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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 seventh quarter of project work (October-September 2021) at Wayne State University in Detroit.*

Overview

It is widely recognized in many industries that sustainability is a key driver of innovation. Numerous companies, especially large ones who made sustainability as a goal, are achieving clearly more competitive advantages. 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 systematic 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 strategic 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 7)

1. Student participation

Abdurrafay Siddiqui, a PhD student, has been guided by the PI to work on the project. During this project reporting period, the student is fully supported by Wayne State University as a Graduate Teaching Assistant. In addition to his duty as a teaching assistant, he also works on the AESF project and the surface finishing related part of a National Science Foundation (NSF) project for which Prof. Huang also serves as the PI.

2. Project activities and progress

The major activities in this report period are: (1) the development of additional sustainability indicators for the evaluation of sustainability performance of a system of any type when unexpected, severe disruption events, such as the current COVID-19 pandemic, occur to the manufacturing industry, (2) the development of a sustainability assessment method by incorporating a set of extended sustainability indicators into the assessment using the normal sustainability metrics system that was reported in the previous progress reports, (3) the development of an improved software tool for sustainability assessment and (4) four presentations at national conferences. Each of these are briefly reported below.

2.1 Development of new sustainability indicators for extended evaluation of sustainability performance

The COVID-19 pandemic has continued to severely disrupt economic and social systems in the world. In the U.S., one of the hardest-hit segments by the pandemic is the manufacturing industry. Industries look beyond the fog of uncertainty towards long-term changes and develop strategies for more sustainable and resilient development. One challenging question involves the effectiveness and completeness of normal sustainability metrics systems and a need for scope-extended sustainability assessment, which may impact significantly on a decision making process.

We reviewed the scope of widely practiced metrics in the economic, environmental and social sustainability categories and their sub-categories, and discovered insufficiency for sustainability assessment when experiencing unexpected, severe, uncertain and disruptive events. We have identified a number of new types of sustainability metrics and a method for consolidation of the new and existing metrics to avoid overlapped coverage of measurement aspects. It is conceivable that adoption of a reinforced sustainability metrics system will impact the decision-making process more systematically and effectively, especially with the involvement of severe uncertainty. Tables 1 to 3 list a total of 17 new indicators in the economic, environmental and social sustainability categories, respectively, and their subcategories. Each table also includes a column of parameters that are needed for evaluation of indicator values.

Table 1 - New economic indicators for extended assessment

Sub-category	Indicator	Parameter
E-1: New Technologies	E-1-1: Number of new technologies developed and/or adopted	Non-traditional technologies, specifically for mitigating negative impacts on anufacturing caused by unexpected major disruptions
	E-1-2: Investment in new technologies	Plan for spending on the development or adoption
E-2: Supply Chain	E-1-1: Number of new technologies developed and/or adopted	Focus on stability and flexibility
	E-2-2: Stability and flexibility of other supplies	Especially chemicals
E-3: New Market Development	E-3-1: Type of new market developed	Different market opportunities
E-4: Green Employment	E-4-1: Number of green jobs created	Positions created for substantially preserving or restoring environmental quality

Table 2 - New environmental indicators for extended assessment

Sub-category	Indicator	Parameter
V-1: XR Initiative	V-1-1: Implementation and effectiveness of 3R	3R - reduce, reuse, and recycle
	V-1-2: Initiative of additional R's	For instance, "redesign" of some processes for cleaner and safer production, "recover" of chemicals, "reintegration" of certain processes
V-2: Renewable Resources	V-2-1: Type of renewable energy used	For instance, solar energy and biofuels
	V-2-2: Percentage of energy supply	As compared to total energy consumption
V-3: Exchange Networks	V-3-1: Type of green business connections	Networks with other companies for exchanging used/waste materials and energy
V-4: Regulation Compliance	V-4-1: Effectiveness of regulation compliance	Annual report on the effectiveness and action taking for regulation

Table 3 - New social indicators for extended assessment

Sub-category	Indicator	Parameter
L-1: Preparedness for Major Disruption	L-1-1: Response time to major disruption	Time spent for taking action, as compared with other companies
	L-1-2: Types and effectiveness of actions	Effectiveness can be reflected by the damage reduced due to quick actions
L-2: Labor Conditions	L-2-1: Preparedness of health risk prevention	Action plans for health risk prevention
L-3: Advanced Training	L-3-1: Quality of guidelines developed	Training arranged for employees to effectively use new equipment, devices, and technologies
L-4: Customer Services	L-4-1: Types of special services provided	Effective communications with and services to customers during a disruption period

2.2 Development of a method for consolidated sustainability assessment

In the past progress reports, we reported the introduction of 53 sustainability indicators that were divided into two sets, Set A (called the minimum set, 31 in total) and Set B (called the additional set, 22 in total). Those indicators are for normal assessment. We also introduced a set of formulas for evaluating the values of economic, environmental, social and overall sustainability. These formulas are listed in the 2nd column of Table 4 below, where a superscript, "n", is added to all normal indicators and weighting factors, in order to differentiate them from the extended indicators and assessment activities.

The same types of formulas will be used to perform sustainability assessment using the extended indicators, which are listed in the 3rd column of Table 4, where each of the indicators and weighting factors has a superscript, "e", in the extended metrics system. The consolidated assessment of each sustainability category as well as that of the overall sustainability are listed in the 4th column of the same table, where η, ζ and ξ are weighting factors; each has a value between 0 to 1. We will report our study on the selection of all weighting factors in the next report.

Table 4 - Formulas for evaluating sustainability performance in different categories

Category	Normal	Extended	Consolidated
Economic	$E^n = \dfrac{\sum_{i=1}^{N_E^n} a_i^n E^n{}_i}{\sum_{i=1}^{N_E^n} a_i^n}$	$E^e = \dfrac{\sum_{i=1}^{N_E^e} a_i^e E^e{}_i}{\sum_{i=1}^{N_E^e} a_i^e}$	$E = \eta E^n + (1-\eta) E^e$
Environmental	$V^n = \dfrac{\sum_{i=1}^{N_V^n} b_i^n V^n{}_i}{\sum_{i=1}^{N_V^n} b_i^n}$	$V^e = \dfrac{\sum_{i=1}^{N_V^e} b_i^e V^e{}_i}{\sum_{i=1}^{N_V^e} b_i^e}$	$V = \zeta V^n + (1-\zeta) V^e$
Social	$L^n = \dfrac{\sum_{i=1}^{N_L^n} c_i^n L^n{}_i}{\sum_{i=1}^{N_L^n} c_i^n}$	$L^e = \dfrac{\sum_{i=1}^{N_L^e} c_i^e L^e{}_i}{\sum_{i=1}^{N_L^e} c_i^e}$	$L = \xi L^n + (1-\xi) L^e$
Overall	$S^n = \dfrac{\left\lVert \alpha^n E^n, \beta^n V^n, \gamma^n L^n \right\rVert}{\left\lVert \alpha^n, \beta^n, \gamma^n \right\rVert}$	$S^e = \dfrac{\left\lVert \alpha^e E^e, \beta^e V^e, \gamma^e L^e \right\rVert}{\left\lVert \alpha^e, \beta^e, \gamma^e \right\rVert}$	$S = \dfrac{\left\lVert \alpha E, \beta V, \gamma L \right\rVert}{\left\lVert \alpha, \beta, \gamma \right\rVert}$

2.3 Development of a software tool for sustainability assessment

To assist industrial users in sustainability assessment, the PI's laboratory developed a software tool, named the Industrial Sustainability Evaluation and Enhancement (ISEE) tool in 2011 (Liu and Huang, 2011a,b). The tool had a limited function in terms of the type of sustainability indicators and the calculation method. However, that tool was MetLab based, with a flexible design and system structure for improvement. In this report period, we started to significantly improve it, with main financial support from an NSF-funded project. We have decided to include all the indicators we developed from this AESF project in the tool and to improve its assessment method. Figure 1 shows a design of the home screen of the tool, which is renamed the "Industrial Sustainability Assessment and Enhancement" (ISAE) tool. For this AESF project, we plan to complete its assessment and analysis functions, and use it to conduct a number of case studies on electroplating systems using different technologies.

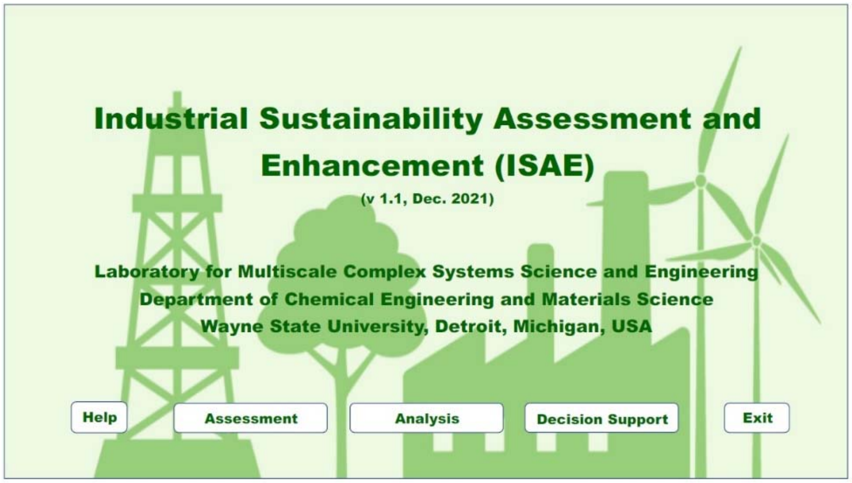
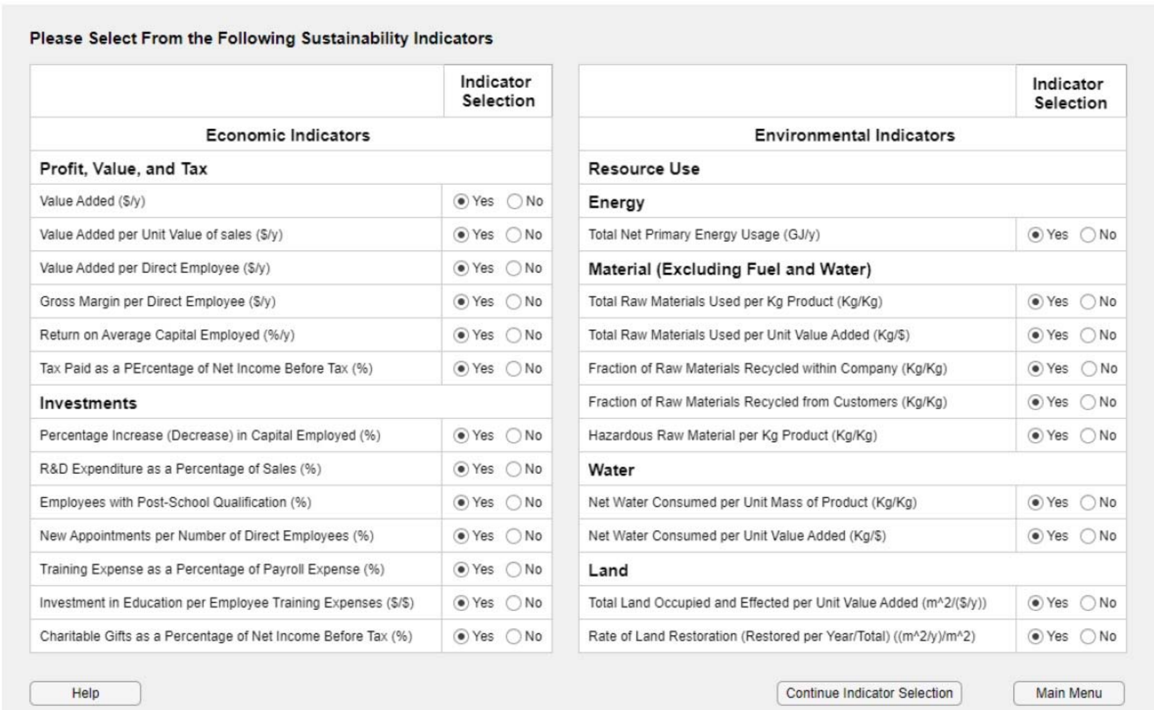


Figure 1 - Home screen design of the ISAE tool.

So far, we have completed part of the Assessment section of the tool, where a large number of sustainability indicators are installed. A user can click on the "Assessment" button in Figure 1. A popup screen will show indicator candidates in different sustainability categories. Figure 2 displays part of the screen. The user can decide which indicators need to be selected for his/her application. As a default, all indicators are marked "Yes" initially. After finishing the indicator selection, the tool will ask the user to enter the parameter data. We will report new progress in the next project reporting period.


Please Select From the Following Sustainability Indicators

Economic Indicators	Indicator Selection
Profit, Value, and Tax	
Value Added ($/y)	(•) Yes ( ) No
Value Added per Unit Value of sales ($/y)	(•) Yes ( ) No
Value Added per Direct Employee ($/y)	(•) Yes ( ) No
Gross Margin per Direct Employee ($/y)	(•) Yes ( ) No
Return on Average Capital Employed (%/y)	(•) Yes ( ) No
Tax Paid as a PErcentage of Net Income Before Tax (%)	(•) Yes ( ) No
Investments	
Percentage Increase (Decrease) in Capital Employed (%)	(•) Yes ( ) No
R&D Expenditure as a Percentage of Sales (%)	(•) Yes ( ) No
Employees with Post-School Qualification (%)	(•) Yes ( ) No
New Appointments per Number of Direct Employees (%)	(•) Yes ( ) No
Training Expense as a Percentage of Payroll Expense (%)	(•) Yes ( ) No
Investment in Education per Employee Training Expenses ($/$)	(•) Yes ( ) No
Charitable Gifts as a Percentage of Net Income Before Tax (%)	(•) Yes ( ) No

Environmental Indicators	Indicator Selection
Resource Use	
Energy	
Total Net Primary Energy Usage (GJ/y)	(•) Yes ( ) No
Material (Excluding Fuel and Water)	
Total Raw Materials Used per Kg Product (Kg/Kg)	(•) Yes ( ) No
Total Raw Materials Used per Unit Value Added (Kg/$)	(•) Yes ( ) No
Fraction of Raw Materials Recycled within Company (Kg/Kg)	(•) Yes ( ) No
Fraction of Raw Materials Recycled from Customers (Kg/Kg)	(•) Yes ( ) No
Hazardous Raw Material per Kg Product (Kg/Kg)	(•) Yes ( ) No
Water	
Net Water Consumed per Unit Mass of Product (Kg/Kg)	(•) Yes ( ) No
Net Water Consumed per Unit Value Added (Kg/$)	(•) Yes ( ) No
Land	
Total Land Occupied and Effected per Unit Value Added (m^2/($/y))	(•) Yes ( ) No
Rate of Land Restoration (Restored per Year/Total) ((m^2/y)/m^2)	(•) Yes ( ) No

Help | Continue Indicator Selection | Main Menu

Figure 2 - Sample page to screen for the indicator selection in the ISAE tool.

3. List of papers presented

In this project period, we presented four papers at three national meetings, as below:

1. A. Siddiqui, R. Potoff and Y. Huang, "Sustainability Assessment of Electroplating Facilities: Metrics System Development," NASF SUR/FIN 2021, Detroit, MI, Nov. 2-4, 2021.
2. A. Siddiqui and Y. Huang, "Methodological Study on Sustainability Assessment and Selection of New Technologies for Process Performance Improvement," Paper No. 269e, presented at the AIChE Annual National Meeting, Boston, MA, Nov. 7-13 (in-person) and Nov. 14-19 (virtual), 2021.
3. A. Siddiqui and Y. Huang, "Reinforced Sustainability Assessment and Decision Making in the Post-COVID-19 Manufacturing Era," Paper No. 732d, presented at the AIChE Annual National Meeting, Boston, MA, Nov. 7-13 (in person) and Nov. 14-19 (virtual), 2021.
4. R. Potoff. A. Siddiqui and Y. Huang, "Sustainability Assessment of Electroplating Systems: A Methodological Study," Council on Undergraduate Research – 2021 Research Experiences for Undergraduates (REU) Symposium, Washington, D.C., Oct. 25, 2021.

4. Plan for the 7th quarter of the project (01/01/22 – 03/30/22)

Three tasks are planned for the next project period, which are briefly described below:

1. We will develop an effective method for weighting factor selection, especially for the selection of the weighting factors that are to be used to perform consolidated sustainability assessment.

2. We will continue the development of the ISAE software tool. For this task, an undergraduate student in chemical engineering at Wayne State University has been appointed as an NSF research assistant by the PI, with financial support from the PI's NSF grant, to work together with the PhD student in the Winter Semester.
3. We will review a number of technologies for possible sustainability performance improvement in electroplating plants. For this task, an undergraduate student in chemistry at SUNY Binghamton University has been appointed as an NSF research assistant by the PI, with financial support also from the PI's NSF grant, to work together with the PhD student in the Winter Semester.

5. 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.
4. Quarter 4 (January-March 2021): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 85 (11), 13 (August 2021); Full paper: http://short.pfonline.com/NASF21Aug1.
5. Quarter 5 (April-June 2021): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 86 (1), 19 (October 2021); Full paper: http://short.pfonline.com/NASF21Oct2
6. Quarter 6 (July-September 2021): Summary: *NASF Report* in *Products Finishing*; *NASF Surface Technology White Papers*, 86 (4), 19 (January 2022); Full paper: http://short.pfonline.com/NASF22Jan3

6. About the Principal Investigator

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.