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

by
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Editor's Note: *This NASF-AESF Foundation research project report covers the fourth quarter of project work (January-March 2021) at Wayne State University in Detroit. The success of this project depends on data. The data needed comes from industry and other stakeholders. The reader is encouraged to complete the survey form discussed in this report. It is available as a printable pdf in the online version at http://short.pfonline.com/NASF21Aug1 and can be submitted to Dr. Huang at yhuang@wayne.edu .*

Overview

It is widely recognized in many industries that sustainability is a key driver of innovation. Numerous companies, especially large ones that 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.

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.

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Progress Report (Quarter 4)

1. Student participation

Abdurrafay Siddiqui, a Ph.D. student, has been guided by the P.I. to work on the project. His research activities are reflected in Section 3 of this report.

2. Scheduled project tasks for Quarter 4

The main technical tasks for this quarter are listed below:

1. Refine the sustainability indicators in Sets A and B to generate a document about the sustainability metrics system and a guideline for the evaluation of the metrics system.
2. To initiate the development a sustainability assessment method, with a main effort on the development of an Analytic Hierarchy Process (AHP) based methodology.

3. Project activities and progress

3.1 Refinement of sustainability indicator sets and development of a survey document

We have reviewed all the proposed sustainability indicators that were divided into two sets: a primary one and a secondary one. Some of those and the parameters required for evaluating indicator values are refined so that the definition, coverage and importance become clearer and more accurate. The creation and refinement of the indicators are all based on the P.I.'s research and industrial experience in the past two decades. However, to ensure the sustainability metrics system is truly useful, acceptable and applicable in the metal finishing sector in the future, the indicators in the metrics system should be thoroughly reviewed by industrial experts. Therefore, the P.I.'s group has generated a survey form, namely SMS Survey Form, where SMS stands for Sustainability Metrics System. The survey form (as an Excel file) lists all the indicators in both sets, with a definition or explanation for each indicator (see the following table). The survey form includes two additional two columns: one column for evaluators to enter a rating number between 1 and 5, with 1 for the least importance and 5 for the highest importance, and the other column for evaluators to enter their comments or suggestions for each indicator. Furthermore, there is a space for additional comments or suggestions in the end.

We need the NASF/AESF Foundation's help in distributing the survey form to the following types of businesses: (1) electroplating, (2) other types of metal finishing, (3) chemical supply, (4) OEMs for metal finishing, (5) technology, (6) consulting, as well as (7) customers, communities or other stakeholders, government, state/local agencies, professional organization, etc. We hope to have responses from people with different job responsibilities and expertise, such as management, process engineering/production, EHS (environmental, health and safety), technology/research, supply/sales, education, customer relation, etc. A complete form is provided at the end of this report.

3.2 Development of an AHP-based sustainability assessment method

The sustainability assessment method that is being developed consists of seven main steps: (1) selection of sustainability indicators in the economic, environmental and social categories, (2) selection of weighting factors that are to be associated with indicators, (3) determination of parameters that are needed for evaluating each indicator, (4) collection and analysis of plant and other data, (5) calculation and normalization of indicator values, (6) assessment of categorized sustainability (*i.e.*, economic, environmental and social sustainability) as well as overall sustainability, and (7) analysis of assessment results with recommendations. In the third quarter report, we described a few mathematical formulas for calculating sustainability values in the economic (E), environmental (V) and social (L) categories, as well as the overall sustainability (S) value; they are:

$$E = \frac{\sum_{i=1}^{N_E} a_i E_i}{\sum_{i=1}^{N_E} a_i}, \quad V = \frac{\sum_{j=1}^{N_V} b_j V_j}{\sum_{j=1}^{N_V} b_j}, \; L = \frac{\sum_{k=1}^{N_L} c_k L_k}{\sum_{k=1}^{N_L} c_k} \text{ and } S = \frac{\|(\propto E, \beta V, \gamma L)\|}{\|(\alpha, \beta, \gamma)\|}$$

where E_i, V_j and L_k are individual normalized indicators in different sustainability categories; N_E, N_V and N_L are the total numbers of selected indicators in different sustainability categories; a_i, b_j and c_k are weighting factors associated with different indicators; and α, β and γ are weighting factors associated with each categorized sustainability. All weighting factors will take values between 1 and 10, with 10 as the most important and 1 as the least.
The assessment results will be greatly influenced by the selected values of a large number of weighting factors that are assigned to indicators. Except for a very few cases, the values of weighting factors cannot be theoretically calculated. As stated in the third quarter report, we decided to adopt the Analytic Hierarchy Process (AHP) method, which is a scientific method developed by Thomas Saaty, a member of US National Academy of Engineering (Saaty, 1980, 2008). It is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. The method allows individual experts' experiences to be utilized to estimate the relative magnitudes of factors through pair-wise comparisons. This is the main reason for us to develop the SMS survey form and to invite industrial experts to provide their views, in terms of giving ratings to various sustainability indicators. We hope in the next quarter or so, we will be able to receive a good number of responses from the industry, so that we can conduct a statistical analysis on the feedback. We will formulate the weighting factor determination process, and test it using some case study problems. If we have enough responses from the industry, we should be able to report this research work in subsequent reports.

Recently, we submitted an Abstract, entitled "Development of a Sustainability Metrics System for the Assessment and Improvement of Metal Finishing Facilities' Sustainability Performance, for presentation at the SUR/FIN Conference in Detroit, November 2-4, 2021. In this presentation, we will introduce a metal-finishing-specific sustainability metrics system, which is composed of three sets of indicators for measuring over forty aspects of sustainability. Case studies will be illustrated to show the practical usage of the sustainability metrics system in metal finishing plants.

We also submitted an abstract, entitled "Reinforced Sustainability Assessment and Decision Making in the Post-COVID-19 Manufacturing Era," for presentation at the AIChE Annual National Meeting in Boston, MA in mid-November. At the conference, we plan to introduce an AHP-based sustainability assessment and decision-making method, with an applied study on small and medium sized electroplating facilities for sustainable development in the post COVID-19 manufacturing era.

4. Plan for the 5th quarter of the project (4/1/21 – 6/30/21)

The primary effort in the coming quarter will be on the test of the sustainable metrics system. We need NASF/AESF Foundation's strong support in distributing the survey form to industrial experts as widely and as many as possible. We will then collect the industrial feedback on the sustainability indicators and conduct a statistical analysis. A number of metal finishing facilities will then be contacted for possible collaboration, mainly for data collection and analysis. Meanwhile, we will continuously work on the decision making method. There could be a number of theoretical challenges, especially related to data and information uncertainty, that need to be studied.

5. References

T.L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, New York, 1980.
T.L. Saaty, "The analytic hierarchy and analytic network measurement processes: applications to decisions under risk," *European J. of Pure and Applied Mathematics*, 1 (1), 122-196 (2008).
A. Siddiqui and Y. Huang, *Reinforced Sustainability Assessment and Decision Making in the Post-COVID-19 Manufacturing Era*, submitted for presentation at the AIChE Annual National Meeting, Boston, MA, Nov. 7-11, 2021.

6. Past project reports

1. Quarter 1 (April-June 2020): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 84 (12), 14 (September 2020); Full paper: http://short.pfonline.com/NASF20Sep1
2. Quarter 2 (July-September 2020): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 85 (3), 13 (December 2020); Full paper: http://short.pfonline.com/NASF20Dec1
3. Quarter 3 (October-December 2020): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 85 (7), 9 (April 2021); Full paper: http://short.pfonline.com/NASF21Apr1.

7. About the authors

Dr. Yinlun Huang is a Professor at Wayne State University (Detroit, Michigan) in the Department of Chemical Engineering and Materials Science. He is Director of the Laboratory for Multiscale Complex Systems Science and Engineering, the Chemical Engineering and Materials Science Graduate Programs and the Sustainable Engineering Graduate Certificate Program, in the College of Engineering. He has ably mentored many students, both Graduate and Undergraduate, during his work at Wayne State.

He holds a Bachelor of Science degree (1982) from Zhejiang University (Hangzhou, Zhejiang Province, China), and M.S. (1988) and Ph.D. (1992) degrees from Kansas State University (Manhattan, Kansas). He then joined the University of Texas at Austin as a postdoctoral research fellow (1992). In 1993, he joined Wayne State University as Assistant Professor, eventually becoming Full Professor from 2002 to the present. He has authored or co-authored over 220 publications since 1988, a number of which have been the recipient of awards over the years.

His research interests include multiscale complex systems; sustainability science; integrated material, product and process design and manufacturing; computational multifunctional nano-material development and manufacturing; and multiscale information processing and computational methods.

He has served in many editorial capacities on various journals, as Co-Editor of the *ASTM Journal of Smart and Sustainable Manufacturing Systems*, Associate Editor of *Frontiers in Chemical Engineering*, Guest Editor or member of the Editorial Board, including the *ACS Sustainable Chemistry and* Engineering, Chinese *Journal of Chemical Engineering,* the *Journal of Clean Technologies and Environmental Policy,* the *Journal of Nano Energy and Power Research.* In particular, he was a member of the Editorial Board of the AESF-published *Journal of Applied Surface Finishing* during the years of its publication (2006-2008).

He has served the AESF and NASF in many capacities, including the AESF Board of Directors during the transition period from the AESF to the NASF. He served as Board of Directors liaison to the AESF Research Board and was a member of the AESF Research and Publications Boards, as well as the Pollution Prevention Committee. With the NASF, he served as a member of the Board of Trustees of the AESF Foundation. He has also been active in the American Chemical Society (ACS) and the American Institute of Chemical Engineers (AIChE).

He was the 2013 Recipient of the NASF William Blum Scientific Achievement Award and delivered the William Blum Memorial Lecture at SUR/FIN 2014 in Cleveland, Ohio. He was elected AIChE Fellow in 2014 and NASF Fellow in 2017. He was a Fulbright Scholar in 2008 and has been a Visiting Professor at many institutions, including the Technical University of Berlin and Tsinghua University in China. His many other awards include the AIChE Research Excellence in Sustainable Engineering Award (2010), AIChE Sustainable Engineering Education Award (2016), the Michigan Green Chemistry Governor's Award (2009) and several awards for teaching and graduate mentoring from Wayne State University, and Wayne State University's Charles H. Gershenson Distinguished Faculty Fellow Award.

Abdurrafay Siddiqui is a Ph.D. student at Wayne State University and has been guided by Prof. Yinlun Huang to work on the project.

8. Appendix

The survey form, “Evaluation of the Proposed Sustainability Metrics for Metal Finishing,” without the 1-to-10 rating columns, is provided below:

Proposed SMS Survey Form: Evaluation of the Proposed Sustainability Metrics for Metal Finishing

Sustainability Category	Subcategory	Indicator	Definition or Explanation
E: Economic Sustainability	E-1: Profit, Value and Tax	E-1-1: Value Added ($/yr)	Based on the difference between the product price to consumers and the manufacturing cost
		E-1-2: Value Added per Direct Employee ($/yr)	Average amount each employee adds in value to the company
		E-1-3: Net Profit Margin (%/$)	Based on the difference between the income from produce sale after tax and the production cost
		E-1-4: Net Profit per Direct Employee ($/yr)	Average amount of profit each employee makes for the company
		E-1-5: Tax Paid as a Percentage of NIBT (%)	Amount of tax paid as a percentage of Net Income Before Tax (NIBT)
		E-1-6: Return on Average Capital Employed ($/yr)	Amount of money received back with respect to the average capital employed
	E-2: Investments	E-2-1: Percentage increase in capital Employed (%/yr)	Increase of average capital employed from last year
		E-2-2: Percentage of New Employees (%/yr)	Percentage of new employees hired in the company per year
		E-2-3: Percentage of Training vs Payroll Expense (%)	Amount of money spent on training of employees as a percentage of payroll expense
		E-2-4: Investment for Employee's Education/Training ($)	Amount of money spent on employee education and training regarding important aspects of their jobs
		E-2-5: Investment on New Technology (%/yr)	Percent increase spent on new technology from last year
	E-3: Technology Advancement	E-3-1: Production Increment Percentage per Dollar Investment on New Technology (%/$-new tech)	Amount of production increase from last year vs the amount of money invested on new technologies since last year
		E-3-2: Production Increment Percentage per Dollar Investment on Technology Improvement (%/$-existing tech)	Amount of production increase from last year vs the amount of money invested on existing technology improvement since last year. Existing technology improvement does not include investment on new technologies
		E-3-3: Production Quality Improvement Percentage per Dollar Investment on New Technology (%/$-new tech)	Quality of production improvement from last year vs the amount of money invested on new technologies since last year
		E-3-4: Production Quality Improvement Percentage per Dollar Investment on Technology Improvement (%/$-existing tech)	Quality of production improvement from last year vs the amount of money invested on existing technology improvement since last year. Existing technology improvement does not include investment on new technologies
		E-3-5: Waste Reduction Percentage per Dollar Investment on new Technology (%/$-new tech)	Amount of waste reduced from last year vs the amount spent on new technologies since last year
		E-3-6: Waste Reduction Percentage per Dollar Investment on Technology Improved (%/$-existing tech)	Amount of waste reduced from last year vs the amount spent on existing technology improvement since last year. Existing technology improvement does not include investment on new technologies
	E-4: Production and Product Quality	E-4-1: Percentage of Product Delivered on Time (%)	Percent of product that was delivered on time based on total products delivered per year
		E-4-2: Product Defect Rate During Production (%)	Amount of defected product vs the total amount of product made per year
		E-4-3: Product Return Rate After Shipment (%)	Amount of product returned after shipment vs the amount of products shipped per year

V: Environmental Sustainability		V-1-1: Chemical Use in Production per Value Added (lb/$)	Amount of chemical use in production per dollar of value added per year

	V-1: Materials (Excluding Fuel and Water)	V-1-2: Chemical Use in Production per Dollar of Product Sales (lb/$)	Amount of chemical use in production per dollar of product sales per year
		V-1-3: Chemical Use in Waste Treatment per Value Added (lb/$)	Amount of chemical use in waste treatment per dollar of value added per year
		V-1-4: Plating Solution Use per Value Added (lb/$)	Amount of plating solution use per dollar of value added per year
		V-1-5: Plating Solution Use per Dollar of Product Sales (lb/$)	Amount of plating solution use per dollar of product sales per year
		V-1-6: Other Material Use per Dollar of Product Sales (lb/$)	Amount of other material use per dollar of product sales per year
	V-2: Water	V-2-1: Fresh Water Use in Production per Dollar of Product Sales (lb/$)	Amount of fresh water use in production per dollar of product sales per year
		V-2-2: Used Water Reused in Production before Treatment (%)	Percentage of used water reused in production per year before treatment of waste
		V-2-3: Fraction of Water Recycled Within Plant (%)	Percentage of water recycled within the plant
	V-3: Energy	V-3-1: Electricity Use per Dollar of Sales (KW/$)	Kilowatts of electricity use per dollar of product sales per year
		V-3-2: Natural Gas and Oil Use per Dollar of Sales (MMBtu/$)	Million Btu of natural gas and oil use per dollar of product sales per year
		V-3-3: Clean Energy Use Among All Energy (%)	Percentage of energy derived from "clean" sources vs all energy consumed
		V-3-4: Non-Production Energy Among All Energy Consumption (%)	Percentage of energy not used in production vs all energy consumed
	V-4: Waste Generation and Effluents	V-4-1: Spent Solutions per Value Added (lb/$)	Amount of spent solution per dollar value added per year
		V-4-2: Wastewater Generated in Production per Value Added (lb/$)	Amount of wastewater generated in production per dollar of value added per year
		V-4-3: Wastewater Treatment Sludge per Value Added (lb/$)	Amount of wastewater treatment sludge used per dollar of value added per year
		V-4-4: Hazardous Waste Generated per Value Added (lb/$)	Amount of hazardous waste generated per dollar of value added per year
		V-4-5: Non-Hazardous Waste Generated per Value Added (lb/$)	Amount of non-hazardous waste generated per dollar of value added per year

L: Social Sustainability	L-1: Workplace	L-1-1: Benefits as Percentage of Payroll Expense (%)	Benefits to employees as a percentage of total payroll expenses per year
		L-1-2: Work Related Re-Education and/or Training (%)	Amount of money spent on work related re-education and training vs total payroll expenses per year
		L-1-3: Employee Turnover (%)	Resigned and redundant employees vs total employed per year
		L-1-4: Promotion Rate (%)	Number of promotions vs total employed per year
		L-1-5: Working Hours Lost as Percentage of Total Hours Worked (%)	Working hours lost vs total hours worked per year
	L-2: Safety and Health	L-2-1: Number of Process Safety Reviews (/yr)	Number of process safety reviews per year
		L-2-2: Number of Accidents in Workplace (/yr)	Number of accidents in the workplace per year
		L-2-3: Chemical Leakage in Plant (/yr)	Amount of chemical leakage in plant per year
		L-2-4: Human Health Burden (Carcinogenic) per Value Added (/$)	Number of people in the workforce and local community with carcinogenic health conditions as a result of the plant per dollar of value added per year
	L-3: Society	L-3-1: Number of Stakeholder Meetings (/yr)	Number of stakeholder meetings per year
		L-3-2: Indirect Community Benefit ($/yr)	Amount of money spent with indirect community benefit per year
		L-3-3: Number of Complaints from Local Community (/yr)	Number of complaints from the local community per year
		L-3-4: Number of Complaints from Customers (/yr)	Number of complaints from customers per year
		L-3-5: Number of Legal Actions per Value Added (/yr)	Number of legal actions per dollar of value added per year