2020 AESF Research Project (No. R-121)

12TH QUARTERLY PROGRESS REPORT
Reporting Period: 01/01/2023 – 03/31/2023

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Project Title: Development of a Sustainability Metrics System and a Technical Solution Method for Sustainable Metal Finishing

Principal Investigator: Yinlun Huang

Project Period: 04/01/2020 – 03/31/2023

Note: The project has been extended for one more year (04/01/23 – 03/31/24) in order to accomplish additional tasks. This report is the last quarterly report describing the activities based on the original proposal.

Overview (copied from the proposal):

It becomes widely recognized in many industries that sustainability is a key driver of innovation. It is shown evidently that numerous companies, especially large ones who made sustainability as a goal, are achieving clearly more competitive advantage. The metal finishing industry, however, is clearly behind others in response to the challenging needs for sustainable development.

Overall Objective (copied from the proposal)

This research project aims to: (1) create a metal-finishing-specific sustainability metrics system, which will contain sets of indicators for measuring economic, environmental, and social sustainability, (2) develop a general and effective method for systematically sustainability assessment of any metal finishing facility that could have multiple production lines, and for estimating the capacities of technologies for sustainability performance improvement, (3) develop a sustainability-oriented strategy analysis method that can be used to analyze sustainability assessment results, identify and rank weaknesses in the economic, environmental, and social categories, and then evaluate technical options for performance improvement and profitability assurance in plants, and (4) introduce the sustainability metrics system and methods for sustainability assessment and strategy analysis to the industry. This will help metal finishing facilities to conduct a self-managed sustainability assessment as well as identify technical solutions for sustainability performance improvement.

Project Schedule (copied from the proposal)

	Task	Year 1 (04/20–03/21)	Year 2 (04/21–03/22)	Year 3 (04/22–03/23)
A. Research and development				
1	Develop and test a sustainability metrics system	xxxxxxxxxxxx		
2	Develop and test a sustainability assessment method	xxxx	xxxx	
3	Develop and test a sustainability analysis method		xxxxxxx	
4	Develop and test a sustainability enhancement method		xxxxxxx	xxx
5	Develop and test a prototype software tool		xxxxxxxxxxxx	xxxxxxxxxxx
B. Introduction of method and tool to the industry				
1	Present the sustainability metrics system, with case studies, at the SUR/FIN	x		
2	Present the sustainability assessment and analysis method, with case studies at the SUR/FIN		x	
3	Present the sustainability enhancement method and tool, with case studies at the SUR/FIN			x
C. Quarterly report to the AESF Research Board		x x x x	x x x x	x x x x

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12TH QUATERLY PROGRESS REPORT

A. STUDENT PARTICIPATION

Abdurrafay Siddiqui, a PhD student in the PI's group, conducted research of this project in this reporting period. The student is financially supported mainly by Wayne State University's Graduate Teaching Assistantship Program, and partially by this AESF research project.

B. PROJECT ACTIVITIES AND PROGRESS

In this reporting period, our main activities are summarized as follows: (i) generation of a manuscript for journal publication, and (ii) paper preparation for conferences.

B.1 Generation of a Manuscript for Journal Publication

We submitted a manuscript to *J. of Cleaner Production* (Impact Factor: 11.07) for publication on March 15, 2023. The manuscript is authored by Abdurrafay Siddiqui (graduate student), Rebecca Potoff (undergraduate student), and Yinlun Huang, and the title is "*Sustainability Metrics and Technical Solution Derivation for Performance Improvement of Electroplating Facilities*". Its abstract is copied below:

Abstract*. The electroplating industry has been highly environmentally regulated due to the use of variety of hazardous or toxic chemicals and waste generation in various forms within and out of the workplace. Electroplating facilities, mostly small and medium-sized, are also operated at a low profit margin. Thus, helping the facilities develop effective strategies for sustainable development becomes a focal point in the industry. In this paper, we introduce a sustainability metrics system specifically designed for the assessment of electroplating systems of any type and any production capacity. Using*

the metrics system, we formulate the sustainability assessment process and introduce a systematic assessment method for evaluating the sustainability performance of facilities and technology candidates, and a holistic solution method for identifying optimal technologies for the system's sustainability performance improvement. The methodological efficacy is demonstrated through a case study on five electroplating facilities.

The manuscript contains some technical contents that were either only partially reported or never reported in the previous quarterly reports. Those contents are summarized below.

(a) Evaluation of the sustainability status of five electroplating plants before being considered for improvement. As we reported before, the five facilities of different production capacities were evaluated using a number of sustainability indicators. The assessment results are summarized in Table 1, where interval numbers are shown in order to accommodate data uncertainty.

Table 1. Categorized and Overall Sustainability Status of Five Facilities Before Improvement

Category	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
Economic (E)	[0.445, 0.499]	[0.437, 0.457]	[0.239, 0.255]	[0.852, 0.877]	[0.493, 0.538]
Environmental (V)	[0.467, 0.531]	[0.347, 0.358]	[0.132, 0.135]	[0.281, 0.395]	[0.149, 0.179]
Social (L)	[0.537, 0.576]	[0.327, 0.372]	[0.623, 0.671]	[0.370, 0.401]	[0.135, 0.214]
Overall (S)	[0.486, 0.536]	[0.374, 0.398]	[0.393, 0.421]	[0.560, 0.602]	[0.307, 0.350]

(b) Sustainability goal setting and budget commitment. After reviewing the assessment results shown in Table 1, it is assumed that each facility plans to improve its sustainability performance in the economic, environmental, and social sustainability categories, and commits a certain amount of funds for performance improvement. These are summarized in Table 2.

Table 2. Sustainability Goal and Budget Commitment Set Independently by Five Facilities

Category	Sustainability Goal				
	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
Economic (E^g)	0.510	0.490	0.270	0.890	0.570
Environmental (V^g)	0.645	0.600	0.300	0.630	0.400
Social (L^g)	0.690	0.480	0.700	0.650	0.360
Overall (S^g)	0.620	0.526	0.467	0.733	0.453
Budget Commitment (B^{lim})	$50,000	$70,000	$76,000	$125,000	$90,000

(c) Technologies for performance improvement. There exist many technologies for performance improvement. In the case study, three technologies are considered for possible adoption by different plants. They are: Technology 1 (T_1) - a chemical use reduction technology, which modifies the cleaning-rinsing system to directly recycle chemical solvent from a static rinsing unit to a cleaning unit while maintaining cleaning quality; Technology 2 (T_2) – a water reuse technology, which implements a direct water reuse network with a plating line while guaranteeing rinsing quality; and Technology 3 (T_3) – an environmentally benign hoist scheduling technology, which optimizes production while reducing waste streams from a plating line. The data for these technologies was collected from our previous studies. Table 3 shows the assessment results of the performance improvement capacity of each technology set (including individual technologies or their combinations) using the same sustainability indicators as those used for the assessment of the facilities. Again, the assessment results are also expressed as interval numbers. As shown in the table, the cost for adopting each technology set is also indicated.

Table 3. Effect of Technology Sets on Individual Indicators and Adoption Cost

Category	Indi-cator	Effect of Implementation						
		$\{T_1\}$	$\{T_2\}$	$\{T_3\}$	$\{T_1,T_2\}$	$\{T_1,T_3\}$	$\{T_2,T_3\}$	$\{T_1,T_2,T_3\}$
Economic (E)	E_1	[11%, 12%]	[8%, 9.6%]	6%	[19%, 21.6%]	[17%, 18%]	[14%, 15.6%]	[25%, 27.6%]
	E_2	[5%, 5.7%]	[2%, 3%]	4%	[7%, 8.7%]	[9%, 9.7%]	[6%, 7%]	[11%, 12.7%]
	E_3	[16%, 17%]	[11%, 13%]	[12%, 13%]	[27%, 30%]	[28%, 30%]	[23%, 26%]	[39%, 43%]
	E_4	N/A	N/A	[-2.5%, -2%]	N/A	[-2.5%, -2%]	[-2.5%, -2%]	[-2.5%, -2%]
Environ-mental (V)	V_1	[-5.5%, -5%]	[-30%, -27%]	[-25.8%, -23%]	[-35.5%, -32%]	[-31.3%, -28%]	[-55.8%, -50%]	[-61.3%, -55%]
	V_2	[-15.5%, -13%]	[-29%, -27%]	[-24%, -23%]	[-44.5%, -40%]	[-39.5%, -36%]	[-53%, -50%]	[-68.5%, -63%]
	V_3	N/A	[27%, 32%]	N/A	[27%, 32%]	N/A	[27%, 32%]	[27%, 32%]
	V_4	[-17%, -13%]	[-27.5%, -27%]	[-8.4%, -6%]	[-44.5%, -40%]	[-25.4%, -19%]	[-35.9%, -33%]	[-52.9%, -46%]
Social (L)	L_1	N/A	[-63%, -60%]	[-13.8%, -10%]	[-63%, -60%]	[-13.8%, -10%]	[-76.8%, -70%]	[-76.8%, -70%]
	L_2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	L_3	[-7.9%, -7%]	[-15.6%, -14%]	[-6.0%, -3%]	[-23.5%, -21%]	[-13.9%, -10%]	[-21.6%, -17%]	[-29.5%, -24%]
Tech Adoption Cost		$47,000	$32,000	$34,000	$75,050	$76,950	$62,700	$101,700

(d) Technical solution identification for sustainability goal achievement. The technical solution identification method reported before was used to identify technologies for each facility to achieve its present sustainability goal, under the budget limit set by the facility. The identified solutions are summarized in Table 4. As shown, among those recommended technology sets, the use of T_2 and T_3 together offers the best performance, satisfying the sustainability goals of Facilities 2, 3, and 5. It also shows that for Facilities 1, 3, and 5, each of them has two to three options for technology adoption. As expected, the technologies improve the environmental sustainability more than the economic and social sustainability. This is because all three individual technologies (i.e., T_1, T_2, and T_3) are mainly environmental technologies, with some added contribution to performance improvement in the other two categories. However, if other technologies would have been used, like technologies that focus on improving the economic and social sustainability performances, the solution identification methodology proposed in this work would be just as effective in completing the technology evaluation in a systematic way.

Note that the same technical solution used by different facilities may give different levels of performance improvement if the facilities' original sustainability statuses are different. It is understandable that a technology may contribute more in performance improvement if a facility's original performance is poor; the technology may not be useful if a facility's performance is already very good. As shown in table, the use of T_1 and T_2 together helps Facilities 5 the most in performance improvement, Facility 3 the second, and Facility 1 the least. This is because the environmental and social sustainability performance of Facility 5 is rather poor, and the economic and environmental sustainability performance of Facility 3 is poorer than Facility 1. To help visualize the solution's sustainability performance improvement capacities in different sustainability categories for different facilities, we generated a bar chat in Fig. 1.

Table 4. Summary of Technology Selection Results for Five Facilities

Facility	Budget B^{lim}	Techs Selected	Cost for Techs	Sustainability Performance (after)			
				$E(P\|T_j)$	$V(P\|T_j)$	$L(P\|T_j)$	$S(P\|T_j)$
F1	$80,000^{(*)}$	{T_1,T_2}	$75,050	[0.485, 0.542]	[0.752, 0.812]	[0.658, 0.699]	[0.641, 0.693]
		{T_2,T_3}	$62,700	[0.480, 0.536]	[0.734, 0.787]	[0.638, 0.691]	[0.626, 0.679]
F2	$70,000	{T_2,T_3}	$62,700	[0.474, 0.500]	[0.601, 0.637]	[0.495, 0.545]	[0.526, 0.563]
F3	$76,000	{T_1,T_2}	$75,050	[0.262, 0.285]	[0.501, 0.544]	[0.746, 0.773]	[0.541, 0.570]
		{T_2,T_3}	$62,700	[0.257, 0.277]	[0.452, 0.479]	[0.745, 0.781]	[0.524, 0.553]
F4	$125,000	{T_1,T_2,T_3}	$101,700	[0.873, 0.902]	[0.729, 0.839]	[0.607, 0.663]	[0.744, 0.808]
F5	$90,000	{T_2}	$32,000	[0.519, 0.571]	[0.410, 0.441]	[0.369, 0.454]	[0.437, 0.492]
		{T_1,T_2}	$75,050	[0.559, 0.616]	[0.530, 0.590]	[0.428, 0.514]	[0.509, 0.575]
		{T_2,T_3}	$62,700	[0.547, 0.600]	[0.500, 0.548]	[0.414, 0.526]	[0.490, 0.559]

(∗) The original funds committed by Facility 1 (F1) ($50,000) were in sufficient for adopting any technology for performance improvement. The facility was then agreed to increase the budget to $80,000.

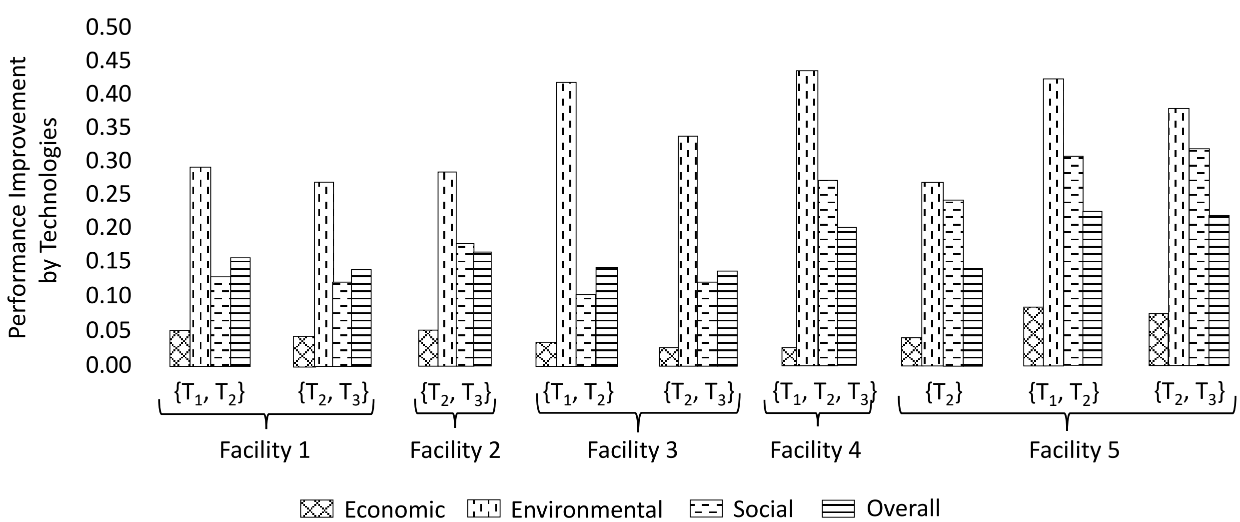

Figure 1. Sustainability performance improvement by technologies in different facilities.

(e) Profitability study. Table 4 shows the effects of the technology sets after implementation in different facilities. It is convenient for them to evaluate their profitability gains after adopting the recommended technologies. For instance, Facility 5 saw a major improvement to economic sustainability after implementing the technology set (T_1 and T_2). Here we take a range of $10,000,000 to $11,000,000 as the yearly pre-tax revenue to understand the effects of the technology on the profit of the facility over 10 years. We also take a maintenance cost of $2,500 every three years for the use of technology set. The technology will be paid off in 3 years with equal payments. From the net present values of Facility 5 with and without the technology set, which can be seen in Fig. 2, it becomes clear that Facility 5 with the technology set always has a better net present value than the facility without the tech set. For the first three years, the difference is low and for the third year, when maintenance is required for the tech set, the difference between the net present values seems to plateau for one year. However, after that, the payments for the technology are finished and the difference continues to increase linearly. By the 10^{th} year, the facility using the tech set has a net present value of $1,430,826. As opposed to the facility without the tech set, which shows a net present value of $1,204,103. This is a $226,723 return after 10 years (an average of $22,672 per year), alongside significantly lowering the amount of waste produced, water used, and product defect rate.

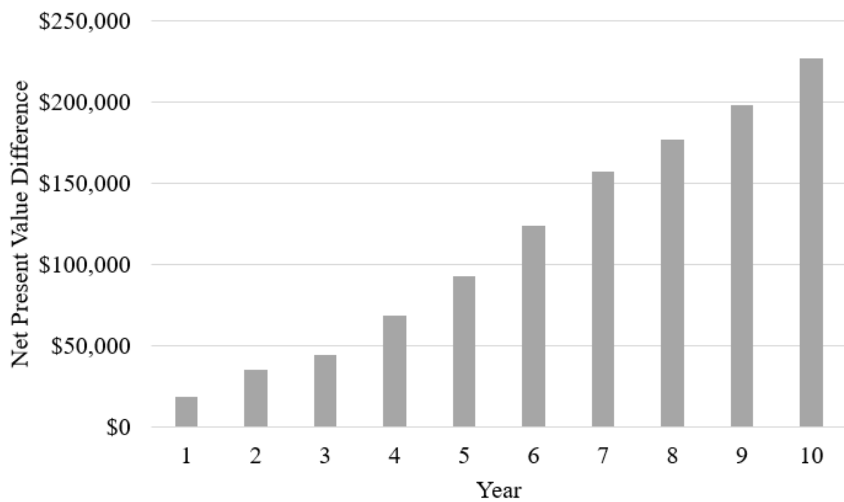

Figure 2. Profitability improvement for Facility 5 after implementing techs T_1 and T_2.

B.2 Paper Preparation for Conferences

(a) The PI's invited lecture. On March 10, 2023, the PI was invited by AIChE's Process Development Division to give a lecture at an AIChE Live Webinar: "Technology Development and Assessment for Smart and Sustainable Manufacturing: A Multiscale Systems Engineering Approach". The lecture, which was well received by the audience, includes some of the results for sustainable surface finishing. The abstract is copied blow:

> ***Abstract****. According to National Science & Technology Council on the "Strategy for American Leadership in Advanced Manufacturing", the next generation of technological competition in manufacturing is dictated by inventions. Although emerging technologies can become an engine of change and progress, the net profit brought to the society could be questionable, if sustainability principles are not fully incorporated into technology development and application phases. It is imperative that more fundamental knowledge, systematic methodologies, and powerful tools be developed to reshape technology innovations and meet industrial sustainable development goals.*

Today, industries are in the midst of significant, compelling smart transformation largely impacted by Industry 4.0, which is mainly featured by digitalization. This provides a variety of opportunities for advancing the innovation of smart and sustainable technologies.

In this presentation, we will introduce a systematic methodology for conducting comprehensive sustainability assessment of emerging technologies in their early development phase and identifying optimal technology sets for smart and sustainable manufacturing in different life-cycle stages. This methodology is developed by resorting to sustainability science, multiscale systems science, and digital-twin technologies. To demonstrate methodological efficacy, we will present a number of case studies, including the assessment of technologies for smart and sustainable nanopaint design and nanocoating manufacturing, plant-wide electroplating, and heat-integrated work exchanger network design for thermal and mechanical energy recovery. Future directions for smart and sustainable manufacturing will also be discussed.

(b) Papers to be presented by the students at the SUR/FIN2023, Cleveland, OH, June 6-8, 2023. The paper abstracts are shown below.

(b-1) Siddiqui, A. and Y. Huang, "Industrial Sustainability Assessment and Enhancement (ISAE) Tool".

Abstract. *Technologies are a catalyst for sustainability improvement as they can help lower natural resource usage and waste production. The surface finishing industry has shown much growth over the past few years related to technological improvement and implementation. However, due to the high levels of environmental regulation, health risks, and low profit margins, applying new technologies could be a risk. And if sustainability principles are not thoroughly implemented and used in the assessment of new technologies, unexpected, and possibly harmful, results may ensue. However, it is also of note that technology assessments can be intensive and require large amounts of resources. Thus, it is important to, not only have a sustainable technology assessment methodology, but also be able to apply this methodology easily.*

In the past two years, we developed a metal-finishing-specific sustainability metrics system, which was composed of three sets of indicators for measuring over forty aspects of sustainability in economic, environmental, and social dimensions. We then introduced a technology evaluation methodology that was scientific and systematic and incorporated said sustainability metrics system. In this presentation, we introduce a sustainability assessment and technology evaluation tool. This tool can be used to evaluate the sustainability performance of electroplating facilities, portray results in an easy to read manner as to facilitate future plans of action, and include technology evaluation to identify the best possible results. The capabilities of this tool will be shown through case studies by studying the sustainability of different electroplating facilities and the effects of implementing identified technologies.

(b-2) Moghadasi, M. and Y. Huang, "Digital Twin-Based Dynamic Sustainability Assessment of Electroplating Facilities".

Abstract. *The rapid growth of digital technologies provides a variety of opportunities for smart manufacturing. Digital Twin (DT) is one of them. Digital twins are used across the whole manufacturing lifecycle, from design to operation of manufacturing facilities. A DT is a virtual representation of a physical system, where real-time data is used to ensure its accuracy and fidelity. As manufacturing sustainability heavily relies on the availability of system information, the DT technology is naturally highly valuable for pursuing a few key tasks in sustainability, including sustainability assessment and analysis, future trend prediction, short-to-long-term strategy development for sustainability performance, and effectiveness evaluation of strategy implementation.*

In this presentation, a DT-based methodology for constructing a virtual electroplating plant and performing dynamic sustainability assessment is introduced. Techniques for acquisition and utilization of dynamic data in various operational scenarios are discussed to ensure DT fidelity. A case study on zinc alloy plating is selected for using the DT platform to conduct sustainability performance evaluation using the sustainability metrics system that we have developed specifically for the metal finishing industry. The advantage of DT-based dynamic sustainability assessment is described after comparing with conventional sustainability assessment.

(c) Abstracts submitted for presentation at the AIChE Annual National Meeting, Orlando, FL, Nov. 5 - 10, 2023. Two electroplating-related abstracts have been submitted for presentation. The titles of the abstracts are: (i) Dynamic Sustainability Assessment in the Digital Age, and (ii) "Fuzzy Decision-Making for Sustainability Performance Improvement of Complex Systems." Both abstracts are authored by A. Siddiqui and the PI.

C. PLAN FOR THE 13TH QUARTER OF THE PROJECT

We will continuously work on the Matlab based tool, ISAE. The tool will be used to conduct more case studies. Besides, we plan to report our research progress on the digital twinning for sustainable metal finishing through developing digital models for characterizing the sustainability performance of electroplating systems.