quality and overall environmentally friendly technique compared to traditional hazardous plating processes. It is very critical to improve substrate material performance without altering existing substrate materials operations. Advanced metal alloys technology will provide superior corrosion resistance; eliminate use of traditional plating and its associated surface finishing chemicals. A novel high strength stainless steel alloy can be utilized to replace traditional high strength, low alloy carbon steels. This new alloy can provide high corrosion resistance and strength necessary for harsh environment performance and to prolong the life cycle of the parts in service. Other advanced metal alloys such as low density aluminum-lithium and aluminum-magnesium-scandium alloys are being developed to reduce weight and to replace aluminum structural components and parts. Light weight alloys are very favorable in aerospace, automotive and military industries due to the vast benefits associated with their use. Those advanced alloys will assist in reducing energy consumption and improve quality and efficiency of the products while meeting specific components and parts requirements. There are several advantages for utilizing new advanced metal alloys such as eliminating the use of harmful toxic substrate plating and its associated chemical usage, operator exposure, and minimize waste generation. Moreover, novel metal alloys provide excellent performance for products that will require reduce failures and prolong the life cycle of the products that will save down time due to repairs (Chalmer, 2008).

Non-metal materials technology. Non-metal materials such as composites and plastics are exceptional technologies for replacing finished metal based substrates. Composites are materials developed to provide relative high strength to weight ratios in comparison with conventional metallic components substrates. Composite based materials are non-metallic and composed of fibrous reinforced by glass, carbon, Kevlar, or other advanced cured resin matrix materials that is hardened to specific properties (Chalmer, 2008). The main purpose of non-metal materials is to generate light weight and high strength durable components that can withstand various environmental conditions. Non-metal materials technology offer many advantages compared to finished metals. Some of their advantages are low investment and manufacturing operating cost to fabricate components compared to metals fabrication, reduction in assembly by manufacturing composite parts that can replace several metal parts. In addition to, their high corrosion resistance, high strength per unit weight, electrical insulating properties, electromagnetic radiation absorption, controlled thermal expansion, and energy transfer depending on the application (Chalmer, 2008). Plastics are widely utilized to replace metal components to provide similar benefits as composite materials. Plastics can offer a variety of design flexibility, color, and decorative appearance. Plastics can be categorized into crystalline or amorphous plastics. Crystalline plastic materials such as nylon, polypropylene, acteal, polyester, and polyethylene are utilized to replace metal components while amorphous plastics include acrylic, acronitrile butadiene styrene (ABS), polystyrene, polyvinyl chloride (PVC), and polycarbonate that are also alternatives to metal alloys. The barrier to non-metal materials technology is recycling. It is a challenging issue to recycle non-metal materials (composites or plastics) compared to recycling metal alloys. However, a continuous development in non-metal material technology is anticipated to further improve material properties and expand their use for niche applications in automotive, aerospace and military industries. Non-metal materials technology development that could enhance the use of plastics is the development of plastics that conduct heat by addition of thermally conductive additives such as specialty graphite fibers, carbon fibers, and ceramics. On the other hand, it is limited in production of thermally conductive plastics due to the high cost of the additives (Chalmer, 2008).

Nanomaterials technology. The development of nanomaterials through nanotechnology has a huge impact on surface finishing technologies. Nanomaterial finishes is developed by vapor phase processing, inert gas condensation, mechanical alloying or high-energy ball milling, chemical synthesis and electroplating. Nanomaterial coatings are characterized with dense, low porosity, and highly uniform fine grain structures. There are various promising benefits accompanied by using nanomaterials technology in the metal finishing industry. Nanomaterial metals provide exceptional corrosion resistant properties compared to traditional metal finishing as well as superior magnetic, hardness and optical properties. Because of the nanometer size scale of these nanomaterials such as cobalt, copper, nickel, palladium, and their alloys, they form relatively thin coatings that have better wear resistance than conventional electroplating finishing processes. Moreover, nanomaterials used in electroplating processes will yield to higher current densities and improve process efficiencies that will minimize hydrogen embrittlement problems as well as higher ductility and fatigue resistance due to lack of microcracking phenomenon on the surface of the substrate. Another advantage for utilizing nanomaterials coatings is the possible weight reduction due to thinner deposition of coating on the surface while maintaining or exceeding desired surface properties and performance (Chalmer, 2008). An example of nanomaterial technology is nanocrystalline cobalt-phosphorous alloy coatings and its deposition process as an alternative to conventional hard chrome plating and its toxic chemical coatings. Nanocrystalline cobalt-phosphorous alloys provide superior corrosion and wear resistance in a variety of temperature ranges that is necessary for extreme environmental conditions. Another nanomaterial technology is the development of nanostainless steel that provides ultra high strength characteristics, high elasticity modulus, easy formability, and excellent corrosion resistance (Chalmer, 2008).

3.1.4 Energy Efficient Technologies

Improving energy efficient technologies will continue development for the surface finishing industry because of the high cost associated with energy consumption and strict environmental and health regulations to reduce pollution, conserve resources, and eliminate operator’s hazardous exposures. A variety of high efficient equipment that can be utilized in the metal finishing industry such as high efficiency chillers, boilers, heaters, motors, pumps, etc. will have significant energy savings for the entire process operation. Furthermore, process layout and piping design for efficient energy conservation will minimize equipment energy consumption by taking in consideration gravity flow and minimizing frictional losses throughout the process. Covering process tanks when not in operation or enclosing process lines will assist in reduction of ventilation requirements and minimize evaporation and heat losses. Efficient ventilation system design can be adjusted depending on process conditions and requirements in order to achieve maximum operation efficiency. Controlling process solutions and contaminants will save rework and processing times that will indirectly save in unnecessary energy required to reprocess parts (Chalmer, 2008).

3.2 Technology Assessment Approach

Preliminary assessment of sustainability three triple bottom lines is based on evaluating sustainability's indicator criteria. Recent researchers (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008) are focusing on combining sustainability assessments with suitable indicators for industrial chemical process design to achieve a successful sustainable development and to determine industrial process sustainability performance.

There is no consistent reasonable methodology assessment in integrating all three aspects of sustainability triple bottom lines into the electroplating industrial systems. The most common methodology that is being adopted by industries is driven by economics. Industrial economics could be micro-economics or macro-economics depending on the industry's globalization, impact, and contribution to the society's economy. However, this is not sufficient to satisfy industrial profitability and success in the future from a sustainability stand point. Industry should adapt a methodology to consider and integrate all three aspects of sustainability economic, environmental and social criteria into their processes and systems. Many researchers are focusing their work on integrating and applying sustainability methodologies to many industrial processes in order to develop a variety of sustainable process alternatives (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008; Halim and Srinivasan, 2008).

This work argues that technological network modeling combined with optimization-based decision-making methodologies will provide an integrated holistic approach to assist industry not only to achieve a sustainable degree but also to enhance their system sustainability performance.

3.2.1 Quantification of Triple Bottom Lines Using Sustainability Metrics

Industries are required to adopt sustainable development using innovative technologies and advanced methodology in order to address global problems such as extensive utilization of natural resources, increase in waste generation, and quality of life.

A strong emphasis on technological sustainability along with global price competition and rising energy costs is influencing electroplating industry to consider various sustainability measures including reducing raw material consumption and energy usage. In addition to, pressuring the electroplating industry processes to switch to renewable resources, waste minimization and recycling techniques. Table 3.11 illustrates combined benefits of sustainability indicators after identifying and implementing several technological applications with further classification for each sustainable category (economic, environmental, and social). The objective is to select an optimal set of technologies that will improve and enhance the overall system sustainability status regardless of its complexity with respect to the industry's goals and future plans. The novel methodology presented in this section is composed of four stages: (a) sustainability assessment of the existing industrial system before introducing technologies, (b) technological assessment via strategically selected sustainability indicators, (c) technology quantification of all possible combination of technologies based on industrial future goals, (d) selection of optimal technology or suite of technologies for overall industrial system sustainability enhancement.

Table 3.11 illustrates the sustainability assessment of each technology or suite of technologies in which it will be computed for each sustainability triple bottom line vertically via averaging the values of the economic sustainability (E^{avg}), environmental sustainability (V^{avg}), and social sustainability (L^{avg}). Then each triple bottom line assessed value will be combined in order to calculate the overall sustainability of each technology (T_i) till the Nth technology (T_N) is selected from the technology base. All equations in Table 3.11 will be explained in details in later chapters of this research with an illustrative case study for clarity; in addition to an in depth electroplating case study utilizing profitable pollution prevention technologies.

Table 3.11. Combined Sustainability Benefits Using Technological Applications.

Sustainability Indicators	Indicator Symbol	Technological Applications				Combined Benefits per Sustainability Indicator	Combined Benefits per Sustainability Single Bottom Line	Combined Benefits of Sustainability After Using (T_N) Technologies
		T_1	T_2	…	T_N			
Economic (E)	E_1	p_{11}	p_{12}	…	p_{1N}	$E_1 = \sum_{i=1}^{N} f(p_{1,i})$	$E = \sum_{j=1}^{M}\sum_{i=1}^{N} f(p_{j,i})$	$S^{Whole} = E + V + L$
	E_{Me}	p_{Me1}	p_{Me2}	…	p_{MeN}	$E_{Me} = \sum_{i=1}^{N} f(p_{Me,i})$		
		______	______	…	______	$E_{Me}^{avg} = \sum_{i=1}^{N} f(p_{Me,i})$		
Environmental (V)	V_1	q_{11}	q_{12}	…	q_{1N}	$V_1 = \sum_{i=1}^{N} f(q_{1,i})$	$V = \sum_{j=1}^{M}\sum_{i=1}^{N} f(q_{j,i})$	
	V_{Mv}	q_{Mv1}	q_{Mv2}	…	q_{MvN}	$V_{Mv} = \sum_{i=1}^{N} f(q_{Mv,i})$		
		______	______	…	______	$V_{Mv}^{avg} = \sum_{i=1}^{N} f(q_{Mv,i})$		
Social (L)	L_1	r_{11}	r_{12}	…	r_{1N}	$L_1 = \sum_{i=1}^{N} f(r_{1,i})$	$L = \sum_{j=1}^{M}\sum_{i=1}^{N} f(r_{j,i})$	
	L_{Ml}	r_{M1}	r_{M2}	…	r_{MN}	$L_{Ml} = \sum_{i=1}^{N} f(r_{Ml,i})$		
		______	______	…	______	$L_{Ml}^{avg} = \sum_{i=1}^{N} f(r_{Ml,i})$		
Combined Benefits of Sustainability per Technology		S_1	S_2	…	S_N	$S_{T_i} = \sum_{i=1}^{N} f(s_i)$		$S_{T_i} \neq S^{Whole}$

3.2.2 Technology Integration Framework

A technological network modeling framework along with analysis procedures is required to assess the effect of selected technologies on the electroplating and metal finishing industries future sustainable development. This technology integrated sustainability enhancement (TISE) holistic approach is used to effectively enhance the overall industrial system sustainability by evaluating each technology or suite of technologies based on strategically selected indicators and combined benefits methodology assessment. Figure 3.7 illustrates the components of TISE framework which includes (a) well defined technology base consists of feasible technologies with their detailed description of functionality and related applications, (b) sustainability assessment module that has strategic selection of sustainability metrics and indicators, (c) sustainability decision analysis module that determines the optimal selection of technology or suite of technologies for any desired industrial system.

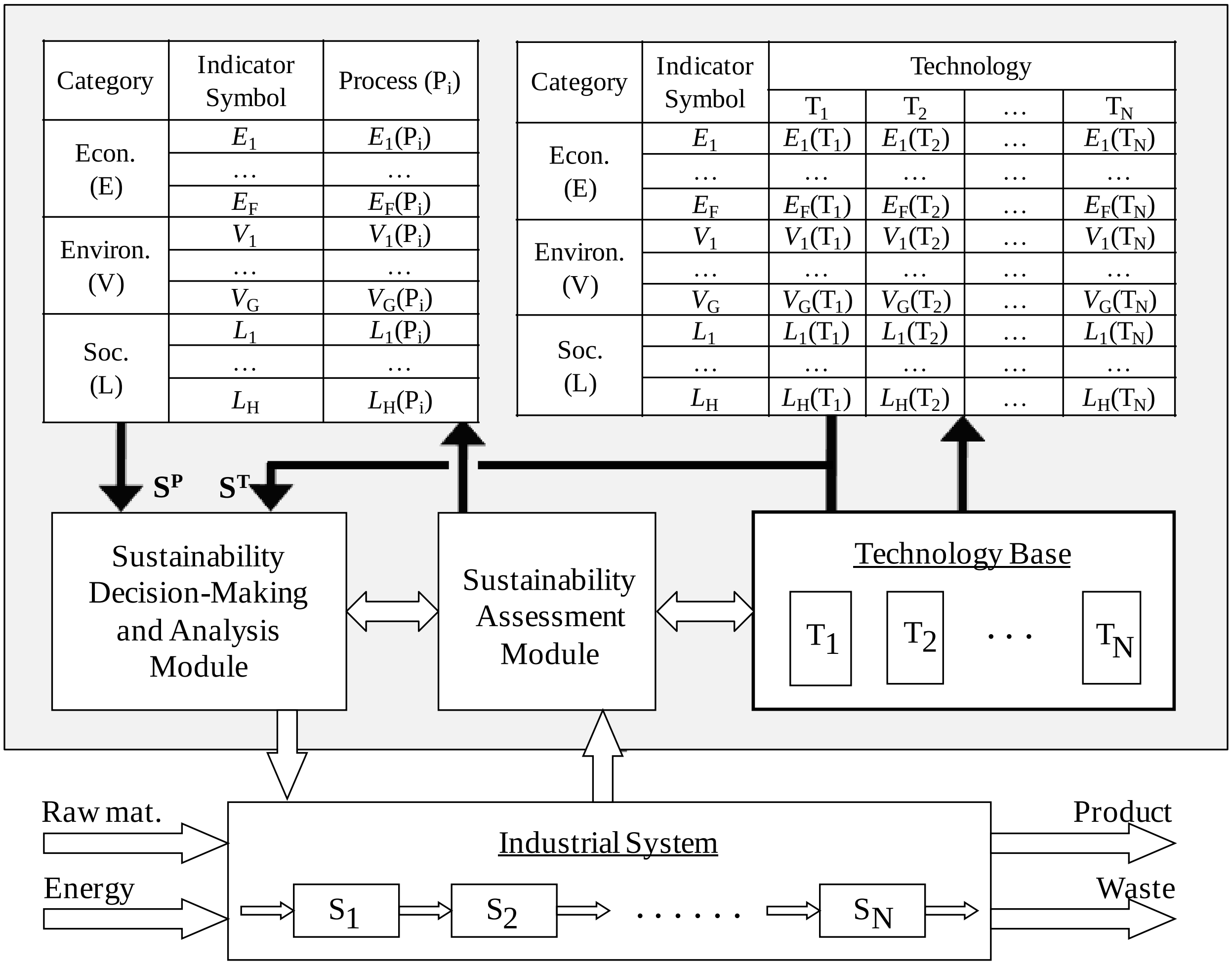


Figure 3.7. Technology Integrated Sustainability Enhancement (TISE) holistic approach for industrial systems.

In Figure 3.8 there is technology flow from the technology data base and information flow from various industrial systems input output components for sustainability assessment and decision making modules.

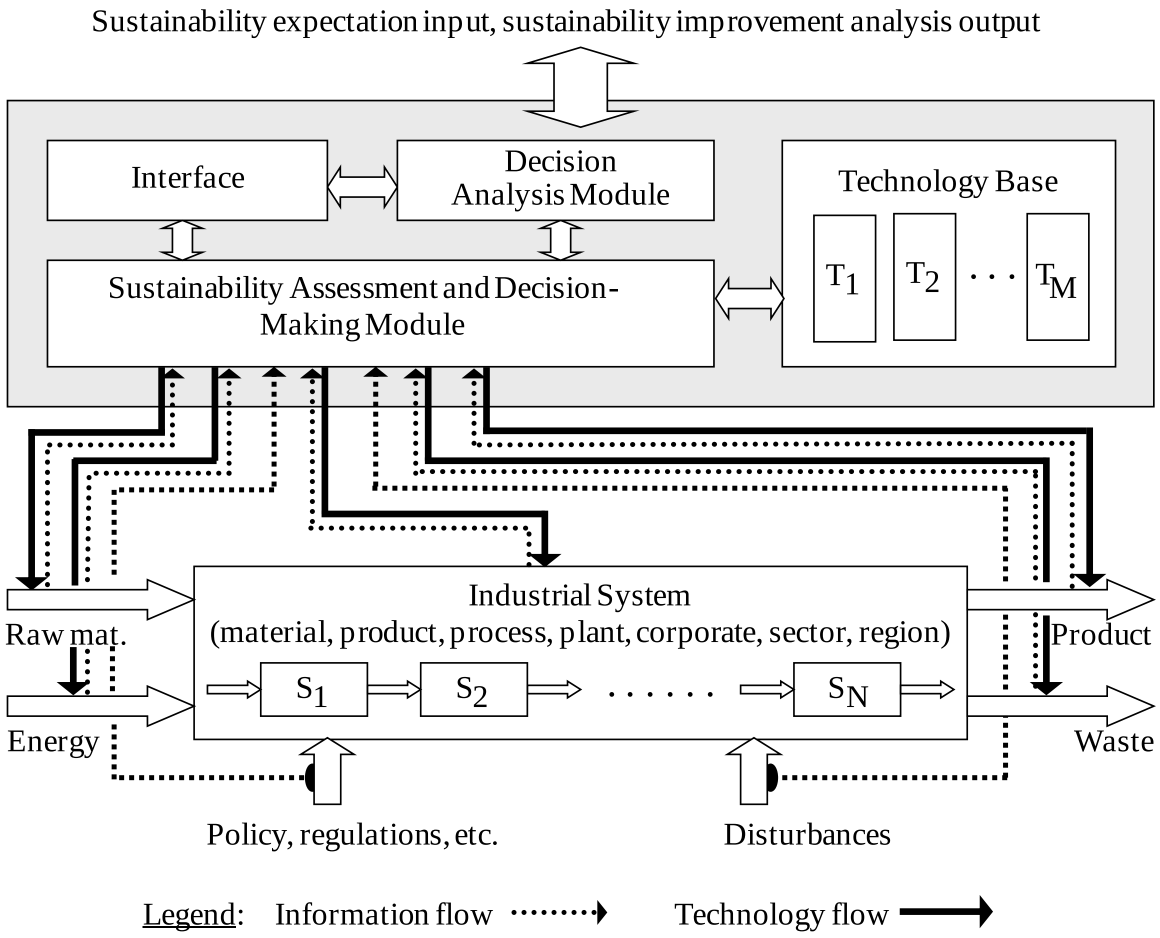


Figure 3.8. Technology flow for industrial system sustainability enhancement.

3.2.3 Profitable Pollution Prevention (P3) Technology Sustainability Performance Quantification

Optimum Cleaning and Rinsing System Technology (P3$_1$). Thirty barrels of parts processed in a simulated cleaning/rinsing system. Each barrel load is (200 kg) and initial dirtiness is (0.0035 g/cm^2). Initial concentration is 7.6% for base and optimum case is 6.2%. It is required that 80% of dirt to be removed from parts after cleaning and rinsing processes. Operating mode for each barrel in the cleaning tank is 4.16 minutes while the first and second rinsing tanks are 0.41 and 0.5 minutes respectively. The dirt residue on the parts through this process should be less than 0.0007 g/cm^2. Over-cleaning is unnecessary and proposes an opportunity for reducing chemical and rinse water usage. The simulation reveals that using an initial chemical concentration of 6.2 % and rinse water flow rate of 5.8 gal/min and adding chemical after every 10 barrels being processed will ensure that the cleaning and rinsing quality maintained simultaneously (Gong et. al, 1997).

Table 3.12. Cleaning-Rinsing Process Simulation Results of 30 Barrels (Gong et. al, 1997).

Parameter	Case 1 (Base)	Case 2 (Optimal)	Percent Change
Cleaning Tank Capacity (gal)	320	320	
1st Rinsing Tank Capacity (gal)	220	220	
2nd Rinsing Tank Capacity (gal)	220	220	
Number of Barrels	30	30	
Cleaning Time (min)	4.16	4.16	
1st Rinsing Time (min)	0.41	0.41	
2nd Rinsing Time (min)	0.5	0.5	
Rinse water Flow Rate (gal/min)	7	5.8	-17.1%
Initial Chemical Conc. (vol.%)	7.6	6.2	-18.4%
Chemical Consumption (gal/barrel)	0.235	0.223 (I_{VM1})*	-5.1% (I_{VI1})*
Rinse Water Consumption (gal/barrel)	30.3	25.1(I_{VW1})*	-17.2%
Wt% dirt remaining after cleaning 10 bbls	9.7 -19.9	14.6 - 19.9	

* Data used to calculate environmental indicator values in Appendix A1.

According to the 2002 United States Census Bureau, the number of all electroplating industrial establishments in the United States is about three thousand establishments. However, this number was reduced to about twenty seven hundred establishments as published in the 2007 economic census due to the poor economic condition the United States is going through. Table 3.13 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division.

Table 3.13. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	All Establish-ments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electro-plating	2,720	$4,721,777	$1,735,947 ($I_{EP1}$)*	$7,139,847	$2,625,000 ($I_{EP2}$)*

***** Data used to calculate economic indicator values in Appendix A1.

It is very important to define value added and total value of shipments in order to clarify the meaning of both indicators. According to the United States Census Bureau, value added is defined as the measure of manufacturing activity which is derived by subtracting the cost of materials, supplies, containers, fuel, purchased electricity, and contract work from the value of shipments (products manufactured plus receipts for services rendered). In other words, value added is the difference between the sales value and the cost of merchandise sold without further manufacture, processing, or assembly. Total value of shipments defined by United States Census Bureau as the received or receivable net selling values, f.o.b. plant (exclusive of freight and taxes), of all products shipped, as well as all miscellaneous receipts, such as receipts for contract work performed for others, installation and repair, sales of scrap, and sales of products bought and sold without further processing. (2007 Economic Census)

Tables 3.14 – 3.16 illustrates $P3_1$ optimum cleaning and rinsing technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.14. P3$_1$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		P3$_1$: Optimum Cleaning and Rinsing Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials used per kg product	0.0029 kg.sodium bicarbonate/kg.Parts	Sodium Bicarbonate cleaning chemistry reduced by 18.4% for tank make up and chemical consumption reduced by 5.1% during operation
I_{VM2}	Total raw materials used per unit value added	1.27 x 10^{-4} kg.sodium bicarbnate/$	Chemical solutions used for tank make up
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.475 kg.water/kg.parts	Amount of water used in operating process per barrel load
I_{VW2}	Net water consumed per unit value added	2.08 x 10^{-2} kg.water/$	Amount of water used during operation per value added
2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	9.17 x 10^{-7} liter.sodium bicarbonate/kg.Parts.$	Chemical solution used during operation per value added
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	5.24 x 10^{-7} kg.sodium bicarbonate/kg.parts.$	Chemical reduction corresponds to nearly same amount of hazardous waste generated

Table 3.15. P3$_1$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		P3$_1$: Optimum Cleaning and Rinsing Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	$4,577/y	5.1% savings of 10% chemical cost of 51.7% material cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	1.74 x 10^{-3}/y	Value of sales calculated from value of shipments according to 2007 Census data
I_{EP3}	Value added per direct employee	$229/y	Based on average number of direct employees (20) required for entire operation and process

Table 3.16. $P3_1$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		$P3_1$: Optimum Cleaning and Rinsing Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.13%	Assuming 2 incidences each half a shift (4 hrs) per year not including holidays (50 weeks)
2. Society			
I_{SS1}	Number of stakeholder meetings per unit value added	4.36×10^{-4}/$	Based on two meeting for cost savings and benefits

Optimum Design for Water Allocation and Reuse Technology ($P3_2$). Huang research group established an optimal design methodology for water reuse and allocation for general electroplating process fresh water network rinsing systems. This methodology is used to determine the optimum distribution of fresh water and used water throughout various rinsing tanks in the electroplating process. The methodology also examines the feasibility of potential reuse of each water steam in proper rinsing tanks (Lou and Huang, 2000). The main objective is to design a water reuse and allocation network for minimizing the total rinsing operation cost which includes fresh water consumption and pipes installation for water network distribution. The base case for the rinsing operation consumed 16 gal/min of total fresh water however by using Water Use and Reuse Network (WURN), the fresh water consumption is reduced to 9 gal/min. This is a reduction of about 44% of fresh water or waste water while maintaining rinsing quality (Lou and Huang, 2000).

In electroplating operations, chemical contamination and losses from either cleaning or electroplating units is due to drag-out into succeeding rinsing units which can be as high as 60% and 30% of overall consumption, respectively (Xu and Huang, 2005). The lost solutions from either cleaning or electroplating is rinsed off by fresh rinsed water which will flow into waste water treatment facilities that will not only increase the operating cost for chemical additions and replenishing solutions but also the waste treatment of such excessive waste generated.

In Figure 3.9, three rinsing subsystems, each containing two rinse tanks with countercurrent rinse water flow, the total fresh water flow rate is 16 gal/min. Table 3.17 illustrates a comparison between the original and optimal fresh water consumption and allocation flow rates. After implementing WARN optimal design, the fresh water consumption is reduced to 9 gal/min, which is 44% reduction in fresh water or waste water generated from the system while maintaining the rinsing quality. The rinse water cut off is after 5.2 min of rinsing since the contamination concentration in the rinse tank is at the range to accept the next barrel of parts to be rinsed. (Lou and Huang, 2005)

Table 3.17. Optimum Design of Process Rinse Water Network Reuse and Allocation Technology (Lou and Huang, 2000)

Water Stream	Fresh Water Consumption and Allocation Flow rates (gallons per minute)		Percent Change
	Original	Optimal	
Fresh Water 1	4	1.5	
Fresh Water 2	6	5	
Fresh Water 3	6	2.5	
Waste Water 1	4	2.2	
Waste Water 2	6	6.4	
Waste Water 3	6	0.4	
Reused Water 1	0	2.3	
Reused Water 2	0	3	
Total Fresh Water	16	9 (I_{VW1})*	-44%(I_{VI1})*

* Data used to calculate environmental indicator values in Appendix A2.

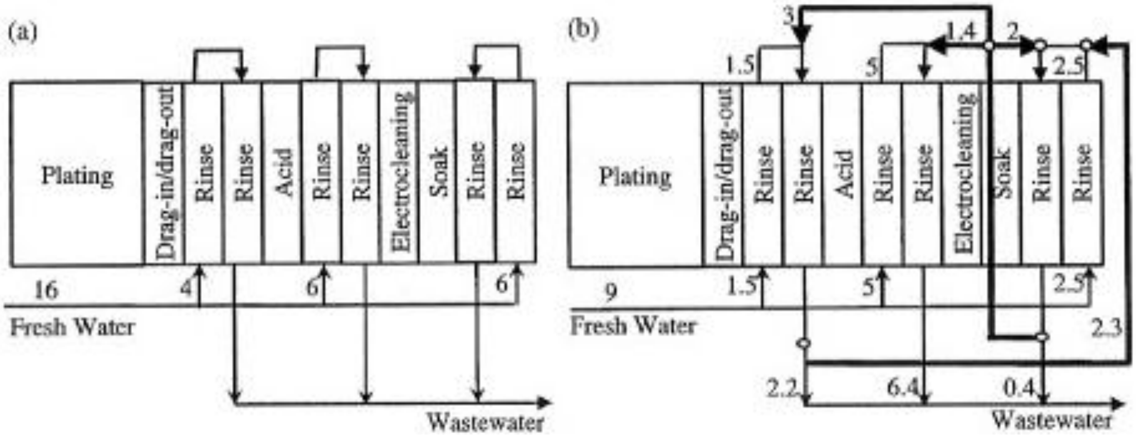


Figure 3.9. Water use and reuse in an electroplating process line: (a) Original process flow sheet; (b) Optimal design process flow sheet using WURN Technology (Lou and Huang, 2000)

Table 3.18 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division. Tables 3.19 – 3.21 illustrates $P3_2$ optimum design for water allocation and reuse technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.18. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	Total Establish-ments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electro-plating	2,720	$4,721,777	$1,735,947 (I_{EP1})*	$7,139,847	$2,625,000 (I_{EP2})*

***** Data used to calculate economic indicator values in Appendix A2.

Table 3.19. $P3_2$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		$P3_2$: Optimum Design for Water Allocation and Reuse Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials used per kg product	n/a	No raw materials or chemicals used. Only a design for optimal water reuse
I_{VM2}	Total raw materials used per unit value added	n/a	Indicator is only for materials excluding fuel and water so not applicable for this application
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.15 kg.water/kg.parts	Amount of water used 9 gal/min in 6 operating process rinse tanks per 200 kg barrel load in each tank for 5.2 min rinsing
I_{VW2}	Net water consumed per unit value added	9.65×10^{-2} kg.water/$	Amount of water used during operation per value added
2. Emissions, Effluents & Waste			
2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	0 gal/$	Water reuse and allocation is beneficial and has a positive aquatic impact due to less natural fresh water consumption and less waste generated to be treated
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	5.35×10^{-7} kg.sodium bicarbonate/kg.parts.$	Water reduction corresponds to nearly same amount of hazardous waste water generated for treatment

Table 3.20. $P3_2$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		$P3_2$: Optimum Design for Water Allocation and Reuse Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	\$1,833/y	44% savings of 3% water cost of 8% total utilities cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	6.98×10^{-4}/y	Value of sales calculated from value of shipments according to 2007 Census data
I_{EP3}	Value added per direct employee	\$91.7/y	Based on average number of direct employees (20) required for entire operation and process

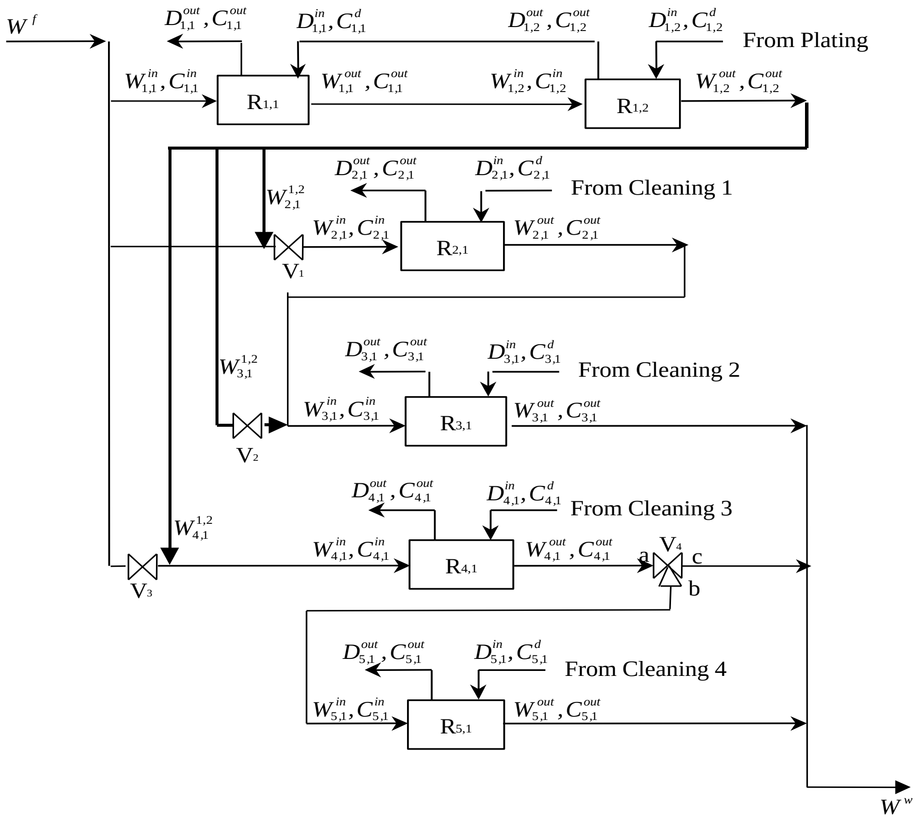
Table 3.21. $P3_2$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		$P3_2$: Optimum Design for Water Allocation and Reuse Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.1%	Assuming 6 hrs per year not including holidays (50 weeks) for piping and repair valves
2. Society			
I_{SS1}	Number of stakeholder meetings per unit value added	1.09×10^{-3}/\$	Based on two meeting for cost savings and benefits

Optimum Design of Switchable Rinse Water Allocation Network Technology ($P3_3$). Huang research group established an optimal design methodology for switchable water allocation network (SWAN) for general electroplating process fresh water network rinsing systems. This methodology is used to determine the optimal water allocation network for any plating line, and developing optimal operation strategy based on rinse network dynamics (Zhou *et al*., 2001; Yang *et al*., 2000). The operation strategy can provide the control policies for switching water flow patterns during the operations. The methodology also examines the feasibility of potential reuse of each water steam in proper rinsing tanks (Lou and Huang, 2000). The main objective is to design a switchable water allocation network for minimizing the total rinsing operation cost which includes fresh water consumption, pipes installation, valves and controls for water network distribution. The base case for the rinsing operation consumed 16 gal/min of total fresh water however by using SWAN, the fresh water consumption is reduced to 9.5 gal/min. This is a reduction of about 59% of fresh water or waste water while maintaining rinsing quality (Zhou *et al*., 2001).

In electroplating operations, chemical contamination and losses from either cleaning or electroplating units is due to drag-out into succeeding rinsing units which can be as high as 60% and 30% of overall consumption, respectively (Xu and Huang, 2005). The lost solutions from either cleaning or electroplating is rinsed off by fresh rinsed water which will flow into waste water treatment facilities that will not only increase the operating cost for chemical additions and replenishing solutions but also the waste treatment of such excessive waste generated.

In Figure 3.10, three rinsing subsystems, each containing two rinse tanks with countercurrent rinse water flow, the total fresh water flow rate is 16 gal/min. In table 3.22, implementing SWARN optimal design, the fresh water consumption is reduced to 9.5 gal/min, which is 59% reduction in fresh water or waste water generated from the system while maintaining the rinsing quality. In each operation cycle of 10 min, the primary WAN runs for the first 7.5 min and the secondary WAN for the next 2.5 min. The switch of the two WANs (rinse water flow patterns) is accomplished by four valves. The economic analysis of the case study (Zhou *et al.*, 2001) shows that the SWAN can reduce 39.3% of the total annualized costs.



(a)

SWAN	Valve Control Strategies				
				V_4	
	V_1	V_2	V_3	a→b	a→c
Primary WAN	Open	Close	Open	Open	Close
Secondary WAN	Close	Open	Close	Close	Open

(b)

Figure 3.10. (a) SWAN Flowsheet (b) Operational scheme the SWAN (Zhou *et al*. 2001).

Table 3.22. Optimum Design of Switchable Rinse Water Network Allocation Technology (Zhou *et al.*, 2001)

Water Stream	Switchable Fresh Water Consumption and Allocation Flow rates (gallon per minute)		Percent Change
	Original	Optimal	
Fresh Water 1	6	6	
Fresh Water 2	6	2	
Fresh Water 3	4	1.5	
Waste Water 1	6	4.8	
Waste Water 2	6	1.25	
Waste Water 3	4	3.3	
Reused Water 1	0	2.5	
Reused Water 2	0	0.25	
Reused Water 3	0	3.1	
Total Fresh Water	16	9.5 (I_{VW1})*	-59% (I_{VI1})*

* Data used to calculate environmental indicator values in Appendix A3.

Table 3.23 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division. Tables 3.24 – 3.26 illustrates $P3_3$ optimum design for switchable water allocation and reuse technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.23. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	Total Establishments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electroplating	2,720	$4,721,777	$1,735,947 ($I_{EP1}$)*	$7,139,847	$2,625,000 ($I_{EP2}$)*

***** Data used to calculate economic indicator values in Appendix A3.

Table 3.24. P3$_3$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		P3$_3$: Optimum Design for Switchable Water Allocation and Reuse Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials used per kg product	n/a	No raw materials or chemicals used. Only a design for optimal water reuse
I_{VM2}	Total raw materials used per unit value added	n/a	Indicator is only for materials excluding fuel and water so not applicable for this application
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.16 kg.water/kg.parts	Amount of water used 9.5 gal/min in 6 operating rinse tanks per 200 kg barrel load in each tank for 5.2 min rinsing
I_{VW2}	Net water consumed per unit value added	7.6×10^{-2} kg.water/$	Amount of water used during operation per value added
2. Emissions, Effluents & Waste			
2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	0 liter/$	Switchable Water Reuse and Allocation is beneficial and has a positive aquatic impact due to less natural fresh water consumption and less waste generated to be treated
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	2.93×10^{-7} kg.sodium bicarbonate/$	Water reduction corresponds to nearly same amount of hazardous waste water generated for treatment

Table 3.25. P3$_3$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		P3$_3$: Optimum Design for Switchable Water Allocation and Reuse Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	\$2,460/y	59% savings of 3% water cost of 8% total utilities cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	9.37×10^{-4}/y	Value of sales calculated from value of shipments according to 2007 Census data
I_{EP3}	Value added per direct employee	\$123/y	Based on average number of direct employees (20) required for entire operation and process

Table 3.26. P3$_3$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		P3$_3$: Optimum Design for Switchable Water Allocation and Reuse Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.13 %	Assuming 8 hrs per year not including holidays (50 weeks) for piping and repair valves
2. Society			
I_{SS1}	Number of stakeholder meetings per unit value added	8.13×10^{-4}/\$	Based on two meeting for cost savings and benefits

Optimum Design of Sludge Reduction Technology (P3$_4$). Huang research group established an optimal design methodology for sludge elimination and reduction for general electroplating process cleaning and rinsing systems. This methodology is used to determine quantitative estimation and minimization of avoidable sludge that is generated due to high flow rate of fresh rinse water, excessive drag-out into rinsing tanks, improper use of cleaning chemical solutions, and short bath life that will result in excessive dumping to waste treatment facilities. The operation strategy can provide a model for sludge reduction during operation. The majority of the mixture of dirt and chemicals generates sludge which is found in cleaning tanks and the remaining portion will enter rinsing systems via drag-out from the cleaning tanks. The methodology also examines the feasibility of optimizing rinsing water flow rates in proper rinsing tanks (Luo *et al.*, 1998). The main objective is to develop a mathematical model for estimating sludge from cleaning and rinsing units not only for minimizing the total rinsing operation cost but also the chemicals used in waste water treatment as well as minimizing drag-out into rinsing tanks.

In Table 3.27., the base case for a total of 70 barrels of parts each equally loaded (180 kg/barrel), the chemical concentrations in the presoak, soak, and electroclean are all 8 %. The water flow rate through two rinsing tanks is set to 6 gal/min. After process optimization, the concentration in the presoak, soak and electroclean tanks are set to 10%, 8%, and 6% respectively. On the other hand, the drag-out rate is reduced to from 0.012 to 0.009 g/cm^2. This assisted in the reduction of fresh rinse water flow rate from 6 gal/min to 5 gal/min. With respect to those parameter modifications, the total amount of sludge can be reduced to 66 kg, which corresponds to a 15% reduction (Luo *et al.*, 1998).

Table 3.27. Optimum Design of Sludge Reduction Technology (Luo *et al.*, 1998)

Process Unit	Sludge Reduction Technology Process Parameters		
	Original	Optimal	Percent Change
Presoak	8%	10%	2%
Soak	8%	8%	0%

Electroclean	8%	6%	-2%
Rinse Water 1	6 gal/min	5 gal/min	-16.6%
Rinse Water 2	6 gal/min	5 gal/min (I_{VW1})*	-16.6%
Drag-out	0.012 g/cm^2	0.009 g/cm^2	-25%
Sludge reduction	440 kg	374 kg	-15% (I_{VI1})*

* Data used to calculate environmental indicator values in Appendix A4.

In electroplating operations, 69.5% of total sludge generation is mainly from chemical contamination and losses from either cleaning or electroplating units due to drag-out into succeeding rinsing units which can be as high as 60% and 30% of overall consumption, respectively (Luo *et al.*, 1998; Xu and Huang, 2005). The lost solutions from either cleaning or electroplating is rinsed off by fresh rinsed water which will flow into waste water treatment facilities that will not only increase the operating cost for chemical additions and replenishing solutions but also the waste treatment of such excessive waste generated.

Table 3.28 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division. Tables 3.29 – 3.31 illustrates $P3_4$ optimum design of sludge reduction technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.28. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	Total Establish-ments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electro-plating	2,720	$4,721,777	$1,735,947 ($I_{EP1}$)*	$7,139,847	$2,625,000 ($I_{EP2}$)*

* Data used to calculate economic indicator values in Appendix A4.

Table 3.29. P3$_4$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		P3$_4$: Optimum Design for Sludge Reduction Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials used per kg product	0.0032 kg.sodium bicarbonate/kg.parts	Sodium Bicarbonate chemical used for cleaning tank make up
I_{VM2}	Total raw materials used per unit value added	8.64 x 10^{-5} kg.sodium bicarbonate/$	Sodium Bicarbonate cleaning chemistry solution used per unit value added
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.11 kg.water/kg.parts	Amount of water used 5 gal/min in 3 cleaning and 2 operating rinse tanks per 180 kg barrel load in each tank for 5.2 min rinsing
I_{VW2}	Net water consumed per unit value added	1.47 x 10^{-2} kg.water/$	Amount of water used during operation per value added
2. Emissions, Effluents & Waste			
2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	5.2 x 10^{-7} liter.sodium bicarbonate/ kg.parts.$	Amount of cleaning chemical solution drag-out reduced by 25% and water flow rate reduction of 17.4%
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	2.45 x 10^{-7} kg.sodium bicarbonate/ kg.parts.$	Sludge reduction of 15% by optimizing cleaning concentration, water flow rate, and reducing drag-out contaminating other operating units

Table 3.30. $P3_4$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		$P3_4$: Optimum Design for Sludge Reduction Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	\$6,731/y	15% savings of 5% chemical water treatment cost of 51.7% material cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	2.56×10^{-3}/y	Value of sales calculated from value of shipments according to 2007 Census data
I_{EP3}	Value added per direct employee	\$336.5/y	Based on average number of direct employees (20) required for entire operation and process

Table 3.31. $P3_4$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		$P3_4$: Optimum Design for Sludge Reduction Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.53%	Assuming 32 hrs per year not including holidays (50 weeks) for sludge clean up and tank maintenance
2. Society			
I_{SS1}	Number of stakeholder meetings per unit value added	4.46×10^{-4}/\$	Based on three meeting for cost savings and benefits

Optimum Design for Chemical Recovery Technology ($P3_5$). Huang research group established an optimal design methodology for Chemical loss and reduction for general electroplating process cleaning and rinsing systems. This methodology is used to determine quantitative estimation and minimization of chemical solution loss by providing detailed system analysis and process information integration for optimal design and operation of a closed loop electroplating system for preventing solution loss and ensue proper plating thickness quality. The operation strategy provide a model for an integrated plating system that consists of a plating unit and solution recovery subsystem. The main objective is to develop a mathematical model design and operation approach not only for chemical solution recovery operation cost but also the chemicals used in waste water treatment to treat the loss solutions from relevant rinsing tanks. Therefore, the prevention of solution loss into waste streams is of great economic and environmental significance (Xu *et al.*, 2005).

In Table 3.32, the base case for an alkali zinc electroplating system with a production rate of 11 barrels per hour. A total of 120 barrels of parts each equally loaded (200 kg/barrel), the chemical solution loss was 104,000 gallons per year based on 300 production days per year (Huang, 1999). Model based simulation will identify optimal design and operation strategy and determining the efficiency of chemical solution recovery under specific plating quality constraints such as plating thickness and uniformity. The chemical concentration of Zinc metal in the electroplating tank is 0.21 mol/L while the water flow rate time in the rinse tank is set at 2 minutes. The volume of drag out solution from electroplating unit is 2 L/barrel. After process optimization, the simulation shows that each additional rinse unit can significantly reduce the concentration of chemical solution loss by 81-85% (Xu *et al.*, 2005).

Table 3.32. Optimum Design for Chemical Recovery Technology (Xu *et al.*, 2005)

Parameter	Original	Optimal	Percent Change
Plating Tank	1200 L	1200 L	
Rinse Tank	1200 L	1200 L	
Zinc Concentration	0.21 mol/L	0.21 mol/L (I_{VM1})*	
Drag-out	2 L/Barrel	2 L/Barrel	
Zinc Loss	0.446 mol/Barrel (I_{VQ3})*	0.0892 mol/Barrel	-80% (I_{VI1})*
Zinc Recovered	-	42.8 mol	17%

* Data used to calculate environmental indicator values in Appendix A5.

With respect to design modification, the total amount of chemical solution loss and recovery can give near zero discharge of valuable plating solution chemistries if three rinse units used after plating. Figure 3.11 illustrates a general superstructure of an electroplating and a rinsing solvent recovery design scheme. However, an integrate electroplating system with only one rise unit can still recover at least 80% of valuable chemistries otherwise will be lost into the waste water stream facilities. With such high chemical and metal concentration entering the waste water system, additional economic burden will be added to recover or treat those chemicals (Xu *et al.*, 2005).

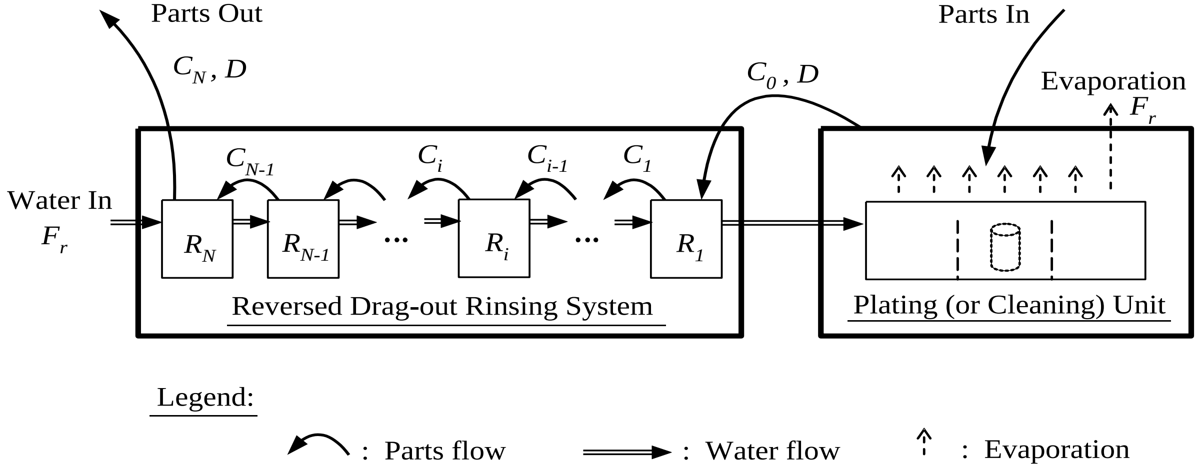


Figure 3.11. A general superstructure of electroplating and rinsing solvent recovery design scheme (Xu *et al.*, 2005).

Table 3.33 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division. Tables 3.34 – 3.36 illustrates $P3_5$ optimum design for chemical recovery technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.33. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	All Establish -ments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electro-plating	2,720	$4,721,777	$1,735,947 ($I_{EP1}$)*	$7,139,847	$2,625,000 ($I_{EP2}$)*

***** Data used to calculate economic indicator values in Appendix A5.

Table 3.34. $P3_5$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		$P3_5$: Optimum Design for Chemical Recovery Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials	0.1059	Sodium Bicarbonate concentration used in

	used per kg product	kg.$NaHCO_3$/kg.parts	electroplating tank make up
I_{VM2}	Total raw materials used per unit value added	1.39×10^{-3} kg. $NaHCO_3$/$	Sodium Bicarbonate concentration used in electroplating chemistry solution per unit value added
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.19 kg.water/kg.parts	Amount of water used 5 gal/min in 3 operating rinse tanks per 200 kg barrel load in each tank for 2 min rinsing
I_{VW2}	Net water consumed per unit value added	2.49×10^{-3} kg.water/$	Amount of water used during operation per value added
2. Emissions, Effluents & Waste			
2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	1.44×10^{-8} gal. $NaHCO_3$/kg.parts.$	Amount of Sodium Bicarbonate waste is reduced by 17% which is the amount metal concentration recovered in the operating units.
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	2.42×10^{-9} kg. $NaHCO_3$/ kg.parts.$	Sodium Bicarbonate recovery is 80% of traditional solution loss concentration and drag-out contaminating other operating units is 2 L/barrel

Table 3.35. $P3_5$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		$P3_5$: Optimum Design for Chemical Recovery Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	$15,260/y	17% savings of 10% chemical cost of 51.7% material cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	5.8×10^{-3}/y	Value of sales calculated from value of shipments according to 2007 Census data
I_{EP3}	Value added per direct employee	$760/y	Based on average number of direct employees (20) required for entire operation and process

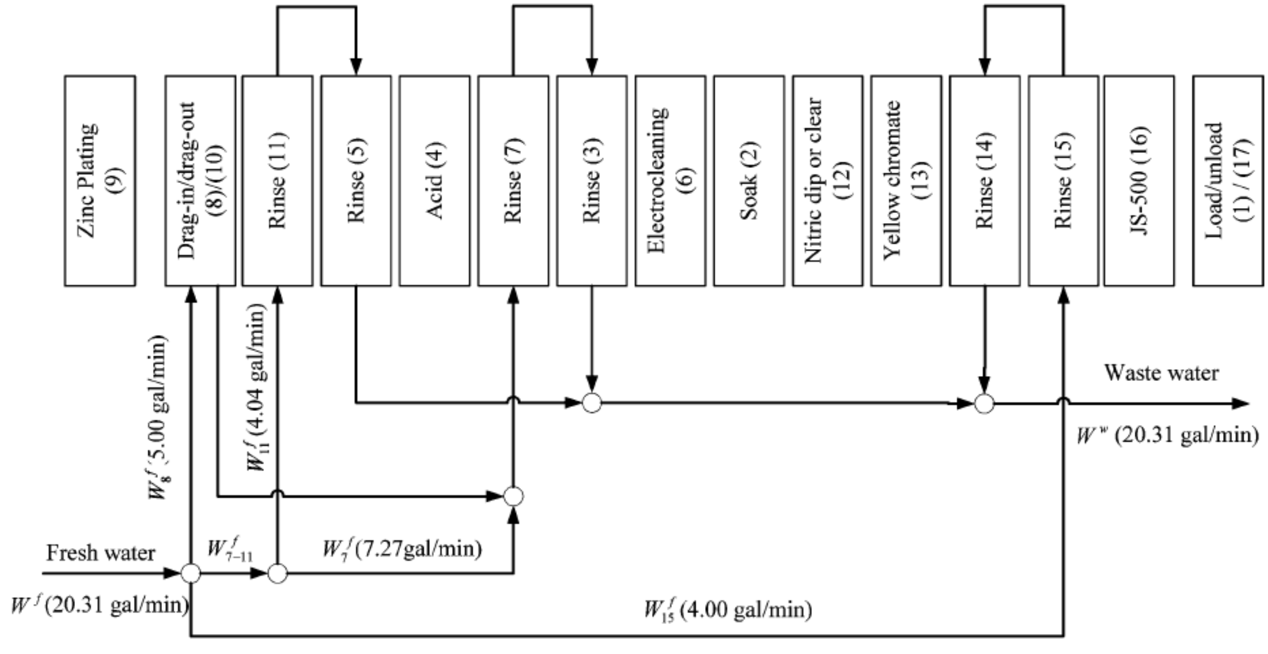
Table 3.36. $P3_5$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		$P3_5$: Optimum Design for Chemical Recovery Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.6%	Assuming 40 hrs per year not including holidays (50 weeks) for sludge clean up and tank maintenance
2. Society			
I_{SS1}	Number of stakeholder meetings per unit value added	2.62×10^{-4}/\$	Based on four meeting for cost savings and benefits

Optimum Design for Hoist Scheduling Technology ($P3_6$). Huang research group established an optimal design methodology for graph assisted dynamic hoist scheduling for general electroplating process systems. This methodology is used to develop an optimal hoist schedule for a single production type multistage process system to quantitatively determine the maximum production rate and minimize waste generation simultaneously. Due to process uncertainties, real time dynamic scheduling is of utmost importance. Recently Huang's group revealed that hoist scheduling affects the environmental performance of the plate line (Kuntay *et al.*, 2005). In other words, optimizing online dynamic hoist scheduling to ensure or improve productivity while minimize waste generation from the plating line simultaneously.

Hoist scheduling Technology used to generate online optimal schedules to meet various production order requests, and improve both economic and environmental objectives. After operator specifies the processing time range for each unit in an electroplating line, Hoist scheduling design technology will direct the dynamic hoist movements in a reactive mode. Every element of uncertainty such as, random arriving of any type of barrels with characterized processing job request, will initiate a new static hoist scheduling cycle. A logistic-based searching algorithm will be employed to make all the jobs going through the production line in a precise timely manner. This scheduling technology can be used for online real application since every decision making can be accomplished in less than 10 seconds (Pentium III 800/512).

Table 3.37 shows the base case for an alkali zinc electroplating system with a production rate of 8.96 min per barrel in comparison with the optimal case. Parts are equally loaded in each production barrel (200 kg/barrel). In this electroplating production line, there are three types of unit operations: cleaning, rinsing, and plating, which are performed in 16 processing tanks. The water allocation network used on seven rinsing tanks is illustrated in Figure 3.12.



Job processing sequence in the units: (1)-(2)-(3)- … -(15)-(16)-(17)

Figure 3.12. General flowsheet of an electroplating line (Xu and Huang, 2004)

The total water consumption is 20.31 gal/min before system optimization which also corresponds to the amount of waste that will be generated from the process. The original hoist schedule with water consumption has a cycle time of 8.96 min which is 31 seconds longer than the optimal schedule. After implementing hoist scheduling technology the cycle time is reduced to 8.45 min which implies an increase in the production rate by 6%. Furthermore, the total rinsing fresh water consumption is reduced from 20.31 gal/min to 18.72 gal/min which is a 7.8% reduction than the original schedule. In general, material handling and electroplating operations requires optimal hoist scheduling technology to maximize the production rate for enhancing the industries operations economically and environmentally (Xu and Huang, 2004; Kuntay *et al.*, 2005).

Table 3.37. Optimum Design for Hoist Scheduling Technology (Xu and Huang, 2004)

Parameter	Original	Optimal	Percent Change
Rinse Tank	250 gal	250 gal	
Water consumption	20.31 gal/min	18.72 gal/min (I_{VW1})*	-7.8% (I_{VI1})*
Production Rate	8.96 min	8.45 min	6%

* Data used to calculate environmental indicator values in Appendix A6.

Figure 3.13 illustrate an example where one hoist is employed in a line to process three different types of jobs continuously. With the aid of the hoist scheduling technology, the plating bath can accommodate eight jobs simultaneously using the developed real time scheduling strategy. A snapshot of the hoist schedules is shown in Fig. 3.14, which illustrates a timed graph (Xu and Huang, 2004) and complete descriptions for dynamic hoist movements responding to a new loaded job.

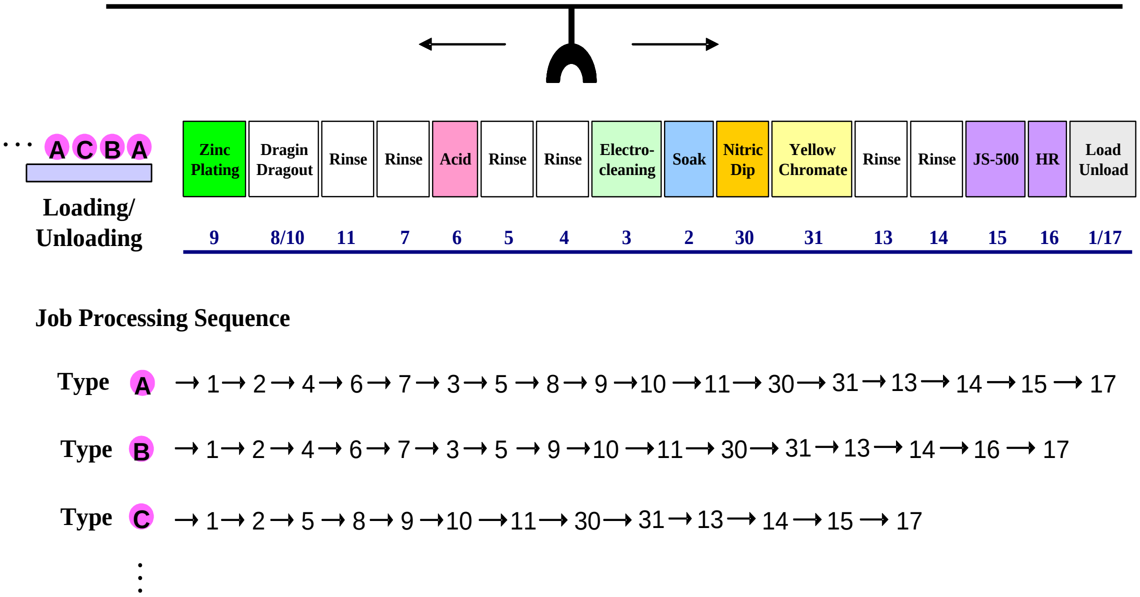
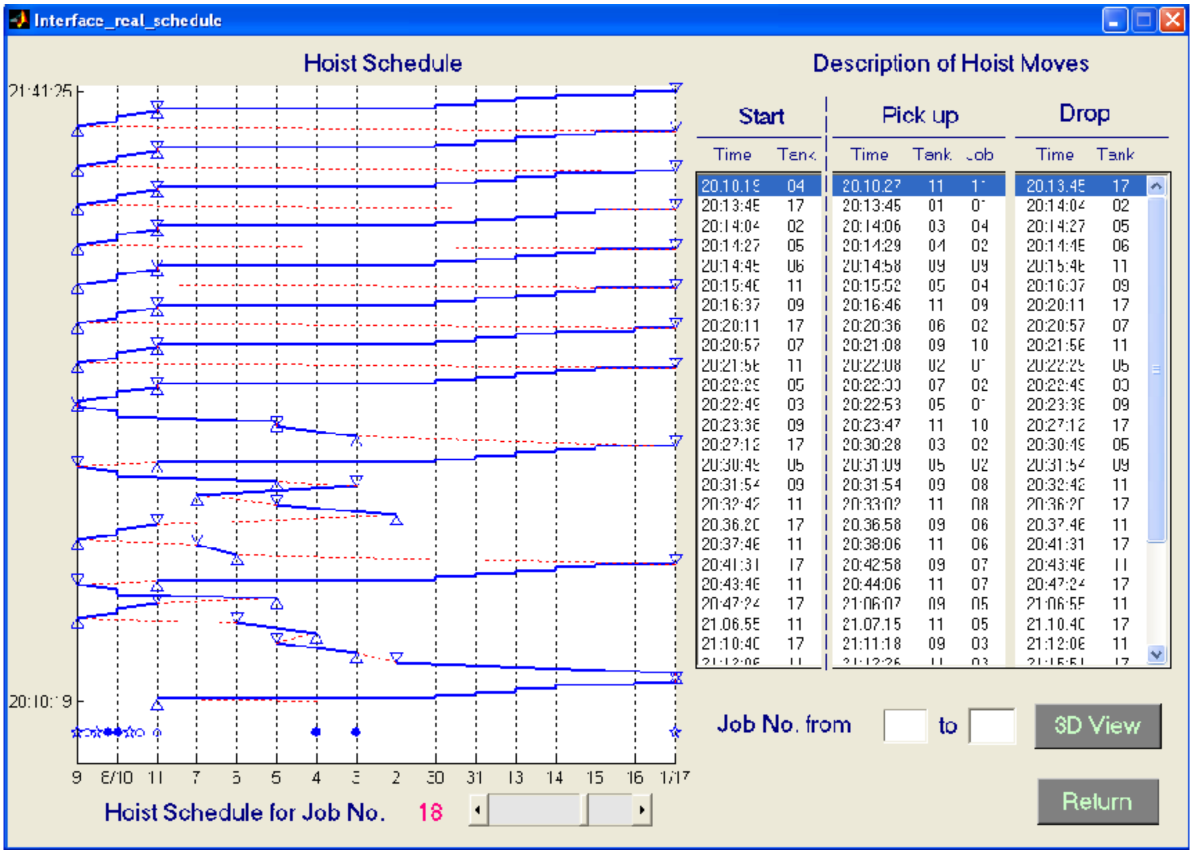


Figure 3.13. Flowsheet of an electroplating line (Xu and Huang, 2004).



Description of Hoist Moves

Start		Pick up			Drop	
Time	Tank	Time	Tank	Job	Time	Tank
20.10.19	04	20.10.27	11	17	20.13.45	17
20:13:45	17	20:13:45	01	07	20:14:04	02
20:14:04	02	20:14:06	03	04	20:14:27	05
20:14:27	05	20:14:29	04	02	20:14:45	06
20:14:45	06	20:14:58	09	09	20:15:46	11
20:15:46	11	20:15:52	05	04	20:16:07	09
20:16:37	09	20:16:46	11	09	20:20:11	17
20:20:11	17	20:20:36	06	02	20:20:57	07
20:20:57	07	20:21:08	09	10	20:21:56	11
20:21:56	11	20:22:08	02	07	20:22:29	05
20:22:29	05	20:22:30	07	02	20:22:49	03
20:22:49	03	20:22:53	05	07	20:23:38	09
20:23:38	09	20:23:47	11	10	20:27:12	17
20:27:12	17	20:30:28	03	02	20:30:49	05
20:30:49	05	20:31:09	05	02	20:31:54	09
20:31:54	09	20:31:54	09	08	20:32:42	11
20:32:42	11	20:33:02	11	08	20:36:20	17
20.36.20	17	20.36.58	09	06	20.37.46	11
20:37:46	11	20:38:06	11	06	20:41:31	17
20:41:31	17	20:42:58	09	07	20:43:46	11
20:43:46	11	20:44:06	11	07	20:47:24	17
20:47:24	17	21:06:07	09	05	21:06:55	11
21.06.55	11	21.07.15	11	05	21.10.40	17
21:10:40	17	21:11:18	09	03	21:12:06	11
21:12:06	11	21:12:26	11	03	21:15:51	17

Figure 3.14. Hoist movements responding to a new loaded job (Xu and Huang, 2004).

Table 3.38 shows the value added and total value of shipments based on the reported information gathered by the economic industrial census division. Tables 3.39 – 3.41 illustrates $P3_6$ optimum design for hoist scheduling technology evaluation of its sustainability performance for electroplating process source reduction techniques and technologies.

Table 3.38. Industry Statistics for Industry Groups and Industries: 2007 Economic Census

NAICS Code	Industry	All Establish-ments	Value Added ($1,000)	Value Added per Establishment	Total Value of Shipments ($1,000)	Total Value of Shipments per Establishment
332813	Electro-plating	2,720	$4,721,777	$1,735,947 ($I_{EP1}$)*	$7,139,847	$2,625,000 ($I_{EP2}$)*

***** Data used to calculate economic indicator values in Appendix A6.

Table 3.39. $P3_6$ Environmental performance evaluation of electroplating process source reduction technologies.

Environmental Indicators		$P3_6$ Optimum Design for Hoist Scheduling Technology	
		Indicator Value	Comments
Resources Usage			
1.2 Material (excluding fuel and water)			
I_{VM1}	Total raw materials used per kg product	n/a	
I_{VM2}	Total raw materials used per unit value added	n/a	
1.3 Water			
I_{VW1}	Net water consumed per unit mass of product	0.17 kg.water/kg.parts	Amount of water used 18.72 gal/min in 4 operating rinse tanks per 200 kg barrel load in each tank for 0.5 min rinsing
I_{VW2}	Net water consumed per unit value added	9.24×10^{-3} kg.water/$	Amount of water used during operation per value added
2. Emissions, Effluents & Waste			

2.2 Aquatic impacts			
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	0	Hoist scheduling has no aquatic life impact
2.3 Impact to land			
I_{VI1}	Hazardous solid waste per unit value added	4.17×10^{-7} kg.sodium bicarbonate.y/ kg.parts.$	Sodium Bicarbonate waste is reduced by 7.8% which is the amount of waste water reduction due to less fresh water consumed by the same amount compared to traditional operations

Table 3.40. P3$_6$ Economic performance evaluation of electroplating process source reduction technologies.

Economic Indicators		P3$_6$ Optimum Design for Hoist Scheduling Technology	
		Indicator Value	Comments
Profit, Value, and Tax			
I_{EP1}	Value added	$3,833/y	92.2% savings of 3% water cost of 8% total utilities cost from total value added according to 2007 Census data
I_{EP2}	Value added per unit value of sales	1.46×10^{-3}/y	Value of sales calculated from value of shipments according to 2002 Census data
I_{EP3}	Value added per direct employee	$191/y	Based on average number of direct employees (20) required for entire operation and process

Table 3.41. P3$_6$ Social performance evaluation of electroplating process source reduction technologies.

Social Indicators		P3$_6$ Optimum Design for Hoist Scheduling Technology	
		Indicator Value	Comments
1. Workplace			
1.1 Employment situation			
I_{SE4}	Working hours lost as percent of total hours worked	0.83%	Assuming 50 hrs per year not including holidays (50 weeks) for programming and hoist maintenance
2. Society			

I_{SS1}	Number of stakeholder meetings per unit value added	$5.22 \times 10^{-4}/\$$	Based on two meeting for cost savings and benefits

3.2.4 Energy Reduction (ER) Technology

The chemical industry is facing major economic crisis due to increasing energy costs that affects their profit margins. Capital investments are highly dependent on the economy and driven by customer demands. The chemical industry has been influenced by modern science and technology advancements. Profitable preventive technologies have been directed to improve plant operations, alternative materials and solvents, in-process modification, and utilizing renewable energy. The chemical industry depends on electricity and natural gas as their source of energy for their daily operations. It is very crucial to find alternative clean energy sources and more efficient to enable the industry to be more profitable and environmentally friendly. There are many energy efficiency opportunities available to the chemical industry; however, the economic challenges the industry faces forces that improvements to be from retrofitting existing technologies with other more efficient equipment instead of changing the entire process. A set of energy reduction (ER) technologies has been developed by the Department of Energy (DOE), each of which focuses on in-process energy reduction and production improvement through addressing opportunities in specific modifications in the chemical industry, i.e., equipment modification, process modification, controls modification, employee training, equipment repair, and other supplementary modifications.

The proposed approach is very similar to the profitable pollution prevention technology previously discussed earlier in this chapter which is structured in the following way. First, an ER technology sustainability assessment is designed for a given process. A precise defined metrics and indicators suitable for determining sustainability triple bottom lines status (i.e., economic, environmental, and social). Second, ER technologies are to be introduced, which should have a positive impact on the industry sustainability. Third, we need to determine the best integrated energy reduction (IER) technology selection based on the quantified sustainability assessment results. Therefore, it is clear to determine the benefits of the proposed IER technologies that will provide scientific guidance to the industry sustainability enhancement.

The opportunities for developing IER technologies are not assessed fully in this research; however, the methodology is capable of quantitatively evaluating the sustainability level of any industrial system that implements IER technologies enhancement strategies. The main advantage of the introduced methodology is its effectiveness to analyze IER technologies for a given chemical process by quantifying and integrating various energy reduction technologies that affect the overall industry sustainability enhancement. The methodological efficacy can be illustrated through sustainability enhancement of a chemical process via assessing IER technologies.

3.3 Summary

Technology-based sustainability modeling and analysis is discussed by understanding the classification of manufacturing technologies. Those manufacturing technologies are focused on process design and equipment or geared towards product, materials and energy efficient technologies. Detailed assessment of profitable pollution prevention technologies performance evaluation of electroplating process source reduction technologies were conducted by using specific indicators for quantitative assessment of each technology. Then a discussion about some potential product oriented technology changes that will have an effect the metal finishing industry. A change from conventional surface finishing product to alternative technologies, in other words, transitioning from wet processes to dry processes technologies will have major improvements towards optimum sustainability. Another introduced concept of technology integrated sustainability enhancement (TISE) holistic approach is used to effectively enhance the overall industrial system sustainability by evaluating each technology or suite of technologies based on strategically selected indicators and combined benefits methodology assessment.

CHAPTER 4

FRAMEWORK OF OPTIMIZATION-BASED DECISION-MAKING

Electroplating systems should be optimized by considering economic, environmental and social objectives simultaneously to improve the overall sustainability triple bottom lines. In order for electroplating industries maintain and increase their market competitiveness, they ought to increase their efficiency by integrating technological innovations in their business operations from raw material and energy consumption stages to final product and waste treatment stages with sustainability considerations. An optimal selection of technologies that meets the industries competitiveness involves a combination of sustainability triple bottom lines. In this study, three optimization-based decision-making models are proposed to address this multi-objective problem with the integration of specific constraints for each model and supplying an optimization solution strategy. It is important to note that the results obtained from the optimization models can be assessed in terms of sustainability indicators which were discussed earlier in previous chapters.

Technological advancements in the metal finishing industry focus on process chemistries and optimization processes to recover metals and treat wastewaters. Process control techniques require critical understanding of metal finishing operation parameters in order to effectively implement chemical recovery technologies, solution maintenance technologies, material and process substitutions, and waste reduction optimization practices at the same time pay attention to environmental, economic and social tradeoffs associated with the technologies implementation (Haveman, 1995).

The survival of the metal finishing industry depends on implementing new technologies or optimization of existing technology that will facilitate market competitiveness which will lead to operating cost reduction, product quality improvement, increase productivity rate, waste generation minimization and expand process capability. Commercially available process control technologies improved metal finishing process performance and resulted in significant profitability for the metal finishing industry. Although automation technologies have been developed for metal finishing process lines, a large number of process lines and lab analysis in metal finishing plants are manually operated and controlled. Automation of manual process lines is a step in the right direction to ensure consistent production quality and provide essential production data for troubleshooting, monitoring, and evaluating process improvement. Optimization of current surface finishing process lines with the purpose to reduce chemical usage, waste generation and operator exposure to harmful chemicals, without compromising production rate and quality (Steward, 1993). Some of the existing technology trends in the metal finishing industry are pursuing sustainable manufacturing; improve in energy efficiency and process monitoring and control systems, and optimizing wet processes to achieve near zero discharge. Pursuing sustainable manufacturing indicates utilizing processes and systems that possess energy conserving, economically efficient, environmentally friendly, and safe for operators and customers. This trend will lead to improvement in the performance of traditional surface finishing processes; however, there is a new technology trend that is being implemented by larger metal finishing industries or during new construction of production lines. They are adopting newly developed technologies such as changing from wet process chemistries to dry process chemistries, using green environmentally friendly chemistries, changing substrate material from metal finishing to non-metals, and incorporating nanotechnology metal coating processes.

A proficient transition in technology trends will start by optimization of existing technologies then implementing new advanced ones which is driven by environmental regulations and economic restrictions. Since there is a continuous pressure to reduce environmental impact and liabilities, the metal finishing industry will implement a long term plan to modify traditional metal finishing processes to maximize material utilization and recovery or converting to green chemistries and dry processes for new processes. The optimum cost effective time to implement process optimization technologies is during new or renovated processes are being designed and installed. Many surface finishing facilities implemented process optimization to achieve near zero discharge and exposure risk. Those implementations lead to significant cost savings due to better process performance by utilizing fewer raw materials and minimizing waste generation (Cushnie, 1994).

From a sustainability point of view, production using processes that are energy conserving, environmentally friendly, economically efficient, and socially safe requires a systematic approach to view the life cycle of the product. Sustainability requires that production and consumption be preserved for future generations. Using green chemistry will reduce or eliminate generation of toxic hazardous wastes. Over the past decade, there have been various green technologies developed to replace or eliminate existing harmful chemistries such as replacement for cyanide and cadmium plating chemistries, development of trivalent passivation to eliminate hexvalent chemistries, and organic stabilized electroless nickel. Proper implementation of sustainable technologies requires strategic planning and process support system for the new chemistry and infrastructure.

Recently, many metal finishing industries are implementing new specialized products and advanced processing technologies that are sustainable and provide competitive market share. This advantage in promoting sustainable alternatives to conventional processes and products will have a positive influence on other manufacturers to take the opportunity to pursue sustainability goals. This will involve decisions to change production strategies and processes such that customers will accept more sustainable products which will result in great business and continuous sustainability improvement. Technological advancements in both process energy efficiency and in process design as well as proper management for reducing energy consumption is a major technology trend in the metal finishing industry due to high and potentially increasing in energy costs and environmental regulations to reduce pollution and conserve resources.

4.1 Optimization Model Development Approach

Preliminary assessment of sustainability triple bottom lines is based on evaluating sustainability's indicator criteria. Recent researchers (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008) are focusing on combining sustainability assessments with suitable indicators for industrial chemical process design to achieve a successful sustainable development and to determine industrial process sustainability performance.

There is no consistent reasonable methodology assessment in integrating all three aspects of sustainability triple bottom lines into the electroplating industrial systems. The most common methodology that is being adopted by industries is driven by economics. Industrial economics could be micro-economics or macro-economics depending on the industry's globalization, impact, and contribution to the society's economy. However, this is not sufficient to satisfy industrial profitability and success in the future from a sustainability stand point. Industry should adapt a methodology to consider and integrate all three aspects of sustainability economic, environmental and social criteria into their processes and systems. Many researchers (Azapagic and Perdan, 2000; Shah *et al.*, 2003; Azapagic *et al.*, 2006; Narayanan *et al.*, 2007; Sugiyama *et al.*, 2008; Halim and Srinivasan, 2008) are focusing their work on integrating and applying sustainability methodologies to many industrial processes in order to develop a variety of sustainable process alternatives.

A holistic sustainability assessment of technologies integrated into an industrial system S must include a set of sustainability metrics that are suitable for the industrial system in which the technology will be implemented. There are various sustainability metrics that are accessible to be utilized depending on the characteristics of the industrial system or process under investigation. The triple bottom lines of sustainability are being addressed by selecting and combining the proper metrics that will assess each sustainability index (economic, environmental, and social) based on the selected technology or suite of technologies that will enhance the overall sustainability performance of the industry.

(4.1)

where

= the j-th type of sustainability index for a specific technology

j = E (economic), V (environmental), or L (social)

N = number of years a specific technology is utilized

K = number of indicators selected in the j-th type of sustainability index

= the n-th normalized indicator value in the i-th technology

It is important to mention that the normalized values of selected indicators is obtained by either real data collection from industry or process simulation based on subject matter experts edification.

Methodology approach. The technology integration sustainability assessment methodology approach will consist of four major stages: (1) evaluate industry current sustainability status by applying sustainability assessment methodology to identify industry drawbacks, (2) determine sustainability improvement and classify technologies suitable for sustainability metrics evaluation such as IChemE (IChemE, 2002) and data collection, (3) generate optimum technology selection based on industrial future goals, and (4) recommend technologies based on options generated from the decision-making sustainability assessment approach.

Process sustainability improvement by technology adoption or integration depends on the industry near and future goals. This research focuses on three different purpose oriented scenarios depending on the industry demands which are a) investment-constraint scenario, b) sustainability-goal-oriented scenario, and c) economic-development-focused scenario. Those scenarios will utilize the methodology approach to provide industry with a decision-making tool for technology adoption in order to enhance their overall sustainability performance.

Technology assessment procedure. To systematically assess the sustainability improvement based on technology adoption, a seven-step procedure is developed to address how to identify the technology or group of technologies to achieve the industry goals. The adoption of technology will be determined based on meeting the industry sustainability triple-bottom-line planned goals and the degree of achievement.

Step 1. Evaluate the current economic, environmental, and social sustainability index status , , and respectively of the industrial process(es) before adopting any type of technology.

Step 2. Create a complete list of relevant technology based on an exhaustive search from a technology base via combinatorial method. The complete list of *N* technologies and their combinations will be entered in the first column as shown in Table 4.2.

Step 3. Evaluate the change in sustainability $\Delta S_{N,Ti}$ for improvement in economic, environmental and social objectives after selecting T_i technologies after (N) number of years. This will be entered in the middle section of the table labeled sustainability improvement in columns 2 - 4 as illustrated in Table 4.2.

Step 4. Evaluate the total change in sustainability for overall improvement in sustainability triple-bottom-line objectives after selecting T_i technologies after (N) number of years. This will be entered in the middle section of the table labeled sustainability improvement in column 5 as illustrated in Table 4.2.

Step 5. Determine the industrial sustainability triple-bottom-line (economic, environmental, and social) goals or demands based on a specified purpose oriented scenario.

Step 6. Calculate the total cost required for technology adoption for each combinatorial technology group. This will be entered in column 6 of the technology assessment as illustrated in Table 4.3.

Step 7. Apply industry constraints on each row of the selected technology depending on the industry scenario selection. Such that if the sustainability improvement does not meet the industry objectives or the budget exceeds the upper limit, then this row of technology set is eliminated as shown in Tables 4.3 and 4.4 for two different budget constraints with different sustainability goals.

Below are three different purpose oriented scenarios based on the industry demands which are a) investment-constraint scenario, b) sustainability-goal-oriented scenario, and c) economic-development-focused scenario. Those scenarios will demonstrate the efficacy of the aforementioned methodology approach and technology procedure that in return will provide industry with a decision-making tool for technology adoption for their overall sustainability performance enhancement.

4.2 Investment-Constraint Scenario

Every chemical industry has a financial budget for each process in order to keep the entire system running at its maximum efficiency. However, there are some cost restrictions on each unit process in order to maintain its productivity. The optimum design of electroplating processes and equipment is performed by some cost function. This function includes cost for raw materials, energy utilization, sales, management, financial, transport, inventory, salary, facility depreciation and technological investments. For an investment constraint optimization model, it is not necessary to include some of the fixed costs such as management cost, financial cost, salary, and facilities depreciation in the objective function, since the industry's interest is in their net profit value for a specific investment. Thus, the objective function for the investment constraint optimization model can be written as:

$$\max \Delta S_{N,T_i} = \left\| S_E(N), S_V(N), S_L(N) \right\| - \left\| S_E(0), S_V(0), S_L(0) \right\| \tag{4.2}$$

where

$\Delta S_{N,Ti}$ = change in the sustainability state including economic, environmental and social objectives after selecting T_i technologies after (N) number of years

$S_E(N)$ = economic sustainability index value after (N) number of years

$S_V(N)$ = environmental sustainability index value after (N) number of years

$S_L(N)$ = social sustainability index value after (N) number of years

On the other hand, the initial sustainability triple-bottom-line state of the current industrial system is expressed by $S_E(0)$, $S_V(0)$, and $S_L(0)$ for economic , environmental and social sustainability index.

where

$S_E(0)$ = current economic sustainability index value without technology adoption

$S_V(0)$ = current environmental sustainability index value without technology adoption

$S_L(0)$ = current social sustainability index value without technology adoption

Therefore the objective function for the investment-constraint optimization model could be reduced to:

$$\max \Delta S_{N,T_i} = \left\| S_E(N), S_V(N), S_L(N) \right\| \tag{4.3}$$

where

$\Delta S_{N,Ti}$ = change in the sustainability state performance including economic, environmental and social objectives after selecting T_i technologies after (N) number of years This investment-constraint optimization model is subject to the following inequalities:

$$S_E(N) \geq S_E(0) \geq 0 \tag{4.4}$$

$$S_V(N) \geq S_V(0) \geq 0 \tag{4.5}$$

$$S_L(N) \geq S_L(0) \geq 0 \tag{4.6}$$

The path to achieve the industries sustainability objective could be illustrated by integrating the triple-bottom-lines of sustainability in a unit cube as shown in Figure 4.1. Each coordinate represents one of sustainability triple-bottom-lines economic, environmental, and social (Piluso *et al.*, 2010). The technologies to be integrated in the industrial process will be determined according to the best sustainability value close to the (1, 1, 1) corner which represents complete sustainability. In other words, the closer the technology selected to the starting point in the sustainability unit cube (0, 0, 0) represents poor sustainability and that technology will be discarded.

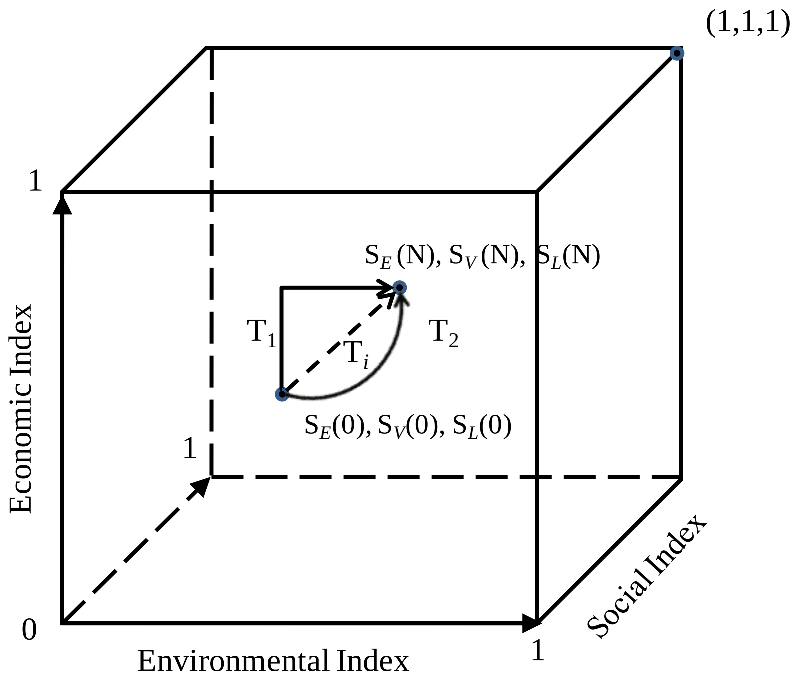


Figure 4.1 Investment-constraint Scenario

This research will address a simplified illustrative example of a combinatorial method based on exhaustive search of all combinations to generate a limited number of optimum technology selection for solution derivation to achieve maximum sustainability improvement under investment constraint based on industries budget limitations. The following example only considers three technologies to be selected. For simplicity, each technology is assumed to be already proven to enhance the sustainability status or at least not reducing the categorized sustainability of the industrial process. Note that all sustainability values are normalized for discussion simplicity.

(4.7)

(4.8)

(4.9)

where

= current economic sustainability index before integrating any technology

= current environmental sustainability index before integrating any technology

= current social sustainability index before integrating any technology

4.3 Sustainability-Goal-Oriented Scenario

Every chemical industry has specific goals implemented each year. Industry would like to achieve those goals by utilizing their processes to its maximum efficiency. However, there are some restrictions and limitations depending on the method that the industry selects to maintain its productivity and meet their goals. A sustainability goal oriented optimization example could be selecting the best technology in order to attain maximum optimum sustainable state using the minimum investment cost. For a goal oriented optimization model, it is necessary to select the best technological innovation for the industry's sustainability using the minimum investment cost in the objective function, since the industry's main goal is to make the most of the selected technology with the least possible investment without compromising the three aspects of sustainability. Thus, the objective function for the sustainability goal oriented optimization model can be written as:

$$\max \Delta S_{N,T_i} = \left\| S_E(N), S_V(N), S_L(N) \right\| \tag{4.10}$$

where

$\Delta S_{N,Ti}$ = change in the sustainability state performance including economic, environmental and social objectives after selecting T_i technologies after (N) number of years

In order not to exceed the investment cap goal of the electroplating industry for the selected technologies required to accomplish their future sustainability enhancement economically S_E(N), environmentally S_V(N), and socially S_L(N), certain restrictions are applied to meet the industry's goal. Thus, sustainability goal oriented optimization model is subject to the following inequalities:

$$S_E(N) \geq S_E^P(N) \geq S_E(0) \tag{4.11}$$

$$S_V(N) \geq S_V^P(N) \geq S_V(0) \tag{4.12}$$

$$S_L(N) \geq S_L^P(N) \geq S_L(0) \tag{4.13}$$

where

= is the planned economic sustainability index after integrating technology

= is the planned environmental sustainability after integrating technology

= is the planned social sustainability index after integrating technology

If the goal is to maximize the economic benefit and the net profit of the electroplating industry by 10% of their original economic state after a certain number of years $\left(+\eta\right)S_E(0)$

without compromising environmental and social aspects, certain restrictions will be implemented taking into account that the goal is to utilize the least investment in the selected technologies needed to accomplish it. Therefore, the sustainability goal oriented optimization model can be expressed as:

$$S_E^P(N) \geq (1+\eta)S_E(0) \tag{4.14}$$

$$S_V^P(N) \geq S_V(0) \tag{4.15}$$

$$S_L^P(N) \geq S_L(0) \tag{4.16}$$

where

η = is the percentage of future economic net profit goal of industry after N years of technology implementation

The path to achieve the industries sustainability objective could be illustrated by integrating the triple bottom lines of sustainability as shown in Figure 4.2. This model attempts to minimize the deviation from pre-specified goals which are considered to be simultaneously linked but are weighted according to their relative importance through industries objectives.

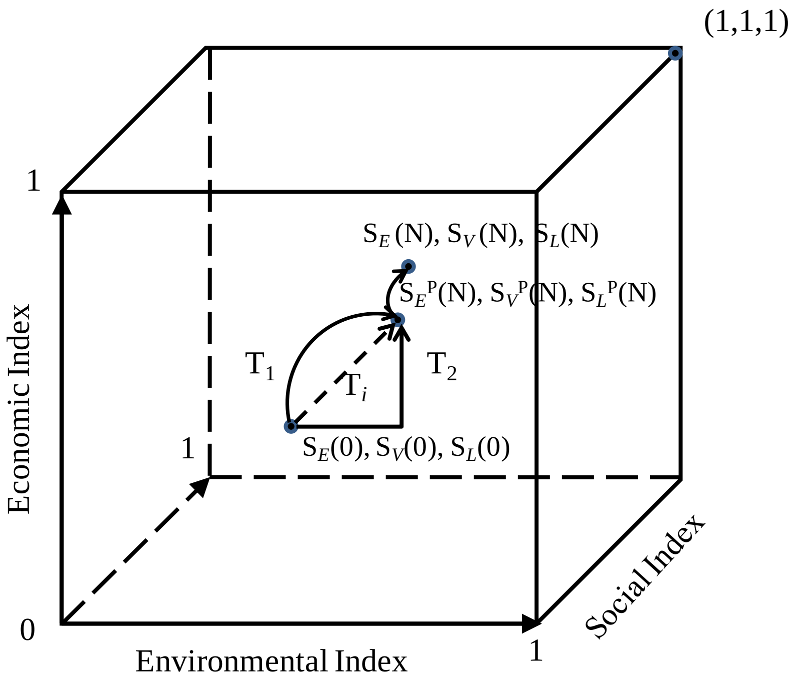


Figure 4.2 Sustainability-goal-oriented Scenario

4.4 Economic-Development-Focused Optimization Model

The objective of the economic development focused optimization model in this study is to maximize the electroplating process profitability. This is defined as the difference between the income and the annual cost per process. The objective of maximizing the economic benefits can be expressed as minimizing the energy and raw materials consumption cost without compromising the environmental and the social aspects of sustainability. Therefore, the objective function for the economic development focused optimization model can be expressed as:

$$\max \Delta S_{N,T_i} = \left\| S_E(N), S_V(N), S_L(N) \right\| \tag{4.17}$$

where

$\Delta S_{N,Ti}$ = change in the sustainability state performance including economic, environmental and social objectives after selecting T_i technologies after (N) number of years

In order to increase the electroplating industry economic benefits $\xi S_E(0)$ by 30% using technological innovations to accomplish the industry's future sustainability state economically, environmentally and socially without exceeding the allowable investment cost, there are certain restrictions need to be addressed to meet the industry's goal. The economic development focused optimization model is subject to the following inequalities:

$$S_E^P(N) \geq \xi S_E(0) \tag{4.18}$$

$$S_V^P(N) \geq S_V(0) \tag{4.19}$$

$$S_L^P(N) \geq S_L(0) \tag{4.20}$$

where

ξ = is the percentage of future economic benefit of industry after N years of technology implementation

The path to achieve the industries sustainability objective could be illustrated by integrating the triple bottom lines of sustainability as shown in Figure 4.3.

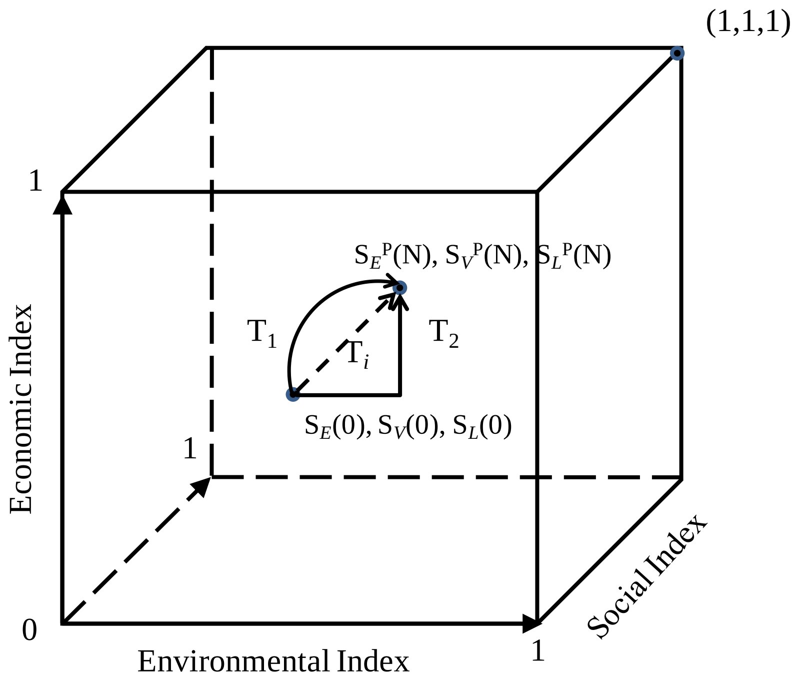


Figure 4.3 Economic-development-focused Scenario

4.5 Illustrative Case Study

The introduced methodology has been used to determine the improvement in industrial sustainability current status. In this section, an electroplating industrial sustainable development problem is selected for demonstrating the efficacy of the methodology. The focus of the study is on the assessment of the technology integration impact on the electroplating industry.

Problem description. If we have the following data shown in Table 4.1 about each technology for a specific process evaluation, all data are hypothetical for the convenience of illustration, for solution derivation for maximum sustainability improvement under budget limitations.

where

= change in economic sustainability state after selecting technologies.

= change in environmental sustainability state after selecting technologies.

= change in social sustainability state after selecting technologies.

= cost for using technology .

Assume that the current economic sustainability index value without incorporating technologies $S_E(0)$ is 0.2; the current environmental sustainability index value without incorporating technologies $S_V(0)$ is 0.1; and the current social sustainability index value without incorporating technologies $S_L(0)$ is 0.05.

Table 4.1. Sustainability improvement per technology selection

	T_1	T_2	T_3
	0.2	0.1	0.1
	0.1	0.4	0.1
	0.3	0.4	0.1
	$10,000	$15,000	$5,000

Since our objective function is defined as the maximization of the overall sustainability S through selecting technologies for adoption, but under investment constraints according to the permissible budget, then the optimization problem can be defined as follows:

$$- \qquad - \qquad - \qquad (4.21)$$

$$-$$

$$-$$

$$- \qquad (4.22)$$

$$-$$

$$-$$

$$- \qquad (4.23)$$

where

are constant coefficients meaning that if those technologies are implemented together, what will be the impact on the corresponding categorized sustainability status. Again, for simplicity, let , , and be 1. Therefore;

$$-$$

(4.24)

Investment constraints;

(4.25)

where is the upper limit of the budget available for sustainability improvement. Note that which are integers or zero.

For example:

(4.26)

If , then we have (4.27)

This is a combinatorial programming problem, which can be solved based on the governing equation and the constraints associated with it. For simplicity, Table 4.2 illustrates solution identification from an exhaustive search of combinatorial method for technology selection based on budget constraints.

Table 4.2. Combinatorial Technology selection based on budget constraints.

Technology Selection	Sustainability Improvement				Cost ($)
	Economic	Environmental	Social	Overall	
T_1	0.2	0.1	0.3	0.2	10,000
T_2	0.1	0.4	0.4	0.3	15,000
T_3	0.1	0.1	0.1	0.1	5,000
T_1 , T_2	0.3	0.5	0.7	0.5	25,000
T_1 , T_3	0.3	0.2	0.4	0.3	15,000
T_2 ,T_3	0.2	0.5	0.5	0.4	20,000
T_1 , T_2 , T_3	0.4	0.6	0.8	0.6	30,000

Case 1 - Budget limit of $20,000. After solving the integer-linear programming problem, it is clear that there are five possible choices that satisfied the budget constraint not to exceed $20,000 which can be summarized in Table 4.3. Since the maximum overall sustainability for a budget constraint of $20,000, then there is only one option of technology selection to implement which is T_2 and T_3 combined. On the other hand if the budget constraint maximum upper limit is increased or decreased, then the technology selection will change based on the new investment constraint. Figure 4.4 displays a comparison between selected technology options based on sustainability enhancement and budget constraint.

Table 4.3. Maximum sustainability improvement with a $20,000 budget constraint.

Technology	Sustainability Improvement				Cost ($)
	Economic	Environmental	Social	Overall	
T_1	0.2	0.1	0.3	0.2	10,000
T_2	0.1	0.4	0.4	0.3	15,000
T_3	0.1	0.1	0.1	0.1	5,000
T_1 , T_3	0.3	0.2	0.4	0.3	15,000
T_2 ,T_3	0.2	0.5	0.5	0.4	20,000

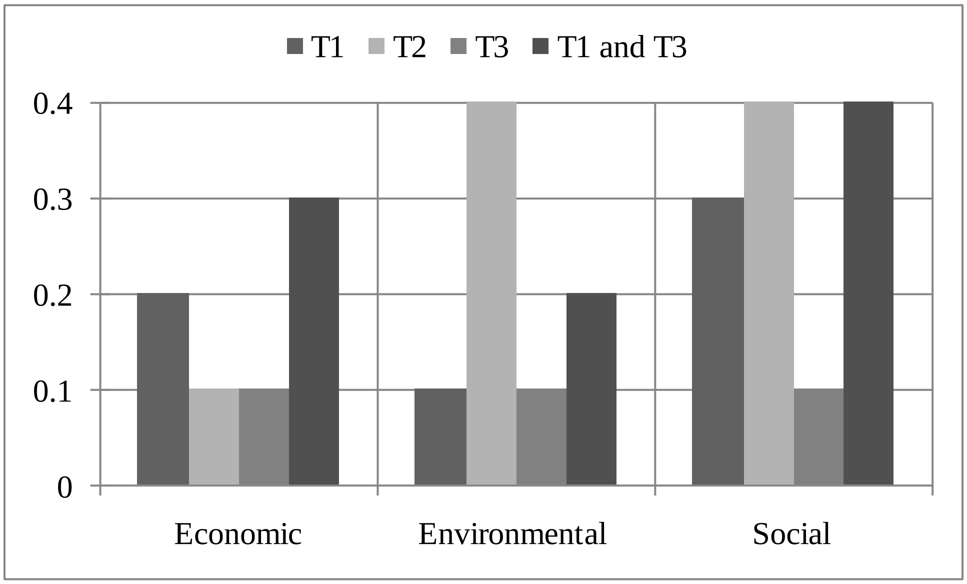


Figure 4.4. Comparison of sustainability improvement based on technology implementation options with a $15,000 budget constraint.

Case 2 - Budget limit of $15,000. After solving the integer-linear programming problem, it is clear that there are four possible choices that satisfied the budget constraint not to exceed $15,000 which can be summarized in Table 4.4. Since the maximum overall sustainability for a budget constraint of \$15,000, then in this scenario there are two options of technology selection to implement which are either T_2 or T_1 and T_3 combined. The cost of each is \$15,000 which satisfies the investment constraint.

Table 4.4. Maximum sustainability improvement with a \$15,000 budget constraint.

Technology	Sustainability Improvement				Cost ($)
	Economic	Environmental	Social	Overall	
T_1	0.2	0.1	0.3	0.2	10,000
T_2	0.1	0.4	0.4	0.3	15,000
T_3	0.1	0.1	0.1	0.1	5,000
T_1 , T_3	0.3	0.2	0.4	0.3	15,000

Analysis of technology integration and sustainability improvement options. If technologies T_1 and T_3 combined are selected, they can improve the economic performance more than just only using technology T_2 by itself. On the other hand, the improvement in the environmental performance is not as good as selecting technology T_2 only. Figure 4.5(a) illustrates the overall sustainability enhancement from the current sustainability state after implementing technology T_2, while Figure 4.5(b) illustrates the overall sustainability enhancement after implementing technologies T_1 and T_3 combined per sustainability triple-bottom-line. Therefore, the final selection of technologies is up to the decision makers to determine the industries vision for their future success and business competitiveness.

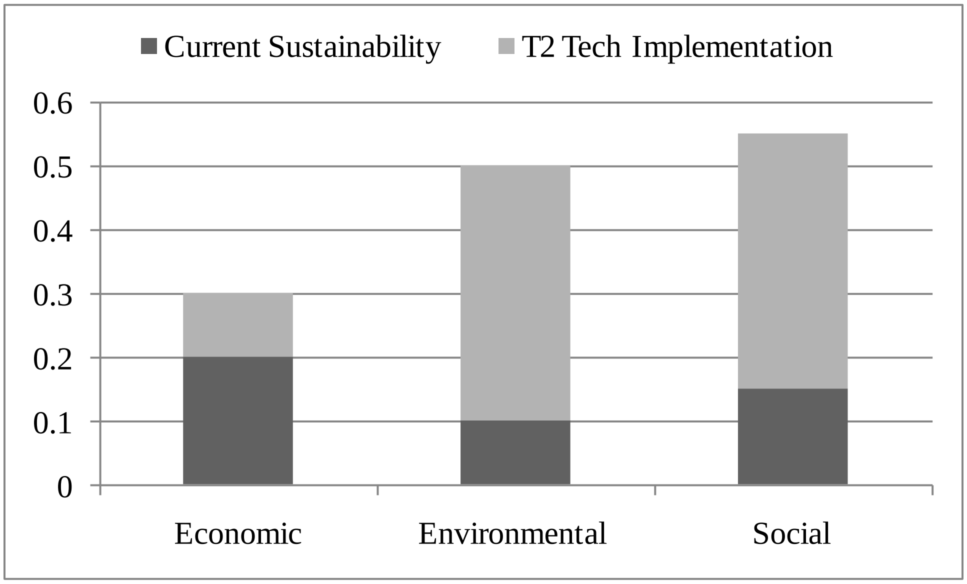


Figure 4.5(a). Sustainability triple-bottom-line enhancement after implementing T_2 technology

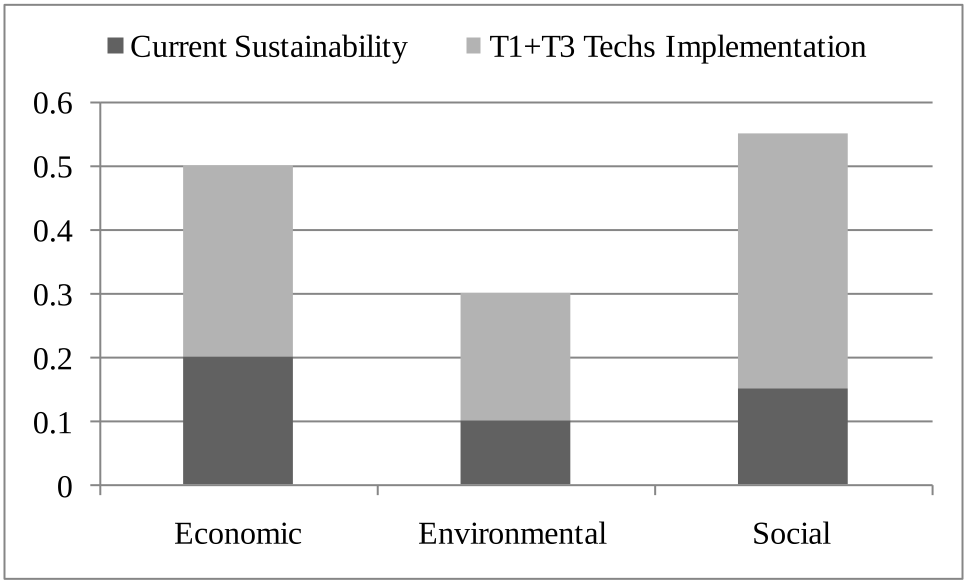


Figure 4.5(b) Sustainability triple-bottom-line enhancement after implementing $T_1 + T_3$ technologies

From the aforementioned sustainability results, it is clear that for implementing technology T_2 equations 28 - 30 satisfy the inequality for each sustainability triple-bottom-line.

(4.28)

(4.29)

(4.30)

therefore

(4.31)

(4.32)

(4.33)

Similarly, implementing technologies T_1 and T_3 combined will satisfy equations 4.34 - 4.36 for the same budget constraint and maximum overall sustainability of 0.3; however, the value of each triple-bottom-line enhancement is different compared with implementing various stand alone technologies such as T_2.

(4.34)

(4.35)

(4.36)

therefore

(4.37)

(4.38)

(4.39)

Comparison of technology integration sustainability options. According to the sustainability assessment methodology, the overall economic sustainability is greater by 0.2 using technologies T_1 and T_3 combined than incorporating technology T_2 on its own. On the other hand, the overall environmental sustainability is greater by 0.2 using technology T_2 than incorporating both technologies T_1 and T_3 while the improvement in the overall social sustainability is 0.4 by incorporating either technology options T_2 or T_1 and T_3 technologies combined.

4.6 Summary

Electroplating systems should be optimized by considering economic, environmental and social objectives simultaneously to improve the overall sustainability triple bottom lines. In order for electroplating industries maintain and increase their market competitiveness, they ought to increase their efficiency by integrating technological innovations in their business operations from raw material and energy consumption stages to final product and waste treatment stages with sustainability considerations. An optimal selection of technologies that meets the industries competitiveness involves a combination of sustainability triple bottom lines. This research has introduced an optimization based approach for a proficient sustainability assessment of industrial systems via technology integration. The methodology is general, systematic, and easy to apply to any industrial operation. In this study, three optimization-based decision-making models are proposed to address this multi-objective problem with the integration of specific constraints for each model and supplying an optimization solution strategy. The metal finishing industry case study has clearly demonstrated the efficacy of the methodology.

CHAPTER 5

APPLIED STUDIES OF ELECTROPLATING SYSTEMS SUSTAINABLE DEVELOPMENT

The optimization-based decision-decision making and sustainable technological analysis are demonstrated on three case studies. These case studies are aimed to illustrate what kinds of sustainability criteria are relevant in each case. The methodology also determines which sustainability criteria should be considered in the electroplating process design and how to carry out its sustainability assessment to determine and improve the overall electroplating industrial sustainability of the system.

5.1 Process Description

Electroplating industry has major effects from economic, environmental, and social aspects. It is one of the major contributors to environmental pollution and health effects on the workers. It also consumes great amount energy to run its operation and raw materials of various chemistries and natural resources such as freshwater. Moreover, the amount of waste generated during operation from toxic chemical complexes and metals have impacted the electroplating industry economy for waste treatment and disposal.

Electroplating industries are in need of innovative technologies that can be implemented to minimize the amount of waste generated. This could be accomplished through the proposed technological modeling approach for raw material reduction, recycling, and pre-treatment process operations. Sustainable development is essential to integrate the effect of these selected technologies or techniques on the industry's economic, environmental and social aspects. It is also important to note that a considerable amount of investment is required to implement those technologies and may require some changes in the process design. Figure 5.1 illustrates an electroplating operation process layout with parts flow sequence.

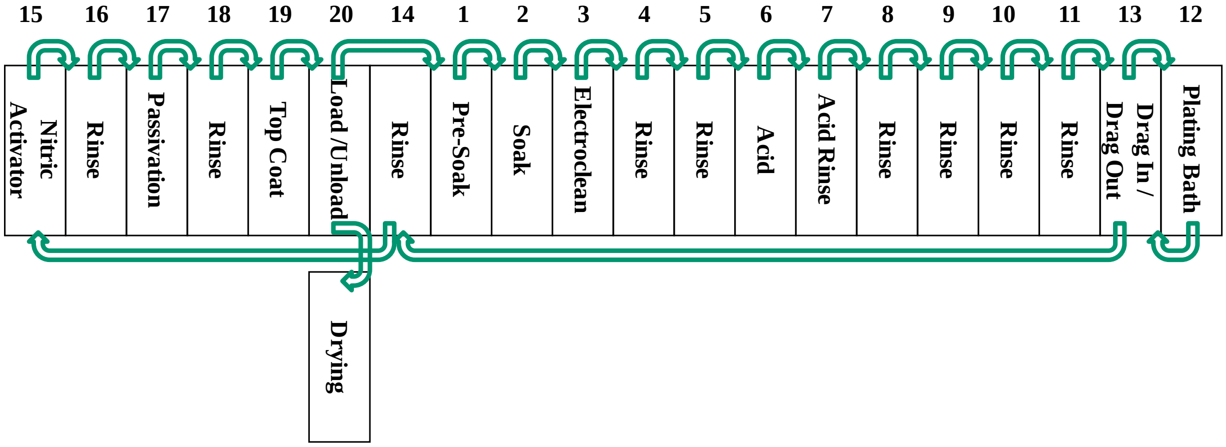


Figure 5.1. Electroplating Process Line Flow Diagram.

During normal operating conditions, the operation cycle of a plating line is set by hoist schedule for a given production rate which varies from one plating line to another depending on the bath efficiency, load size, surface pre-treatment, and production quality. For an automated zinc plating barrel operation process line with a hoist schedule 7.5 minutes cycle time, the production rate will be 8 barrels per hour. In other words, the annual production rate will be 48,000 barrels per year, assuming the plant is running three shifts per day for five working days per week and an annual plant shut down conducting overall operation and equipment maintenance for 2 weeks. Assuming the average weight of processed parts is 200 Kg per barrel load and the customers production cost is $0.44 per Kg weight, then the annual sales for such process line is approximately $4.2 million dollars per year.

Figure 5.1 electroplating process flow diagram of parts plated with metal or metal alloys illustrates the complexity of the system to minimize the amount of toxic effluent streams after each step and avoiding contamination between processes. Improper waste reduction methods and technologies will affect the plating process performance which will compromise the overall production rate and quality. In an electroplating plant, energy, chemicals, and water are consumed during rinsing, cleaning, and electroplating operations; in addition to, waste generated from the process tanks in each line requires treatment and chemical recovery. In order to reduce waste generated by process tanks, an implementation of selective technologies, alternative energy and materials are required to be utilized to provide a sustainable developed industrial process.

A detailed electroplating control parameter per chemical tank is thoroughly depicted in Table 5.1. A complete identification of each process chemical tank step sequence and parameters is very critical for continuous quality control of the overall process. Specified parameter limits and ranges corresponding to each process tank as well as the frequency of inspection and a precise inspection method will enhance the quality of the final plated product.

Table 5.1. Electroplating chemical process tank sequence and chemical control parameters.

Process Step	Tank	Parameters	Parameter Limits	Inspection Frequency	Inspection Method
1	Pre-Soak clean	Concentration	2 - 6 % by Vol.	1/day	Titration
		Temperature	120 -180 F	1/shift	Thermometer
2	Soak clean	Concentration	2 - 6 % by Vol.	1/day	Titration
		Temperature	120 -180 F	1/shift	Thermometer
3	Electro clean	Concentration	5 - 10 % by Vol.	1/day	Titration
		Temperature	120 - 180 F	1/shift	Thermometer
		Voltage	4 - 6 V	1/shift	Digital Indicator
4	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
5	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
6	Inhibited Acid Dip (HCl)	Concentration	10 - 45 % by Vol.	1/shift	Visual
		Temperature	60 - 100 F	1/shift	Thermometer
7	Acid Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
8	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
9	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
10	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
11	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
12	Zinc Plating	Zn Concentration	3 - 5.5 oz/gal	1/day	Titration
		Temperature	70 -120 F	1/shift	Thermometer
		Cl Concentration	16 - 20 oz/gal	1/day	Titration
		pH	5 - 6	1/shift	pH Meter
		Voltage	10 V	1/shift	Digital Indicator
		Plating Thickness	0.5 micron / 10 min	1/day	Hull Cell
		Impurities (Fe)	70 - 80 ppm	1/month	Atomic Absorption
		Impurities (Cu)	10 - 15 ppm	1/month	Atomic Absorption

Process Step	Tank	Parameters	Parameter Limits	Inspection Frequency	Inspection Method
13	Drag In /Drag Out	Flow Rate	0 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
14	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
15	Nitric Acid Dip	Concentration	0.25 - 0.5 % by Vol.	1/shift	Titration
16	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
17	Passivation	Concentration	8 - 12 % by Vol.	1/shift	Titration
		Temperature	140 -170 F	1/shift	Thermometer
		pH	1.8 - 2.2	1/shift	pH Meter
		Impurities (Fe)	70 - 100 ppm	1/week	Atomic Absorption
		Impurities (Zn)	1000 - 5000 ppm	1/week	Atomic Absorption
18	Rinse	Flow Rate	3 - 5 gpm	1/shift	Visual
		Temperature	Ambient	1/shift	Thermometer
19	Top Coat	Concentration	10 - 15 % by Vol.	1/shift	Titration
		pH	9 - 12	1/shift	pH Meter

The type of technology selected must be the most effective for the improvement of product quality and production rate in order to maintain competitiveness in the industrial region. The most important operation in the electroplating process is the cleaning cycle. This will have major implications on the surface being plated if it is not according to the surface cleaning quality with attention to the minimum contamination level on the surface that is acceptable without affecting plating quality and performance. Most of the waste generated is stationary in the cleaning and rinsing tanks; however, major chemical contamination and waste are transferred through drag in/drag out barrel operations. Furthermore, some chemicals are being wasted during operations because of overflowing into rinse tanks which will end up in the waste treatment facility of the plant.

Selecting a suitable technology can guide electroplating operations to achieve an enhanced sustainable state by reducing freshwater consumption, chemical additions, and waste water treatment operations costs. According to Plating Surface Finishing (1993), without upfront process optimization for a pursuit of zero water discharge can cost the electroplating industry 2 – 5 times more than conventional end of pipe treatment. According to the EPA, in an electroplating industry the plant greatest cost contributions affecting its profitability are waste water treatment, plating chemistry loss, hazardous waste disposal, and other process solution loss. The most valuable benefit of the optimization based technological network development approach is to target and prioritize industrial process areas of improvement by selecting the best technology according to its performance and contribution to the electroplating industrial sustainability advancement. The EPA suggests that there are three types of activities that are undervalued in an electroplating operation. First, episodic activities such as disposal of process tanks, filter replacement, and decommissioning of electroplating process lines. Second, rework activities due to poor product and process quality control which will generate additional wastes, discharges, and increase chemical usage. Third, rinsing activities in which unnecessary freshwater is utilized compared to the actual rinsing operation required. Those aforementioned undervalued activities require technological investments in process control and implementing a quality control technology to prevent unnecessary pollution or over utilization of raw materials and chemistries.

In the electroplating industry, the most common cost for coating materials are determined at the production level especially if the coated material is expensive in case of precious metals or high production volume. It is more accurate to calculate the cost from industrial records of chemical additions, plating bath concentrations, surface area being plated, and the desired thickness of the metal coating. The traditional cost estimation is determined by a multiplication factor for example, 1000 square feet surface area to be plated to a thickness of 0.0005 inches will have a factor of 20% added to the price. This factor will change depending on the surface area and the desired coating thickness of the product. Therefore it is essential to integrate chemical recovery technologies to improve the sustainability status of the process.

A successful optimization based decision making methodology with technological network model will minimize the consumption of chemicals, freshwater, and overall process operation time will be reduced. It is very important to understand the plating process in order to directly relate this reduction to the production quality and the relationship between investment cost, waste minimization, and production rate and quality. The optimization based decision making should be incorporated on the entire process line rather than on a specific unit operation for maximum sustainability performance. This concept will reflect major economic, environmental and social incentives to enhance the electroplating industry competitiveness and ensure a sustainable positive future. Sustainability triple bottom lines will be achieved via optimization based decision making and technological modeling, since to minimize amount of chemical usage per process will require minimizing, water and energy consumption which will be reflected on reduction in total waste generated per process and the overall plant waste treatment facility. As a result of the reduction of waste generation, a significant reduction in the operating cost and improvement in the production quality is at hand.

5.2 Sustainability Assessment of Zinc Plating System

The best opportunity to conserve freshwater and chemical usage is through continuous improvements in the efficiency of the electroplating process lines rinsing and plating stages. Major investments in science and technology is required to address the industrial waste water issues in the current situation and in the future as more sticker regulations and policies from the social, environmental and economic aspects will be enacted. Advancements are needed in this industry to improve rinsing and plating efficiency, which will include technological development of inexpensive monitoring and control devices; such as, advanced technologies in spent plating bath chemicals, water recycling systems, new plating technologies and water rinsing processes utilizing spraying systems instead of submerging parts in process tanks.

Achieving sustainability in an electroplating industry requires management commitment and action. Solving freshwater supply and chemical consumption in electroplating industry requires process optimization based on decision making and technological network modeling. There are many technological innovations needed to improve process efficiency and safety and to reduce overall process cost. For example, water treatment technologies and recycle systems are needed that can be operated by solar energy or wind technologies. Moreover, advanced technologies are essential in waste water treatment facilities to monitor water supply and quality such as liquid sensors and actuators to track and regulate water flow and measure water quality parameters.

Technology Integrated Sustainability Enhancement (TISE) approach will utilize profitable pollution prevention technologies discussed in Chapter 3 in order to improve the current sustainability status of a traditional zinc plating process line.

Sustainability enhancement of current process line C requires implementation of profitable pollution prevention (P3) technologies. Assume that N number of technologies are available, which are evaluated using the same sustainability indices as those used to assess the current process line C. Tables 5.2, 5.4, and 5.6 illustrate the environmental, economic and social assessment results of the current process as well as each selected technology that will be integrated in the process. The evaluation data is acquired from various reliable sources such as technology inventors, providers, current users, and process simulation. Any deficiency in obtaining specific data from the process or the technology performance, it ought to be derived by technology evaluators using reliable system simulations techniques.

Table 5.2. Environmental sustainability assessment evaluation of current process and technologies.

Environmental Indicators	Current Process	Technology 1	Technology 2	Technology 3	.....	Technology N
					.....	
					.....	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					.....	

After evaluating the environmental sustainability composite for the current process and each individual technology under consideration, normalization for all values is required to facilitate computation of composite sustainability indexes. Tables 5.3, 5.5, and 5.7 illustrate the environmental, economic and social normalized assessment results of the current process as well as each selected technology that will be integrated in the process.

Table 5.3. Normalized Environmental evaluation values of current process and technologies.

Environmental Indicators	Current Process	Technology 1	Technology 2	Technology 3	…..	Technology N
					…..	
					…..	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					…..	

The Normalization equation approach based on the environmental indicator selected that has the minimum impact or effect environmentally is favored compared to others that has a higher impact environmentally is expressed in equation 5.1.

$$\frac{\quad}{\quad} \qquad (5.1)$$

Equation 5.2 is used to calculate the environmental sustainability index for a single technology .

$$\frac{\quad}{\quad} \qquad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M_v \qquad (5.2)$$

On the other hand equation 5.3 is used to express the calculation result of environmental sustainability index for combined technologies T^{Com}.

$$\frac{\quad}{\quad} \qquad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M_v; \qquad (5.3)$$

where

efficiency of technology

Finally, equation 5.4 is used to evaluate the overall environmental sustainability index for combined technologies .

$$\frac{\quad}{\quad} \qquad i = 1, 2, \ldots, \mathrm{N};\ j = 1, 2, \ldots, M_v \qquad (5.4)$$

Table 5.4. Economic sustainability assessment evaluation of current process and technologies.

Economic Indicators	Current Process	Technology 1	Technology 2	Technology 3	.....	Technology N
					.....	
					.....	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					.....	

Table 5.5. Normalized Economic evaluation values of current process and technologies.

Economic Indicators	Current Process	Technology 1	Technology 2	Technology 3	…..	Technology N
					…..	
					…..	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					…..	

The Normalization equation approach based on the economic indicator selected that has the maximum economic impact or effect is favored compared to others that has a lower economic impact is expressed in equation 5.5.

$$\frac{\quad}{\quad} \qquad (5.5)$$

Equation 5.6 is used to calculate the economic sustainability index for single technology

.

$$\overline{} \qquad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M_e \qquad (5.6)$$

On the other hand equation 5.7 is used to express the calculation result of economic sustainability index for combined technologies T^{Com}.

$$\overline{} \qquad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M_e\,; \qquad (5.7)$$

where

efficiency of technology

Finally, equation 5.8 is used to evaluate the overall economic sustainability index for combined technologies .

$$\overline{} \qquad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, M_e \qquad (5.8)$$

Table 5.6 Social sustainability assessment evaluation of current process and technologies.

Social Indicators	Current Process	Technology 1	Technology 2	Technology 3	…..	Technology N
					…..	
					…..	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					…..	

Table 5.7. Normalized Social evaluation values of current process and technologies.

Social Indicators	Current Process	Technology 1	Technology 2	Technology 3	…..	Technology N
					…..	
					…..	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					…..	

The Normalization equation approach based on the social indicator selected that has the minimum impact or effect socially is favored compared to others that has a higher impact socially is expressed in equation 5.9.

(5.9)

Equation 5.10 is used to calculate the social sustainability index for single technology .

i =1, 2, ..., N; j = 1, 2, ..., M_l (5.10)

On the other hand equation 5.11 is used to express the calculation result of social sustainability index for combined technologies T^{Com}.

i =1, 2, ..., N; j = 1, 2, ..., M_l; (5.11)

where

efficiency of technology

Finally, equation 5.12 is used to evaluate the overall social sustainability index for combined technologies :

i =1, 2, ..., N; j = 1, 2, ..., M_l (5.12)

The combined sustainability index for the environmental, economic, and social composites (V, E, L) for a single technology is evaluated by equation 5.13.

(5.13)

The overall combined sustainability index for the environmental, economic, and social composites (V, E, L) for combined technology T^{Com} is evaluated by equation 5.14.

(5.14)

It is necessary to determine the effect or impact of each proposed technology to be implemented and integrated in the current industrial process from a sustainability point of view. Therefore, the normalized values of each technology effect on sustainability triple bottom lines will be assessed as shown in Tables 5.8 – 5.10 for environmental, economic and, social indices respectively.

Table 5.8. Effect of using technology on normalized environmental sustainability values.

Environmental Indicators	Current Process	Technology 1	Technology 2	Technology 3	…..	Technology N
					…..	
					…..	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					…..	

The above index-specific environmental sustainability evaluation results is utilized to evaluate the categorized sustainability improvement level for current industrial process *C* using the formulas below.

Formula used to evaluate effect of using technology on environmental sustainability:

$$i = 1, 2, \ldots, N; \; j = 1, 2, \ldots, M_v; \quad (5.15)$$

where

efficiency of Technology

Formula used to evaluate environmental sustainability benefits for single technology :

$$i = 1, 2, \ldots, \mathrm{N};\ j = 1, 2, \ldots, M_v \qquad (5.16)$$

Formula used to evaluate environmental sustainability benefits for combined technologies T^{Com}:

$$i = 1, 2, \ldots, \mathrm{N};\ j = 1, 2, \ldots, M_v \qquad (5.17)$$

Formula used to evaluate overall environmental sustainability benefits for combined technologies :

$$i = 1, 2, \ldots, \mathrm{N};\ j = 1, 2, \ldots, M_v \qquad (5.18)$$

Table 5.9. Effect of using technology on normalized economic sustainability values.

Economic Indicators	Current Process	Technology 1	Technology 2	Technology 3	.....	Technology N
					.....	
					.....	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					.....	

The above index-specific economic sustainability evaluation results is utilized to evaluate the categorized sustainability improvement level for current industrial process C using the formulas below.

Formula used to evaluate effect of using technology on economic sustainability:

$$i = 1, 2, \ldots, \mathrm{N};\ j = 1, 2, \ldots, M_e; \qquad (5.19)$$

where

efficiency of technology

Formula used to evaluate economic sustainability benefits for single technology :

$$i = 1, 2, ..., N; \; j = 1, 2, ..., M_e \qquad (5.20)$$

Formula used to evaluate economic sustainability benefits for combined technologies T^{Com}:

$$i = 1, 2, ..., N; \; j = 1, 2, ..., M_e \qquad (5.21)$$

Formula used to evaluate overall economic sustainability benefits for combined technologies :

$$i = 1, 2, ..., N; \; j = 1, 2, ..., M_e \qquad (5.22)$$

Table 5.10. Effect of using technology on normalized social sustainability values.

Social Indicators	Current Process	Technology 1	Technology 2	Technology 3	.....	Technology N
					.....	
					.....	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
					.....	

The above index-specific social sustainability evaluation results is utilized to evaluate the categorized sustainability improvement level for current industrial process *C* using the formulas below.

Formula used to evaluate effect of using technology on social sustainability:

$$i = 1, 2, ..., N; \; j = 1, 2, ..., M_l; \qquad (5.23)$$

where

efficiency of technology

Formula used to evaluate social sustainability benefits for single technology :

$$i = 1, 2, ..., N;\ \ j = 1, 2, ..., M_l \qquad (5.24)$$

Formula used to evaluate social sustainability benefits for combined technologies T^{Com}:

$$i = 1, 2, ..., N;\ \ j = 1, 2, ..., M_l \qquad (5.25)$$

Formula used to evaluate overall social sustainability benefits for combined technologies :

$$i = 1, 2, ..., N;\ \ j = 1, 2, ..., M_l \qquad (5.26)$$

The effect of using technology on overall combined sustainability triple bottom lines environmental, economic, and social (V, E, L) is evaluated by the formula below:

$$(5.27)$$

The effect of using combined technologies T^{Com} on overall combined sustainability triple bottom lines environmental, economic, and social (V, E, L) is evaluated by the formula below:

$$(5.28)$$

According to the aforementioned methodology approach, the assessment is based on specific indicator selection per sustainability triple bottom lines which is evaluated via formulas and equations. Taking the environmental sustainability as an example, selecting the first indicator, total raw materials used per unit value added (kg/$). It is clear that the current process assessment value is 2.9×10^{-2} kg/$ without integrating any of the profitable pollution prevention technologies. On the other hand, if selecting the first technology $P3_1$ which is the optimum cleaning and rinsing technology, its assessment value for the same indicator is 1.27×10^{-4} kg/$ as shown in the first two column values of the first environmental indicator row of Table 5.11. The following step is to determine the effect of each technology individually on the current process environmental sustainability for every corresponding indicator based on the technology efficiency. This is conducted using equation 5.15 then all values are tabulated in Table 5.12 which are then normalized values using equation 5.5 mentioned earlier in this section and tabulated in its corresponding cell in Table 5.13. Therefore, the value for the first technology is 2.74×10^{-2} kg/$ compared to current process value of 2.9×10^{-2} kg/$ without integrating any of the profitable pollution prevention technologies. The normalized value for the first technology is 0.614 compared to the current process normalized value which is 0.592.

Following the same evaluation procedure as that for the environmental sustainability assessment, the economic and social indicator assessment and normalization values were assessed in addition to the effect of each technology on the current industrial process from economic and social sustainability aspects. A detailed calculation of each indicator is available in appendices A1 through A6, which refer to the technology being evaluated.

Table 5.11. Environmental sustainability assessment evaluation of current process and technologies.

Environmental Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Resources Usage								
1.1 Energy								
1.2 Material (excluding fuel and water)								
I_{VM2}	Total raw materials used per unit value added (kg/$)	2.90E-2	1.27E-4	n/a	n/a	8.64E-5	1.39E-3	n/a
1.3 Water								
I_{VW2}	Net water consumed per unit value added (kg/$)	1.24E-1	2.08E-2	9.65E-2	7.60E-2	1.47E-2	2.49E-3	9.24E-3
2. Emissions, Effluents & Waste								
2.2 Aquatic impacts								
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other) (t/$)	1.78E-5	9.17E-7	0	0	5.20E-7	1.44E-8	0
2.3 Impact to land								
I_{VI1}	Hazardous solid waste per unit value added (t/$)	1.23E-5	6.02E-7	5.35E-7	2.93E-7	2.5E-7	2.4E-9	4.17E-7

Table 5.12. Effect of using technology on current process environmental sustainability values.

Environmental Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Resources Usage								
1.1 Energy								
1.2 Material (excluding fuel and water)								
I_{VM2}	Total raw materials used per unit value added (kg/$)	2.90E-2	2.74E-2	n/a	n/a	2.46E-2	2.29E-2	n/a
1.3 Water								
I_{VW2}	Net water consumed per unit value added (kg/$)	1.24E-1	8.56E-2	1.54E-2	2.83E-2	9.29E-2	1.01E-1	1.06E-1
2. Emissions, Effluents & Waste								
2.2 Aquatic impacts								
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other) (t/$)	1.78E-5	1.60E-5	9.97E-6	1.05E-5	1.47E-5	1.48E-5	1.64E-5
2.3 Impact to land								
I_{VI1}	Hazardous solid waste per unit value added (t/$)	1.23E-5	1.11E-5	6.59E-6	7.08E-6	1.02E-5	1.02E-5	1.10E-5

Table 5.13. Normalized environmental evaluation values of current process and technology impact on current process.

Environmental Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Resources Usage								
1.1 Energy								
1.2 Material (excluding fuel and water)								
I_{VM2}	Total raw materials used per unit value added	0.592	0.614	n/a	n/a	0.654	0.677	n/a
1.3 Water								
I_{VW2}	Net water consumed per unit value added	0.054	0.350	0.891	0.792	0.294	0.232	0.194
2. Emissions, Effluents & Waste								
2.2 Aquatic impacts								
I_{VQ3}	Ecotoxicity to aquatic life per unit value added (metals and other)	0.249	0.324	0.579	0.557	0.380	0.377	0.308
2.3 Impact to land								
I_{VI1}	Hazardous solid waste per unit value added	0.472	0.524	0.717	0.696	0.560	0.562	0.530

Table 5.14. Economic sustainability assessment evaluation of current process and technologies.

Economic Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Profit, Value, and Tax								
I_{EP1}	Value added from chemicals or water ($/y)	1,522	4,577	1,833	2,460	6,731	15,260	3,833
I_{EP2}	Value added per unit value of sales ($/y)	5.79E-4	1.74E-3	6.98E-4	9.37E-4	2.56E-3	5.80E-3	1.46E-3
I_{EP3}	Value added per direct employee ($/y)	76	229	92	123	336	760	191

Table 5.15. Effect of using technology on current process economic sustainability values.

Economic Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Profit, Value, and Tax								
I_{EP1}	Value added from chemicals or water ($/y)	1,522	2,899	137	553	4,428	11,403	2,131
I_{EP2}	Value added per unit value of sales ($/y)	5.79E-4	1.10E-3	5.24E-5	2.11E-4	1.68E-3	4.33E-3	8.12E-4
I_{EP3}	Value added per direct employee ($/y)	76	145	7	28	221	568	106

Table 5.16. Normalized economic evaluation values of current process and technology impact on current process.

Economic Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Profit, Value, and Tax								
I_{EP1}	Value added from chemicals or water	0.051	0.100	0.001	0.016	0.155	0.405	0.073
I_{EP2}	Value added per unit value of sales	0.051	0.101	0.001	0.016	0.156	0.407	0.073
I_{EP3}	Value added per direct employee	0.051	0.100	0.001	0.016	0.155	0.403	0.072

Table 5.17. Social sustainability assessment evaluation of current process and technologies.

Social Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Workplace								
1.1 Employment situation								
I_{SE4}	Working hours lost as percent of total hours worked (%)	2.10	0.13	0.10	0.13	0.53	0.60	0.83
2. Society								
I_{SS1}	Number of stakeholder meetings per unit value added (/$)	2.63E-3	4.36E-4	1.09E-3	8.13E-4	4.46E-4	2.62E-4	5.22E-4

Table 5.18. Effect of using technology on current process social sustainability values.

Social Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Workplace								
1.1 Employment situation								
I_{SE4}	Working hours lost as percent of total hours worked (%)	2.10	1.87	1.12	1.16	1.33	1.25	1.17
2. Society								
I_{SS1}	Number of stakeholder meetings per unit value added (/$)	2.63E-3	2.08E-3	8.62E-4	1.07E-3	1.86E-3	1.97E-3	1.94E-3

Table 5.19. Normalized social evaluation values of current process and technology impact on current process.

Social Indicators		Current Process	Water and Chemical Savings Technologies					
			$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
1. Workplace								
1.1 Employment situation								
I_{SE4}	Working hours lost as percent of total hours worked	0.163	0.257	0.563	0.546	0.476	0.512	0.542
2. Society								
I_{SS1}	Number of stakeholder meetings per unit value added	0.026	0.232	0.690	0.611	0.317	0.276	0.284

5.3 Technology Integration for Sustainability Improvement and System Optimization

Optimization based decision making strategy takes in consideration the overall industrial sustainability state without neglecting the process operations constraints economically, environmentally and socially. To maximize the sustainability performance, it is essential to utilize selective technology and proper assessment methodologies. Sustainability optimization depends on selecting the best indicators for the process efficiency and determining the most important process development goals and sustainability targets. Technological network approach for sustainability is different than previous approaches such as Industrial Pollution Prevention (P2) (Noyes, 1993; Gallerani, 1996; USEPA, 1999), Profitable Pollution Prevention (P3) (Lou and Huang, 2000), and Collaborative Profitable Pollution Prevention (CP3) (Piluso and Huang, 2009). Industrial Pollution Prevention (P2) focuses only on environmental protection which is one bottom line of sustainability without taking in consideration economic and social aspects. Profitable Pollution Prevention (P3) includes both environmental and economic aspects of sustainability without the social aspect in consideration. Collaborative Profitable Pollution Prevention (CP3) includes all three aspects of sustainability triple bottom lines but using a general methodology to assist decision makers in their decisions. There have been other researchers working on subsystem optimization by selecting operation technology for optimal cleaning and rinse time determination (Zhou and Huang, 2002). Also, technology that had significant reduction in waste and operating cost by Yang *et al.* regarding design methodology for developing a steady state optimal water allocation network (WAN) (Yang *et al.*, 1999, 2000); in addition to, Zhou *et al.* research on a design methodology for developing a dynamic switchable water allocation network (SWAN) (Zhou *et al.*, 2001).

Our technological network approach with optimization based decision making models will assist management and decision makers in selecting suitable technologies without any random comparisons but defining alternative technological options based on sustainability advancement and industrial future goals. For instance, chemicals used during the pre-treatment operation before electroplating and the rinsing tanks using fresh water to maintain a minimum level of contamination. These chemistries and freshwater could be minimized by incorporating a specific technology for water recycling in the rinsing tanks in addition to a modification to the barrel design to improve drag in/drag out of chemicals and contamination of the rinse tanks as well as dilution of the pre-treatment cleaner chemistry. This in return will cause a reduction in the amount of chemical additions to the cleaner tanks and also extending the life of the rinsing tanks and using less water to keep the contamination level within the operating limits. A secondary result will be less water and chemical sent to the waste treatment facility to be treated. Therefore, there will be more cost savings throughout the overall industry by incorporating similar technology to other processing lines within the industry.

The technology and current system evaluation in the previous section can provide some valuable insight information. It is clear that the existing industrial process is environmental and social focused and is lacking in the economic area in addition to more room for improvement in the environmental and social sustainability practices. Table 5.20 depicts the overall sustainability values of the current process as well as selected technology integration and their impact on the current process sustainability status. The effect of using technology on overall combined sustainability triple bottom lines environmental, economic, and social (V, E, L) is evaluated by equation 5.27 mentioned earlier in the previous section.

Table 5.20. Normalized overall sustainability assessment values of current process and effect of using technology on the current process.

Normalized Value of Sustainability	current	$P3_1$	$P3_2$	$P3_3$	$P3_4$	$P3_5$	$P3_6$
Environmental	0.342	0.453	0.729	0.682	0.472	0.462	0.344
Economical	0.051	0.101	0.001	0.016	0.155	0.405	0.073
Social	0.095	0.245	0.626	0.579	0.396	0.394	0.413
Overall Sustainability	0.207	0.303	0.555	0.516	0.367	0.421	0.313
Cost for technology use ($1,000)	n/a	20	5	10	15	25	10

The current system evaluation and technology integration information in Table 5.20 are used to generate the values in Table 5.21 by applying equation 5.28 mentioned in the previous section. Table 5.21 illustrates the overall sustainability values of the current process as well as selected integrated technology integration and their impact on the current process sustainability status.

Table 5.21. Normalized overall sustainability values of current process and technology integration impact on current process.

Normalized Value of Sustainability	Current Process	$P3_1$&$P3_2$	$P3_1$&$P3_2$&$P3_5$	$P3_4$&$P3_5$&$P3_6$
Environmental	0.27	0.59	0.55	0.43
Economical	0.12	0.05	0.17	0.21
Social	0.25	0.44	0.42	0.40
Overall Sustainability	0.22	0.42	0.41	0.36
Technology Cost ($1,000)	n/a	25	50	50

5.4 Technology Performance Evaluation

The introduced Technology Integrated Sustainability Enhancement (TISE) approach and decision making methodology is applied to assess the recommended technology integration based on their performance evaluation and budget limitations. Table 5.21 provide a detailed assessment of the current process without implementing any technology as well as selected combined technology integrated into the process in order to enhance the overall system sustainability. The results of this analysis are very useful because it illustrates and assist decision makers to identify the weak areas in the current industrial process that require improvement in a quantitative way.

In Table 5.21, the second column is the current process case, where sustainability triple bottom lines values as well as the overall sustainability are computed. In this case, the overall sustainability is 0.22 which requires much more improvement especially in the economic sustainability. As a result, the strategy for sustainable development will focus on improving the economic sustainability, while environmental and social sustainability aspects will be maintained or steadily improved.

The third column in Table 5.21 contains the sustainability evaluation of combining two profitable pollution prevention technologies which are the cleaning and rinsing optimization with the optimum water allocation technology. It is clear that the overall sustainability performance has increased from 0.22 to 0.42 because of a significant improvement in the environmental and social sustainability of 0.59 and 0.44 respectively. However, both technologies economic sustainability contribution was only a 0.05 added improvement from the current process economic sustainability. It is clear that the budget cost for implementing both technologies is

$25,000 which is the lowest budget compared to the rest of the other technology integration options.

The second option of technology integration is found in column 4 of Table 5.21, which is a combination of technologies $P3_1$, $P3_2$, and $P3_5$. The technologies implemented are the same as the previous option but with the addition of optimum design for chemical recovery technology. It is clear that the overall sustainability performance has increased from 0.22 to 0.41 because of a significant improvement in all sustainability triple bottom lines environmental, economic, and social to be 0.55, 0.17 and 0.42 respectively. It is clear that the budget cost for implementing all three technologies is $50,000 which is double the budget cost compared to the first technology integration option.

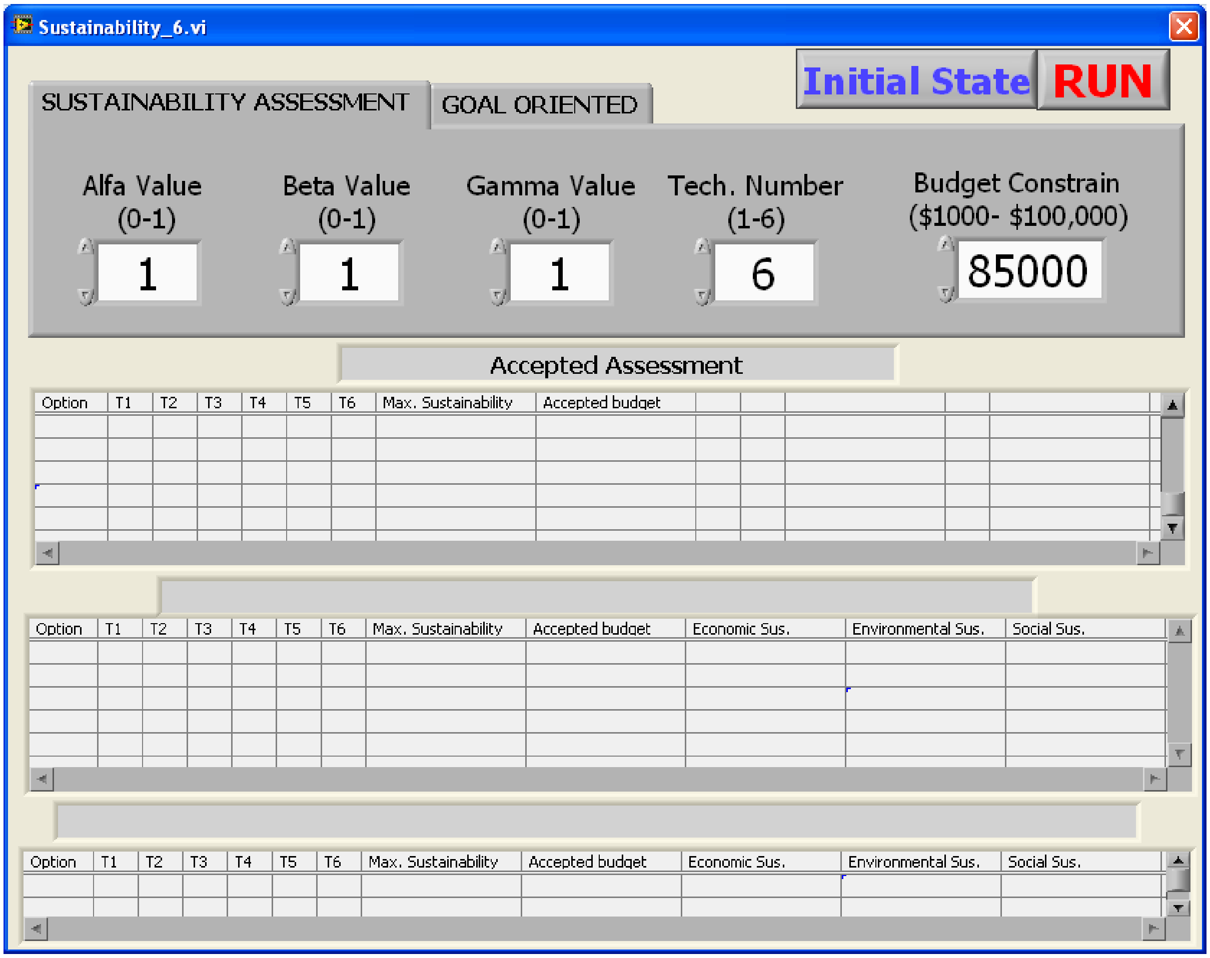
The third option of technology integration is found in the last column of Table 5.21, which is a combination of technologies $P3_4$, $P3_5$, and $P3_6$. The technologies implemented are the different in the method of implementation into the process than the previous two options but with same budget cost of $50,000 to integrate those technologies. It is clear that the overall sustainability performance has increased from 0.22 to 0.36 because of a significant improvement in all sustainability triple bottom lines environmental, economic, and social to be 0.43, 0.21 and 0.40 respectively. It is important to mention that the overall sustainability is the lowest compared to the previous two options nevertheless the third option of technology integration has the highest economic sustainability value amongst the other two technology integration options. It is clear that the budget cost for implementing all three technologies is $50,000 which is double the budget cost of the first technology integration and same as the second option. Therefore, the final selection of technologies is up to the decision makers to determine the industries vision for their future success and business competitiveness.

5.5 Industrial Sustainability Assessment Program

Sustainability assessment for an industrial system or process is a multi-objective operation, which has great challenges due to the process complexity and data authenticity. In order to achieve a sustainable process, technology integration is necessary for overall system improvement via proper technology identification, design and implementation. As a result, a useful sustainability assessment program is developed using previously introduced systematic methods and approaches, which is capable to execute sustainability assessment for achieving the optimum solutions to assist in decisions for future system improvements. Decision makers can assess the sustainability status of any industrial process system, compare various technology integration options, choose alternatives in terms of sustainability performance, and finally identify the best technology integration option(s) through tabulated and graphical illustrations.

This industrial sustainability assessment program will contribute valuable information for decision making via computing sustainability assessment for overall system enhancement. The program is developed by using LabView software and Matlab programming tools without considering any uncertainty in the data collected. Below are detailed snap-shots of the programs graphical user interface functionality and capabilities.

In Figure 5.2, the user inputs five data parameters, which are weighting factors (alpha, beta, and gamma) of each selected sustainability triple bottom line corresponding to economic, environmental and social. Next is inputting the total number of technologies of interest from the technology base. Note that this number should be an integer between 1 and 5. Finally, enter the budget constraint for the cost of implementing technologies for the process system under sustainability investigation. Note that the default value of each weighting factor is set as 1, which reflects equal importance of all sustainability triple bottom lines assessment. The number of technology of interest is equal to six profitable pollution prevention technologies. All accepted sustainability assessment results which are combinatorial results, a total of six technology sets (2^6-1) are identified, which are numbered and listed in the first table in Figure 5.2. finally, the maximum financial budget funding for implementing possible six technologies is $85,000 as shown in Figure 5.2



Alfa Value (0-1): 1

Beta Value (0-1): 1

Gamma Value (0-1): 1

Tech. Number (1-6): 6

Budget Constrain ($1000- $100,000): 85000

Accepted Assessment

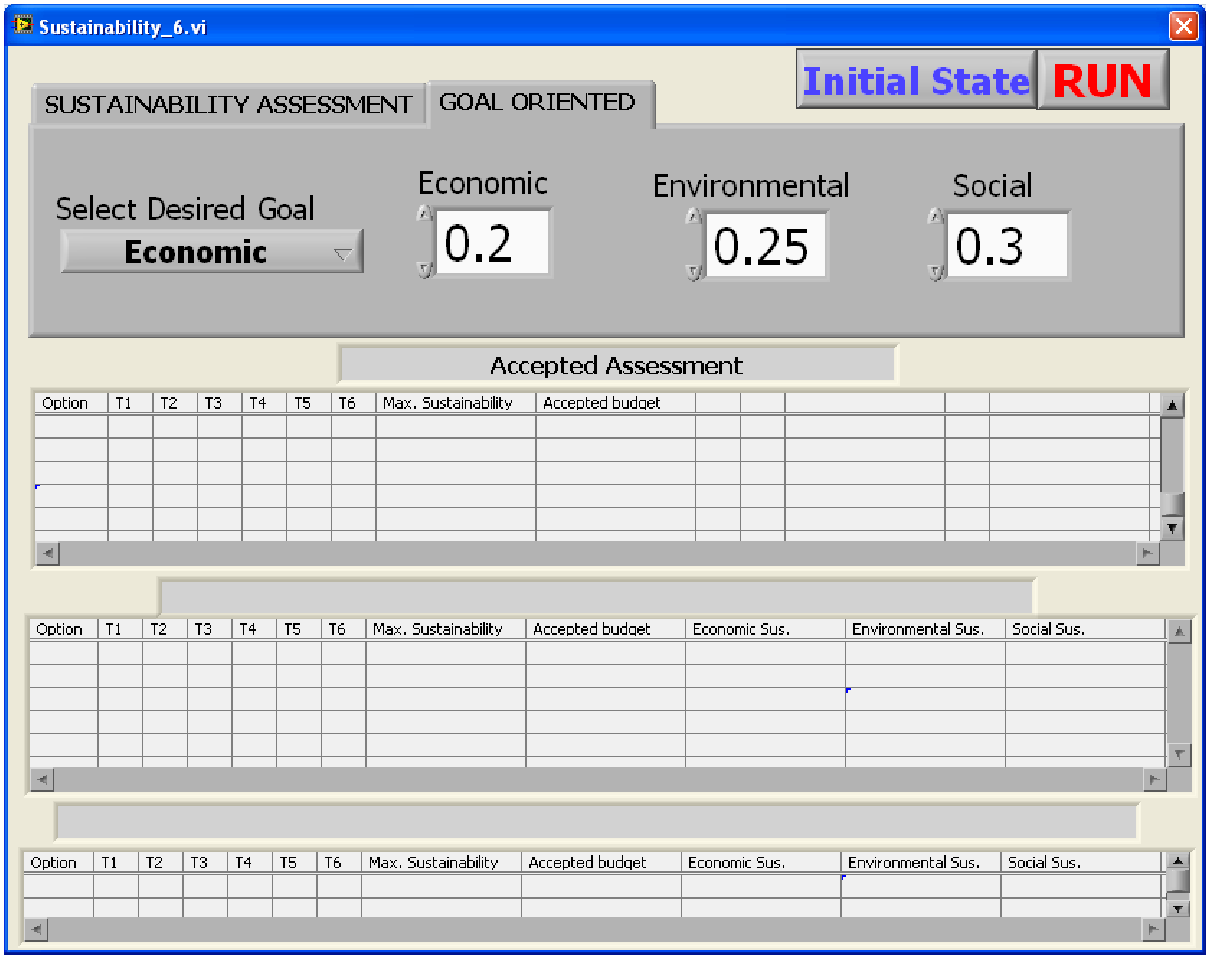
Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget					

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

Figure 5.2. Sustainability assessment parameters.

The data provided in Figure 5.3a. is utilized for determining economic, environmental, or social sustainability goals in which the computed data will be compared to those specified goals.



Select Desired Goal: Economic

Economic: 0.2

Environmental: 0.25

Social: 0.3

Accepted Assessment

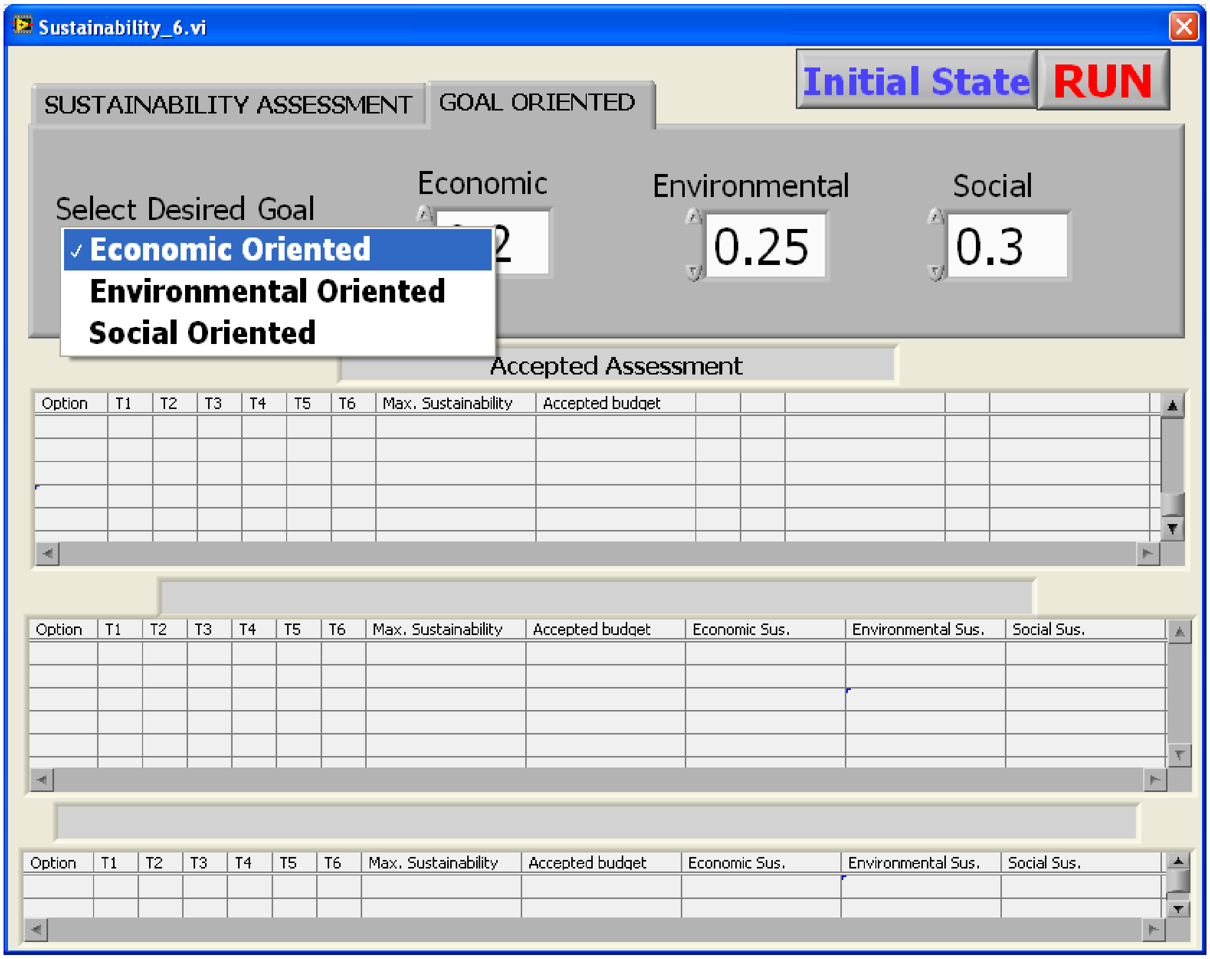
Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget					

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

(a)

In figure 5.3b. the user interest is in the economic goal oriented. Therefore, the selection was made to reflect economic sustainability significance than environmental or social sustainability.



Environmental 0.25

Social 0.3

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.

(b)

Figure 5.3. (a) Goal oriented sustainability data input and selection.
(b) Economic goal oriented sustainability selection.

The following step after selecting the desired goal is to input the initial sustainability state of the current process by clicking on the blue button function on the upper right corner labeled “Initial State”. After clicking the initial state button, a new window will pop up for the user to input the current process sustainability triple bottom lines values before integrating any technologies as shown in Figure 5.4. Then, the user verified the data inputted by clicking ok.

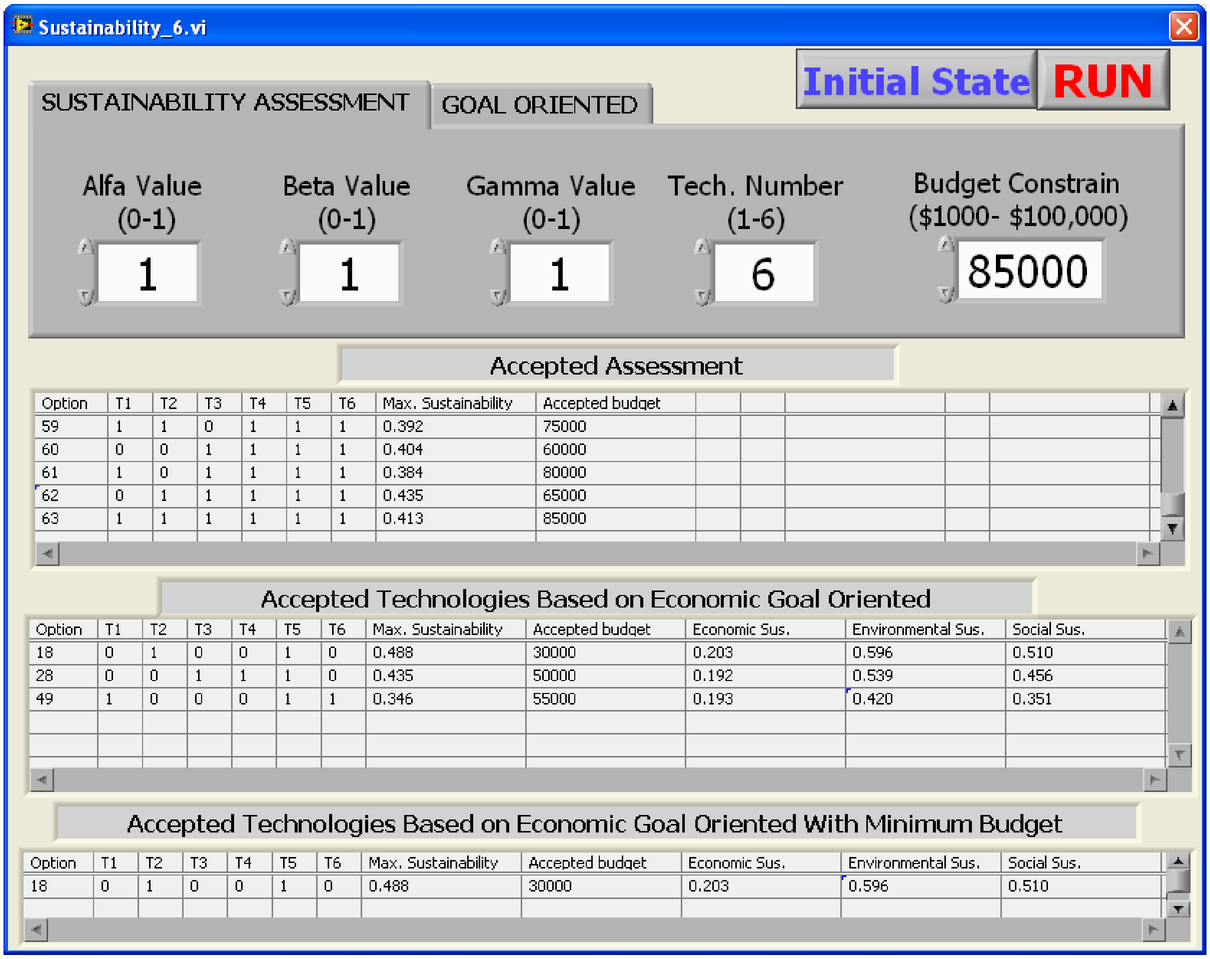

Industrial Sustainability Current State

Please Input Initial Sustainability Conditions.

Economic: 0.12
Environmental: 0.27
Social: 0.25

Figure 5.4. Current process sustainability conditions.

Now the user is ready to run the program by simply clicking on the red button function on the right corner which is labeled “RUN”. Combining sustainability indicators of different units to obtain a definite number as illustrated in the economic sustainability example, the data must be normalized to the value in the range between 0 and 1, with “0” refers to the lowest sustainability value, and “1” refers to the highest sustainability value. Only the data that reflects a value equal or greater than the desired goal and less than the budget constraints will be tabulated in the second table for accepted technologies based on economic goal oriented as shown in Figure 5.5. Simultaneously the program commutes the results for accepted technologies based on the desired economic goal oriented with minimum budget which is the optimum solution required to assist the user in decision making based on quantifiable data from the proposed selection of technology integrated for process sustainability enhancement.



Alfa Value (0-1): 1
Beta Value (0-1): 1
Gamma Value (0-1): 1
Tech. Number (1-6): 6
Budget Constrain ($1000- $100,000): 85000

Accepted Assessment

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget
59	1	1	0	1	1	1	0.392	75000
60	0	0	1	1	1	1	0.404	60000
61	1	0	1	1	1	1	0.384	80000
62	0	1	1	1	1	1	0.435	65000
63	1	1	1	1	1	1	0.413	85000

Accepted Technologies Based on Economic Goal Oriented

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.
18	0	1	0	0	1	0	0.488	30000	0.203	0.596	0.510
28	0	0	1	1	1	0	0.435	50000	0.192	0.539	0.456
49	1	0	0	0	1	1	0.346	55000	0.193	0.420	0.351

Accepted Technologies Based on Economic Goal Oriented With Minimum Budget

Option	T1	T2	T3	T4	T5	T6	Max. Sustainability	Accepted budget	Economic Sus.	Environmental Sus.	Social Sus.
18	0	1	0	0	1	0	0.488	30000	0.203	0.596	0.510

Figure 5.5. Accepted technologies based on economic goal oriented and with minimum budget.

The user can clearly compare the technology performance options and other alternatives in each sustainability goal. Furthermore, the overall maximum sustainability value for each technology is computed in addition to the calculated values of economic, environmental, social, and accepted budget cost are listed for each technology option. The results are plotted in a 3D sustainability cube format as shown in Figure 5.6.

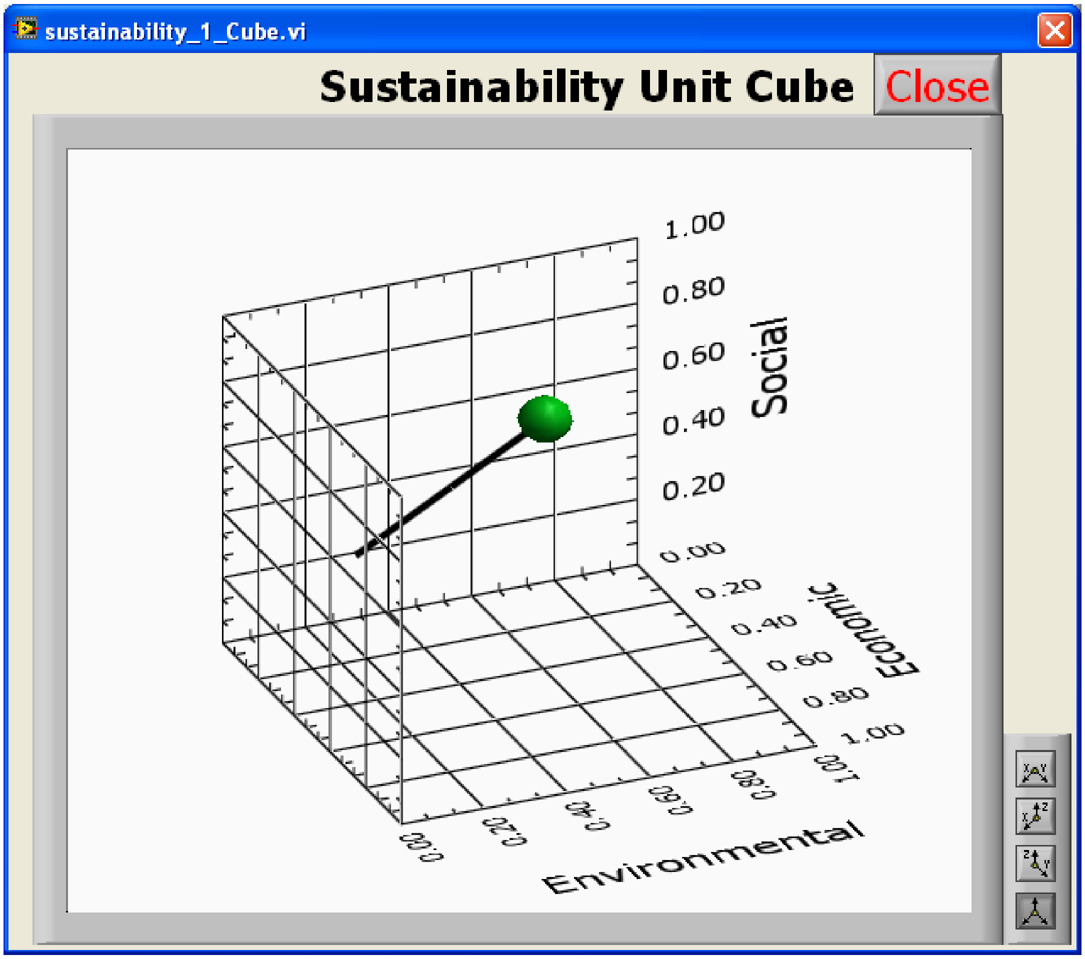


Figure 5.6. 3D sustainability unit cube graphical results.

5.6 Summary

Technology integration sustainability enhancement is a unique approach for industrial sustainability enhancement. However, identification of effective technologies for a given industrial system or process could be a combinatorial solution. If the available data and information about the industrial system and the known technologies are incomplete, imprecise, and uncertain, the technology identification will be difficult to achieve. In this research, we have introduced a simple, yet systematic methodology for identifying all optimum and possible solutions for an industrial system to improve its sustainability performance. The Technology Integrated Sustainability Enhancement (TISE) approach and decision making methodology has demonstrated its efficacy in the manufacturing metal finishing industry case study. The coherent solution identification procedure designed to facilitate the combinatorial solution used to solve efficiently through specified industrial future goal oriented preferences. The identified combinatorial solutions are adequately exhaustive in order to assist the industrial organization leaders in final decision making based on sustainability triple bottom lines. The methodology is general in which it can be applied to any sustainability enhancement challenges of any capacity. The sustainability assessment for various technology options are easily computed using a program developed by LabView software and Matlab programming tools. The assessment results from this program provide different technology integration options and alternatives which can be compared in terms of sustainability triple bottom lines, overall sustainability performance, and the optimum solution can be identified as the one yielding to the highest sustainability value with the minimum budget cost to implement those technologies.

CHAPTER 6

CONCLUSIONS

The major developments and significant contributions of this dissertation are summarized in the first part of this chapter, which is followed by a set of recommendations for future work.

6.1 Conclusions

This research sheds the light on technology assessment of the sustainability status for the metal finishing industry after integrating various technologies in its design or operation by incorporating appropriate quantitative metrics and indices. Moreover, a technological framework development approach is among the earliest that provides a comprehensive methodology to determine how to integrate the optimum technologies together with an expectation that the group of selected technologies will seek the most benefits and profitability as a result of industrial sustainability enhancement. The scope of this methodology is general but our aim is to apply it to electroplating processes as a decision making tool for industrial analysts and policy makers. Our focus is specifically concentrated on the electroplated product and process lines, such as in process environmental issues rather than post or offsite environmental issues.

The research leading to this dissertation yielded to development of a holistic methodology for sustainability assessment and decision-making, which will assist in improving the sustainability level through implementing sustainable technologies in manufacturing systems through case studies, particularly on the electroplating industry. This dissertation presented an industrial sustainability assessment approach specifically for the metal finishing industry. The significance of carefully exploring common sustainability metrics related to the chemical industry and determining the triple bottom lines requirements that will facilitate specific sustainability metrics selection. A technology-based sustainability modeling and analysis is geared towards product, materials and energy efficient technologies. Detailed assessment of profitable pollution prevention technologies performance evaluation of electroplating process source reduction technologies were considered for quantitative assessment of each technology.

To the best of our knowledge, the introduced concept of technology integrated sustainability enhancement (TISE) holistic approach is the first to be used to effectively enhance the overall industrial system sustainability by evaluating each technology or suite of technologies based on strategically selected indicators and combined benefits methodology assessment. Furthermore, an optimization based approach was introduced for a proficient sustainability assessment of industrial systems via technology integration. It is essential to mention that the methodology is general, systematic, and easy to apply to any industrial operation.

In this study, three optimization-based decision-making models were implemented to address this multi-objective problem with the integration of specific constraints for each model and supplying an optimization solution strategy. The industrial process sustainability is evaluated based on three optimization models which are investment-constraint, sustainable-goal-oriented, and economic-development-focused model. The optimal solution strategy for the metal finishing industry technology integration has clearly demonstrated the efficacy of the methodology for overall system improvement and optimization. A coherent solution identification procedure designed to facilitate the combinatorial solution to solve efficiently specified industrial future goal oriented preferences.

Another major contribution in this research is the development of an industrial sustainability assessment program using LabView software and Matlab programming tools to assess the sustainability of various technology options. The assessment results from this program provide different technology integration options and alternatives which can be compared in terms of sustainability triple bottom lines, overall sustainability performance, and the optimum solution can be identified as the one yielding to the highest sustainability value depending on budget cost limitation to implement those technologies.

6.2 Future Work

This dissertation builds a channel from which additional and more in-depth investigations on sustainable systems approaches can be conducted for design and decision making of industrial and energy systems. This section discusses possible directions for future development and potential growth in the industrial sustainability development.

Since the main assessment of technology and the current industrial process focus mainly on material consumption, material cost; in addition to, minor energy consideration were taken into account in the form of the utilities costs. Industrial energy sustainability assessment is a possible area of extension of this work by following the same methodology and technology integration approach. Moreover, secondary assessment of any implemented technology should be re-evaluated via industrial collaboration on the desired process C under investigation for enhancement.

Although a technology assessment program was developed to provide optimum solutions of integrated technologies for the overall industrial sustainability status and assist in decision-making for enhancing the industrial sustainability status. It is very important to include an uncertainty approach to deal with this issue. As a result, decision makers can evaluate the sustainability status of desired industrial process, compare different technology combinations, identify the best design for decision-making, acquire suggestions on potential system improvements, and knowing how to handle uncertainty concerns.

The opportunities for developing IER technologies are not assessed fully in this research; however, the methodology is capable of quantitatively evaluating the sustainability level of any industrial system that implements IER technologies enhancement strategies. The main advantage of the introduced methodology is its effectiveness to analyze IER technologies for a given chemical process by quantifying and integrating various energy reduction technologies that affect the overall industry sustainability enhancement

APPENDICIES

Appendix A1: Sustainability Performance Assessment of the Optimum Cleaning and Rinsing Technology ($P3_1$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

= 0.223 gal/barrel

= 0.5816 kg.sodium bicarbonate/200 kg.parts

= 0.0029 kg.sodium bicarbonate/kg.parts

I_{VM2}: Total raw material used per unit value added (kg/$)

= 0.5816 kg.sodium bicarbonate/$4,577

= 1.27×10^{-4} kg.sodium bicarbonate/$

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 25.1 gal.water/barrel

= 95 kg.water/200 kg.parts

= 0.475 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/$)

= 95 kg.water/$4,577

= 2.08×10^{-2} kg.water/$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (t/$)

= 0.223 gal.sodium bicarbonate/barrel

= 0.844 liter.sodium bicarbonate/200 kg.parts

= (0.0042 liter.sodium bicarbonate/kg.Parts)/($4,577)

= 9.17 x 10^{-7} liter.sodium bicarbonate/kg.parts.$

I_{VI1}: Hazardous solid waste per unit value added (t/$)

= 0.223 gal.sodium bicarbonate/barrel

= 0.5816 kg.sodium bicarbonate/200 kg.parts

= 0.0029 kg.sodium bicarbonate/kg.parts x (100% - 5.1%)

= 0.0029kg.sodium bicarbonate/kg.parts x 94.9%

= (0.00275 kg.sodium bicarbonate/kg.parts) /$4,577

= 6.02 x 10^{-7} kg.sodium bicarbonate/kg.parts.$

Economic Indicators:

I_{EP1}: Value added ($/y)

= (Total value added of all establishments/Number of establishments) x

(% of material cost) x (% of chemical cost)

= [($4,721,777,000/y)/2,720] x

[51.7% material cost] x [(10% chemical cost) x (5.1% chemical reduction)]

= $4,577/y

I_{EP2}: Value added per unit value of sales (/y)

= ($4,577/y)/$2,625,000

= 1.74 x 10^{-3}/y

I_{EP3}: Value added per direct employee (\$/y)

= (\$4,577/y)/20

= 229 \$/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 8 hrs/6000 hrs

= 0.0013 x 100%

= 0.13%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/\$)

= (2/y)/(\$4,577/y)

= 4.36×10^{-4} /\$

Appendix A2: Sustainability Performance Assessment of the Optimum Design for Water Allocation and Reuse Technology ($P3_2$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

n/a

I_{VM2}: Total raw material used per unit value added (kg/\$)

n/a

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 9 (gal.water/min)/barrel

= [34 (kg.water/min) x 5.2 min]/[200 kg.parts x 6 barrels]

= 0.15 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/\$)

= 176.8 kg.water/\$1,833

= 9.65×10^{-2} kg.water/\$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (liter/\$)

= 0/\$1,833

= 0 liter/\$

I_{VI1}: Hazardous solid waste per unit value added (t/\$)

(0.223 gal.sodium bicarbonate/barrel) x (60% drag out)

= 0.134 gal.sodium bicarbonate/200 kg.parts

= 0.35 kg.sodium bicarbonate/200 kg.parts

= 0.00175 kg.sodium bicarbonate/kg.parts x (100% - 44% reduction)

= 0.00175 kg.sodium bicarbonate/kg.parts x 56%

= (0.00098 kg.sodium bicarbonate/kg.parts)/\$1,833

= 5.35×10^{-7} kg.sodium bicarbonate/kg.parts.\$

Economic Indicators:

I_{EP1}: Value added (\$/y)

= (Total value added of all establishments/Number of establishments) x

(% of utilities cost) x (% of water cost)

= [(\$4,721,777,000/y)/2,720] x

[8% utilities cost] x [(3% water cost) x (44% water reduction)]

= \$1,833/y

I_{EP2}: Value added per unit value of sales (/y)

= (\$1,833/y)/\$2,625,000

= 6.98×10^{-4}/y

I_{EP3}: Value added per direct employee (\$/y)

= (\$1,833/y)/20

= 91.7 \$/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 6 hrs/6000 hrs

= 0.001 x 100%

= 0.1%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/$)

= (2/y)/($1,833/y)

= 1.09 x 10^{-3}/$

Appendix A3: Sustainability Performance Assessment of the Optimum Design for Switchable Water Allocation and Reuse Technology (P3$_3$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

n/a

I_{VM2}: Total raw material used per unit value added (kg/\$)

n/a

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 9.5 (gal/min)/barrel

= [36 (kg.water/min) x 5.2 min]/[200 kg.parts x 6 barrels]

= 0.16 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/\$)

= 187 kg.water/\$2,460

= 7.6 x 10^{-2} kg.water/\$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (liter/\$)

= 0/\$2,460

= 0 liter/\$

I_{VI1}: Hazardous solid waste per unit value added (t/\$)

(0.223 gal.sodium bicarbonate/barrel) x (60% drag out)

= 0.134 gal.sodium bicarbonate/200 kg.parts

= 0.35 kg.sodium bicarbonate/200 kg.parts

= 0.00175 kg.sodium bicarbonate/kg.parts x (100% - 59%)

= 0.00175 kg.sodium bicarbonate/kg.parts x 41%

= 0.00072 kg.sodium bicarbonate/kg.parts/$2,460

= 2.93×10^{-7} kg.sodium bicarbonate/kg.parts.$

Economic Indicators:

I_{EP1}: Value added ($/y)

= (Total value added of all establishments/Number of establishments) x

(% of utilities cost) x (% of water cost)

= [($4,721,777,000/y)/2,720] x

[8% utilities cost] x [(3% water cost) x (59% water reduction)]

= $2,460/y

I_{EP2}: Value added per unit value of sales (/y)

= ($2,460/y)/$2,625,000

= 9.37×10^{-4}/y

I_{EP3}: Value added per direct employee ($/y)

= ($2,460/y)/20

= 123 $/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 8 hrs/6000 hrs

= 0.0013 x 100%

= 0.13%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/$)

= (2/y)/($2,460/y)

= 8.13×10^{-4}/$

Appendix A4 - Sustainability Performance Assessment of the Optimum Design for Sludge Reduction Technology ($P3_4$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

= 0.223 gal/barrel

= 0.5816 kg.sodium bicarbonate/180 kg.parts

= 0.0032 kg.sodium bicarbonate/kg.parts

I_{VM2}: Total raw material used per unit value added (kg/$)

= 0.5816 kg.sodium bicarbonate/$6,731

= 8.64×10^{-5} kg.sodium bicarbonate/$

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 5 (gal/min)/barrel

= [19 (kg/min) x 5.2 min]/[180 kg.parts x 5 barrels]

= 0.11 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/$)

= 98.8 kg.water/$6,731

= 1.47×10^{-2} kg.water/$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (t/$)

= 0.223 gal.sodium bicarbonate/barrel

= [0.844 liter.sodium bicarbonate x (100% - 25%)]/180 kg.parts

= (0.0035 liter.sodium bicarbonate/kg.parts)/$6,731

= 5.2 x 10^{-7} liter.sodium bicarbonate/kg.parts.$

I_{VI1}: Hazardous solid waste per unit value added (t/$)

= (0.223 gal.sodium bicarbonate/barrel) x (60% drag out)

= 0.134 gal.sodium bicarbonate/180 kg.parts

= 0.35 kg sodium bicarbonate/180 kg.parts

= 0.00194 kg.sodium bicarbonate/kg.parts x (100% - 15% reduction)

= 0.00194 kg.sodium bicarbonate/kg.parts x 85%

= (0.00165 kg.sodium bicarbonate/kg.parts)/$6,731

= 2.45 x 10^{-7} kg.sodium bicarbonate/kg.parts.$

Economic Indicators:

I_{EP1}: Value added ($/y)

= (Total value added of all establishments/Number of establishments) x

(% of material cost) x (% of treatment chemical cost)

= [($4,721,777,000/y)/2,720] x

[51.7% material cost] x [(5% chemical cost) x (15% chemical reduction)]

= $6,731/y

I_{EP2}: Value added per unit value of sales (/y)

= ($6,731/y)/$2,625,000

= 2.56 x 10^{-3}/y

I_{EP3}: Value added per direct employee ($/y)

= ($6,731/y)/20

= 336.5 \$/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 32 hrs/6000 hrs

= 0.0053 x 100%

= 0.53%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/\$)

= (3/y)/(\$6,731/y)

= 4.46×10^{-4}/\$

Appendix A5 - Sustainability Performance Assessment of the Optimum Design for Plating Solution Recovery Technology ($P3_5$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

= (0.21 mol.$NaHCO_3$/liter)x(Total tank volume)

= (0.21 mol.$NaHCO_3$/liter) x 1200 liter

= 252 mol.$NaHCO_3$ x (0.084 kg.$NaHCO_3$/mol.$NaHCO_3$)

= 21.17 kg.$NaHCO_3$/barrel

= 21.17 kg.$NaHCO_3$/200 kg.parts

= 0.1059 kg.$NaHCO_3$/kg.parts

I_{VM2}: Total raw material used per unit value added (kg/$)

= 21.17 kg.$NaHCO_3$/$15,260

= 1.39×10^{-3} kg.$NaHCO_3$/$

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 5 (gal.water/min)/barrel

= [19 (kg.water/min) x 2 min]/[200 kg.parts]

= 0.19 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/$)

= 38 kg.water/$15,260

= 2.49×10^{-3} kg.water/$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (t/\$)

= 0.446 mol.$NaHCO_3$/barrel

= [0.446 mol.$NaHCO_3$ x (80% recovery)]/200 kg.parts

= (0.0018 mol.$NaHCO_3$/kg.parts)/\$15,260

= (1.18 x 10^{-7} mol.$NaHCO_3$/kg.parts.\$) x (0.084 kg.$NaHCO_3$/mol.$NaHCO_3$)

= 9.91 x 10^{-9} kg.$NaHCO_3$/kg.parts.\$) x (1.45 liter.$NaHCO_3$/ kg.$NaHCO_3$)

=1.44 x 10^{-8} liter.$NaHCO_3$/kg.parts.\$

I_{VI1}: Hazardous solid waste per unit value added (t/\$)

(0.446 mol.$NaHCO_3$ loss/barrel) x (100 % - 80% Recovery)

= 0.0892 mol.$NaHCO_3$ loss/barrel

= 0.0892 mol.$NaHCO_3$ loss /200 kg.parts

= 0.000446 mol.$NaHCO_3$ loss/kg.parts x 0.084 kg.$NaHCO_3$/mol.$NaHCO_3$ loss

= (0.000037 kg.$NaHCO_3$/kg.parts)/\$15,260

= 2.42 x 10^{-9} kg.$NaHCO_3$/kg.Parts.\$

Economic Indicators:

I_{EP1}: Value added (\$/y)

= (Total value added of all establishments/Number of establishments) x

(% of material cost) x (% of treatment chemical cost)

= [(\$4,721,777,000/y)/2,720] x

[51.7% material cost] x [(10% chemical cost) x (17% chemical reduction)]

= \$15,260/y

I_{EP2}: Value added per unit value of sales (/y)

= (\$15,260/y)/\$2,625,000

= 5.8×10^{-3}/y

I_{EP3}: Value added per direct employee (\$/y)

= (\$15,260/y)/20

= 760 \$/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 40 hrs/6000 hrs

= 0.006 x 100%

= 0.6%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/\$)

= (4/y)/(\$15,260/y)

= 2.62×10^{-4}/\$

Appendix A6 - Sustainability Performance Assessment of the Optimum Design for Hoist Scheduling Technology ($P3_6$)

Environmental Indicators:

I_{VM1} : Total raw material used per kg product (kg/kg)

n/a

I_{VM2}: Total raw material used per unit value added (kg/$)

n/a

I_{VW1}: Net water consumed per unit mass of product (kg/kg)

= 18.72 (gal.water/min)/barrel

= [70.8 (kg.water/min) x 0.5 min]/[200 kg.parts]

= 0.17 kg.water/kg.parts

I_{VW2}: Net water consumed per unit value added (kg/$)

= 35.4 kg.water/$3,833

= 9.24 x 10^{-3} kg.water/$

I_{VQ3}: Ecotoxicity to aquatic life per unit value added (metals and other) (t/$)

= 0/$3,833

= 0 liter/$

I_{VI1}: Hazardous solid waste per unit value added (t/$)

= (0.223 gal.sodium bicarbonate/barrel) x (60% Drag Out)

= 0.134 gal.sodium bicarbonate/200 kg.parts

= 0.35 kg.sodium bicarbonate/200 kg.parts

= 0.00175 kg.sodium bicarbonate/kg.parts x (100% - 7.8% reduction)

= 0.00175 kg.sodium bicarbonate/kg.parts x 92.2%

= 0.0016/($3,833/y)

= 4.17 x 10^{-7} kg.sodium bicarbonate.y/kg.Parts.$

Economic Indicators:

I_{EP1}: Value added ($/y)

= (Total value added of all establishments/Number of establishments) x

(% of utilities cost) x (% of water cost)

= [($4,721,777,000/y)/2,720] x

[8% utilities cost] x [(3% water cost) x (92.2% water usage)]

= $3,833/y

I_{EP2}: Value added per unit value of sales (/y)

= ($3,833/y)/$2,625,000

= 1.46 x 10^{-3}/y

I_{EP3}: Value added per direct employee ($/y)

= ($3,833/y)/20

= 191 $/y

Social Indicators:

I_{SE4}: Working hours lost as percent of total hours worked (%)

= 50 hrs/6000 hrs

= 0.0083 x 100%

= 0.83%

I_{SS1}: Number of stakeholder meetings annually per unit value added (/$)

= (2/y)/($3,833/y)

= 5.22×10^{-4}/$

REFERENCES

Azapagic, A., Milington, A., and Collett, A. A Methodology for Integrating Sustainability Considerations into Process Design. Chemical Engineering Research and Design. 2006, 84 (A6), 439 – 452.

Azapagic, A. and Perdan, S. Indicators of Sustainable Development for Industry: A General Framework. Trans. IChemE. Part B. Process Safety and Environmental Protection. 2000, 78 (B4), 243 – 261.

Barnett, W. and P. Harten, “Implementation of U.S. EPA’s metal finishing facility pollution prevention tool,” Proceedings of the 24th AESF/EPA Conference on Environmental Excellence, Daytona Beach, FL, Feb 3-7, 2003.

Bordt, M., 2009, OECD Sustainable Manufacturing Toolkit, Sustainability and U.S. Competitiveness Summit, U.S. Department of Commerce, October 8, 2009.

Cabezas, H., Pawlowsk,i C.W., Mayer, A.L., and Hoagland, N.T., "Sustainability: ecological, social, economic, technological, and systems perspectives," Clean Tech Environ Policy, 5, 167 – 80, 2003.

Chalmer, P., The Future of Finishing. Report prepared for Metal Finishing Industry, submitted by National Center for Manufacturing Sciences. Ann Arbor, MI., 2008.

Cushnie. George C. Jr., Pollution Prevention & Control Technology for Plating Operations, first edition, National Center for Manufacturing Sciences, Ann Arbor, MI, 1994.

Feng, S., Joung, C., and Li, G., "Development Overview of Sustainable Manufacturing Metrics," National Institute of Standards and Technology, Maryland, USA, 2009a.

Feng, S. and Joung, C., "An Overview of a Proposed Measurement Infrastructure for Sustainable Manufacturing," Proceedings of the 7th Global Conference on Sustainable Manufacturing, IIT Madras, Chennai, India, pp. 355-360, 2009b.

Galleriani, P. AESF/EPA Pollution Prevention Training Course for Metal Finishing. Plating and Surface Finishing. 1996, 83(1), 48.

Global Reporting Initiative (GRI). The Global Reporting Initiative - An Overview. Global Reporting Initiative, Boston, USA, 2002.

Gong, J. P., K. Q. Luo, and Y. H. Huang, “Dynamic Modeling and Simulation for Environmentally Benign Cleaning and Rinsing,” J. of Plating and Surface Finishing, 84(11), 63-70, 1997.

Gong, J. P., K. Q. Luo, and Y. H. Huang, “Dynamic Modeling and Simulation for Environmentally Benign Cleaning and Rinsing,” J. of Plating and Surface Finishing, 84(11), 63-70, 1997.

Halim, I. and Srinivasan, R. Designing Sustainable Alternatives for Batch Operations using an Intelligent Simulation-Optimization Framework. Chemical Engineering Research and Design. 2008, 86 (7), 809 – 822.

Haveman, M., Profile of the Metal Finishing Industry. Report prepared for Cleveland Advanced Manufacturing Program under contract to the Energy Environment and Manufacturing project of the Technology Reinvestment Program, submitted by Waste Reduction Institute for Training and Applications Research. Minneapolis, MN., 1995.

Institution of Chemical Engineers (IChemE). The sustainability metrics: Sustainable development progress metrics recommended for use in the process industries. Rugby, UK: Author, 2002.

Jawahir, I., Badurdeen, F., Gupta A., and Jayal, A., "Towards Developing Metrics for Sustainable Manufacturing," Proceedings of the 7th Global Conference on Sustainable Manufacturing, IIT Madras, Chennai, India, pp. 27 - 37, 2009.

Kuntay, I., K. Uygun, Q. Xu, and Y. L. Huang, “Environmentally Conscious Hoist Scheduling in Material Handling Processes,” in press, Chem. Eng. Comm., 2005.

Kuntay, I., K. Uygun, Q. Xu, and Y. L. Huang, "Environmentally Conscious Hoist Scheduling in Material Handling Processes," *Chem. Eng. Comm.*, **193**, 273-293, 2006.

Legg, K.O., Graham, M., Chang, P., Rastagar, F., Gonzales, A., and Sartwell, B. The replacement of electroplating. Surface and Coating Technology, 81, 99 – 105, 1996.

Lou, H. H. and Y. L. Huang, Profitable Pollution Prevention in Electroplating: An In-Process Focused Approach, in Toward Zero Discharge: Innovative Methodology and Technologies for Process Pollution Prevention, T. K. Das (ed.), pp. 476 - 491, Wiley-Interscience, NY, 2005.

Lou, H. H. and Y. L. Huang, “Qualitative and Quantitative Analysis for Environmentally Benign Electroplating Operations,” in Green Engineering, Anastas, Heine, and Willamson (ed.), ACS Symposium Series No. 766, Chapter 5 (pp. 42-61), Oxford Press, NY, 2001

Lou, H. H. and Y. L. Huang, “Profitable Pollution Prevention: Concept, Fundamentals, and Development,” J. of Plating and Surface Finishing, 87(11), 59-66, 2000.

Luo, K. Q., J. P. Gong, and Y. L. Huang, “Modeling for Sludge Estimation and Reduction, J. of Plating and Surface Finishing, 85(10), 59-64, 1998.

Mayer, A. L., "Strength and Weaknesses of Common Sustainability Indices for Multidimensional systems," Environment International, 34, 277 - 291, 2008.

Narayanan, D., Zhang, Y., and Mannan, M.S. Engineering for Sustainable Development (ESD) in Bio-diesel Production. Process Safety and Environmental Protection. 2007, 85 (B5), 349 – 359.

Navinsek, B., Panjan, P., and Milosev, I. PVD coatings as an environmentally clean alternative to electroplating and electroless processes. Surface and Coating Technology, 116 – 119, 476 – 487, 1999.

Noyes, R. Pollution Prevention Technology Handbook. Noyes Data Corporation, Park Ridge, NJ. 1993, Ch. 28.

Piluso, C. and Y. L. Huang. Collaborative Profitable Pollution Prevention: An Approach for the Sustainable Development of Complex Industrial Zones with Uncertain Information. Clean Technologies and Environmental Policy, 11(3), 307 - 322, 2009.

Piluso C, Huang J, Liu Z, Huang YL. Sustainability Assessment of Industrial Systems under Uncertainty: A Fuzzy-Logic-Based Approach to Short-to-Mid-Term Predictions. Ind. Eng. Chem. Res, 2010;49(18):8633-8643.

Ryabchikov, A.I., and Stepanov, I.B. Equipment and methods for hybrid technologies of ion beam and plasma surface material modification. Surface and Coating Technology, 203, 2784 – 2787, 2009.

Shah, S., Fisher, U., and Hungerbuhler, K. Hierarchial Approach for the Evaluation of Chemical process Aspects from the Prespective of Inherent Safety. Trans. IChemE. Part B. Process Safety and Environmental Protection, 81, 430 – 443, 2003.

Sikdar, S. K. Sustainable Development and Sustainability Metrics. AICHE J. 2003, 49(8), 1928 – 1932.

Steward, F.A., Environment & Competitiveness in the Metal Finishing Industry. Report prepared for Congress of the United States Office of Technology Assessment. Washington, D.C.. submitted by F.A. Steward Consulting, Inc.. Wexford. PA (January 28, 1993).

Sugiyama, H., Fisher, U., Hungerbuhler, K., and Hirao, M. Decision Framework for Chemical Process Designing Including Different Stages of Environmental, Health and Safety Assessment. AICHE J. 2008, 54(4), 1037 – 1053.

Surface Finishing Market Research Board, “Metal Finishing Industry Market Survey, 2004 ” MetalFinishing Suppliers Association and National Association of Metal Finishers

Surface Finishing Market Research Board, “Metal Finishing Industry Market Survey, 2005 ” Metal Finishing Suppliers Association and National Association of Metal Finishers

Tanzil, D., Beloff, B.R., "Assessing Impacts: Overview on Sustainability Indicators and Metrics," Environmental Quality Management, 45 (4), 41 - 56, 2006.

United Nations World Commission on Environment and Development, Our Common Future, Oxford University Press, New York, 1987.

U.S. Census Bureau. Industry Statistics Sampler, Available at: http://www.census.gov/econ/census02/data/industry/E332813.html

U.S. Department of Commerce, Economics & Statistics Administration, Bureau of the Census. 2002 Census of Manufactures. Preliminary Report Industry Series, Washington, D.C.

U.S. Department of Commerce, Economics & Statistics Administration, Bureau of the Census, 2007 Census of Manufactures. Industry Series, Washington, D.C.

U.S. Environmental Protection Agency, Energy Trends in Selected Manufacturing Sectors: Opportunities and Challenges for Environmentally Preferable Energy Outcomes, (March, 2007)

U.S. EPA, National Metal Finishing Strategic Goals Program: An Industry's Voluntary Commitment to a Cleaner Environment, EPA 231-F-99-002, OPR/ISPD; EPA: Washington, DC, 1999.

Xu. Q. and Y. L. Huang, "Design of an Optimal Reversed Drag-out Network for Maximum Chemical Recovery in Electroplating Systems", in press, J. of Plating & Surface Finishing, 92(6), 44-48, 2005.

Xu. Q., A. Telukdarie, H. H. Lou, and Y. L. Huang, "Integrated Electroplating System Modeling and Simulation for Near Zero Discharge of Chemicals and Metals," *Ind. & Eng. Chem. Research*, **44**(7), 2156-2164, 2005

Xu, Q. and Y. L. Huang, "Graph-Assisted Optimal Cyclic Hoist Scheduling for Environmentally Benign Electroplating" Ind. & Eng. Chem. Research, 43(26), 8307-8316, 2004.

Yang, Y. H., H. R. Lou, and Y. L. Huang, "Synthesis of an Optimal Wastewater Reuse Network," Int. J. of Waste Management, 20(4), 311-319, 2000.

Yang, Y. H., H. R. Lou, and Y. L. Huang. Optimal Design of a Water Reuse System in an Electroplating Plant. J. of Plating and Surface Finishing, 86(4), 80-84, 1999.

Zhou, Q. and Y. L. Huang, "Hierarchical Optimization of Cleaning and Rinsing," J. Plating and Surface Finishing, 89(4), 68-71, 2002.

Zhou, Q., H. H. Lou, and Y. L. Huang, “Design of a Switchable Water Allocation Network Based on Process Dynamics,” Industrial and Engineering Chemistry Research, 40(22), 4866-4873, 2001.

ABSTRACT

METHODOLOGICAL STUDY ON TECHNOLOGY INTEGRATION FOR SUSTAINABLE MANUFACTURING IN THE SURFACE FINISHING INDUSTRY

by

TAMER GIRGIS

August 2011

Advisor: Dr. Yinlun Huang

Major: Chemical Engineering

Degree: Doctor of Philosophy

Today, industries explore advanced techniques to enhance their development efforts to meet the goals of sustainability due to various challenges which is caused by industrial globalization, high energy and raw material costs, increased environmental regulations and social pressures, and new technological innovations. In order for an industrial process to become sustainable, it is essential to improve the process inputs efficiency from raw materials and energy while maintaining highest productivity and quality; in addition to, minimizing waste generation and the impact on the environment. Engaging in industrial sustainability requires major efforts from decision makers to implement advanced technologies to satisfy each triple bottom line of sustainability. Due to the complexity of industrial systems and lack of quantifiable mechanisms to assess sustainability triple bottom lines, decision makers are facing a very difficult task to solve. In this research a holistic methodology for sustainability assessment and decision-making is developed, which will assist in improving the sustainability level through implementing and

integrating sustainable technologies in manufacturing systems through case studies, particularly on the electroplating industry. The methodology is general but our intent is to apply it to electroplating metal substrate processes. This research is valuable in its methodological contribution for sustainability assessment, decision-making, and technology quantification via known and well established sustainability metrics to assist decision makers to identify desired technologies needed for improving overall industrial sustainability development.

This methodology is applicable for any type of industrial system of any complexity, and its efficacy is demonstrated in a case study identifying desired technologies and their implementation for achieving an overall sustainable level enhancement. Moreover, a computer aided computational tool is developed for industry forecasters to assess their current industrial sustainability and determine future sustainability goals in a quantitative manner using an interactive graphical user interface.

To the best of our knowledge the introduced concept of technology integrated sustainability enhancement (TISE) holistic approach is the first to be used to effectively enhance the overall industrial system sustainability by evaluating each technology or suite of technologies based on strategically selected indicators and combined benefits methodology assessment. Furthermore, an optimization based approach was introduced for a proficient sustainability assessment of industrial systems via technology integration.

Another major contribution in this research is the development of an industrial sustainability assessment program using LabView software and Matlab programming tools to assess the sustainability of various technology options. The assessment results from this program provide different technology integration options and alternatives which can be compared in terms of sustainability triple bottom lines, overall sustainability performance, and the optimum solution can be identified as the one yielding to the highest sustainability value depending on budget cost limitation to implement those technologies.

AUTOBIOGRAPHICAL STATEMENT

EDUCATION

- M.S., Chemical Engineering, Wayne State University, December, 2003
- B.S., Chemical Engineering, Wayne State University, May, 2002
- Certifications:
    - Fundamentals of GD&T per ASME Y14.5M-1994, 2009
    - Counterintelligence Awareness, 2009
    - International Traffic of Armament Regulation (ITAR), 2008
    - ISO9001 / 14001 / 18001 Awareness, 2008

AWARDS AND HONORS

- University Graduate Dissertation Fellowship, Wayne State University, Spring/Summer 2010
- Wayne State University Engineering Student Faculty Board Outstanding Community Service Award, 2004- 2006
- State of Michigan Collegiate Compact Heart and Soul Outstanding Community Service Award, Michigan, 2005
- Tau Beta Pi Engineering Honor Society Inducted, 2001

MEMBERSHIP

- Engineering Alumni Association, Board Member, 2004 – Present
- Engineering Graduate Student Association, President, 2004 – 2008
- Tau Beta Pi Engineering Honor Society, MI-Epsilon Chapter, Alumni Advisor, 2002 – 2011
- American Institute of Chemical Engineer, Detroit Section, Formal Chair, 2001 – 2003

PROFESSIONAL ACCOMPLISHMENTS

- **Senior Thermal Engineer**, General Dynamics Land Systems, Mobility Department, 2008 – 2009
- **Consultant Engineer**, Zoom Environmental Services, 2006 – 2008
- **Process Chemical Engineer**, Reilly Plating Company, 2005 – 2008
- **Project Chemical Engineer**, Reilly Plating Company, 2000 – 2004

PUBLICATIONS AND PRESENTATIONS

1. Girgis, T. and Y. L. Huang, “Technology Assessment and Optimal Integration for Sustainable Metal Finishing,” to be submitted, *Ind. & Eng. Chem. Research*, 2011.
2. Girgis, T. and Y. L. Huang, “Comprehensive Analysis of Profitable Pollution Prevention Technologies: Sustainability Performance and Enhancement Opportunities,” under preparation, 2011.
3. Girgis, T. and Y. L. Huang, “Towards Sustainable Manufacturing: An Approach Evaluating Energy Reduction Techniques for System Improvement,” to be presented, AICHE Annual National Conference, Minneapolis, MN, October 16-21, 2011.
4. Huang, Y. L., Z. Liu, and T. Girgis, “Sustainable Metal Finishing: Challenges and Opportunities,” presented at the 94th SUR/FIN Conference Rosemont, Illinois, June 13-15, 2011