2020 AESF Research Project (No. R-121)

11TH QUARTERLY PROGRESS REPORT
Reporting Period: 10/01/2022 – 12/31/2022

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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

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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11TH 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 effort is on the continuous development of a computer-aided tool for sustainability assessment and decision making, with a focus on the coding for the decision making. We also presented our research at the AIChE Annual National Meeting in Phoenix, AZ, in mid-November.

In the 7th quarterly report, we described our initial effort on the development of a computer-aided prototype tool, named the Industrial Sustainability Assessment and Enhancement (ISAE) tool. That report included two screenshots shown in Fig's. 1 and 2 below. In the 8th quarterly report, we reported that we hired an undergraduate senior student, who was guided to help develop a number of modules for sustainability assessment. The tool is currently able to assess a process' sustainability performance, after a set of sustainability indicators are selected, and plant data are input.

In this period, we continued the tool development, but with a focus on the addition of functions for assessing technology's capability of improving a process' sustainability performance. These include (1) the construction of a number of user interfaces for entering technology information, (2) the implementation of a methodology for technology assessment, and (3) the implementation of the AHP method based weighting factor determination.

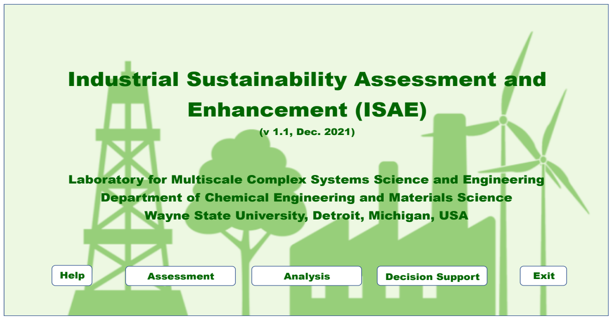

Fig. 1. Home screen design of the ISAE tool.

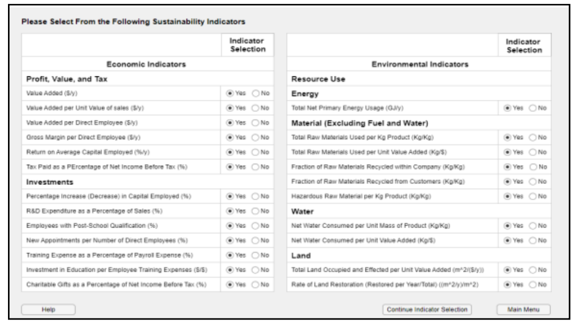

Fig. 2. Sample page to scree for indicator selection in the ISAE tool.

B.1 The ISAE Tool Development – Interface Design for Technology Information Acquisition

The Matlab tool starts with previously submitted data based on the sustainability assessment section. From this point, a tool user (or called a decision maker) needs to input the anticipated economic, environmental, and social sustainability goals into the tool through an input dialog box shown in Fig. 3(a). Once the sustainability goals have been inputted, the budget of the facility committed for the project is then to be input in a dialog box shown in Fig. 3(b). Then the tool prompts the user to input the number of technologies that are to be evaluated for adoption. Let the total number of individual technologies be N. It is possible that a plant needs to use multiple technologies for performance improvement eventually. Thus, given N individual technology candidates, the total number of technology sets, each of which can contain one, two, or even all N technologies, can be calculated as:

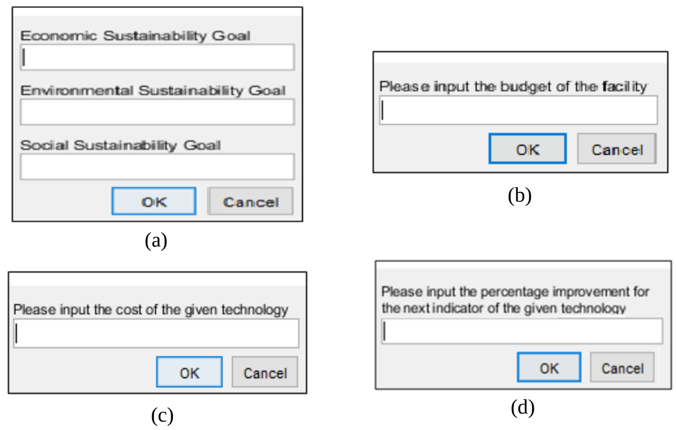

Fig. 3. Tool interface design for the input of: (a) sustainability goal setting, (b) budget limit, (c) technology cost, and (d) technology performance.

$$N_{Tech} = 2^N - 1 \tag{1}$$

where N_{Tech} is the total number of technology sets. The tool then prints out each technology set and asks the user to input regarding the cost of adopting that technology sets (see Fig. 3(c)) as well as the percentage improvement data (see Fig. 3(d)).

B.2 Module Development for Evaluating Technology Set's Sustainability Performance and the Process Performance Improvement after Technology Set Implementation

With all necessary data and information about technology sets and the plant's expectation on the minimum performance improvement, the ISAE tool should contain the methodology for technology evaluation. Note that each technology set must be evaluated for its capacity for performance improvement. The following equations are being implemented in the tool:

$$E_i\left(P \mid T_j\right) = E_i\left(P\right) + \Delta E_i\left(P \mid T_j\right) \tag{2}$$

$$V_i\left(P \mid T_j\right) = V_i\left(P\right) + \Delta V_i\left(P \mid T_j\right) \tag{3}$$

$$L_i\left(P \mid T_j\right) = L_i\left(P\right) + \Delta L_i\left(P \mid T_j\right) \tag{4}$$

where $E_i(P)$, $V_i(P)$, and $L_i(P)$ are, respectively, the individual indicator-based economic, environmental, and social sustainability assessment results of the facility; $\Delta E_i(P|T_j)$, $\Delta V_i(P|T_j)$, and $\Delta L_i(P|T_j)$ are, respectively, the indicator-based performance change of economic, environmental, and social sustainability if technology set T_j is adopted; $E_i(P|T_j)$, $V_i(P|T_j)$, and $L_i(P|T_j)$ are, respectively, the indicator-based performance of economic, environmental, and social sustainability if technology set T_j is implemented in the plant.

Each technology set needs to be evaluated by all sustainability indicators separately. The evaluation results will be combined to derive the categorized sustainability ($E(P|T_j)$, $V(P|T_j)$, and $L(P|T_j)$) using the following equations:

$$E(P|T_j) = \sum_{i=1}^{N_E} a_i E_i(P|T_j) \quad (5)$$

$$V(P|T_j) = \sum_{i=1}^{N_V} b_i V_i(P|T_j) \quad (6)$$

$$L(P|T_j) = \sum_{i=1}^{N_L} c_i L_i(P|T_j) \quad (7)$$

where N_E, N_V, and N_L are, respectively, the total number of indicators in the economic, environmental, and social sustainability categories; a_i, b_i, and c_i are the weighing factors for the corresponding indicators in the economic, environmental, and social sustainability categories.

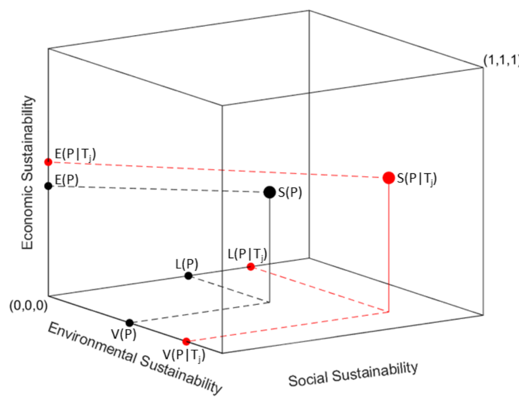

Fig. 4. Design of a module for demonstrating of technology based sustainability performance improvement..

The above equations and the nine-step optimal technical solution method listed in the 10th quarterly report are being coded in the ISAE tool. Figure 4 shows a design of the module in the tool that demonstrates technology based sustainability performance of an electroplating facility before and after implementing a technology set in a sustainability cube. It shows clearly how the process sustainability performance is changed, through comparing the values of $E(P)$ vs $E(P|T_j)$, $V(P)$ vs $V(P|T_j)$, $L(P)$ vs $L(P|T_j)$, and the overall sustainability, i.e., $S(P)$ vs $S(P|T_j)$.

B.3 Module for Weighting Factor Determination by the AHP Method

In the 6th quarterly report, we presented a case study that contained the values of 11 weighting factors that were associated with 11 sustainability indicators; those values were summarized in in a table of that report, which is copied on the right side. Those values were calculated using the AHP method, originally developed by Thomas Saaty in 1980. The method needs to be fully implanted in the ISAE tool. Here we list all equations that are being coded.

Table. Weighing Factors

Weighing Factor	Assigned Indicator	Factor Value
a_1	E_1	3.51
a_2	E_2	3.51
a_3	E_3	1.09
a_4	E_4	1.89
b_1	V_1	0.62
b_2	V_2	1.53
b_3	V_3	1.53
b_4	V_4	6.32
c_1	L_1	2.79
c_2	L_2	0.72
c_3	L_3	6.49

1. <u>Determination of relative importance of sustainability indicators for assessment</u>. The relative importance of each pair of sustainability indicators, e.g., environmental indicators V_i vs V_j, needs to be determined by the decision maker using Saaty's AHP method shown in Table 1.

2. Construction of a relative importance matrix. The relative importance matrix, M_{AHP} , has the following structure. For a categorized sustainability using N indicators, the matrix is:

$$M_{AHP} = \begin{bmatrix} W_{1,1} & W_{1,2} & \cdots & W_{1,N} \\ W_{2,1} & W_{2,2} & \cdots & W_{2,N} \\ \vdots & \vdots & \vdots & \vdots \\ W_{N,1} & W_{N,2} & \cdots & W_{N,N} \end{bmatrix} \quad (8)$$

Table 1. Relative Importance for AHP Method

Relative Importance	Definition
1	Equal Importance
3	Somewhat More Important
5	Much More Important
7	Very Much More Important
9	Absolutely More Important
2,4,6,8	Intermediate Values

where $W_{i,j}$ is the relative importance between the i-th and j-th vectors. Note that $W_{i,j} = 1$ if $i = j$; $W_{i,j} = \frac{1}{W_{j,i}}$ $i \neq j$.

3. Calculation of weighting factors. There are a few steps to follow in the calculation of weighting factor vector ; they are:

$$M_{NR} = \begin{bmatrix} NR_1 \\ NR_2 \\ \vdots \\ NR_N \end{bmatrix} \quad (9)$$

$$NR_T = \sum_{i=1}^{N} NR_i \quad (10)$$

where M_{NR} is the matrix of the nth roots; NR_i is i-th root of the products of the factors in i-th row; NR_T is the sum of all the roots.

$$\alpha_{AHP} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_N \end{bmatrix} \quad (11)$$

$$\alpha_i = \frac{NR_i}{NR_T} \quad (12)$$

where α_i is the weighing factor of i-th indicator.

4. Consistency checking. To confirm the consistency of the calculated weight factor values, the following formulas need be coded also.

$$\vec{\rho}_{AHP} = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \vdots \\ \rho_N \end{bmatrix} = \alpha_{AHP} \times M_{AHP} \quad (13)$$

$$\vec{\lambda}_{AHP} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \end{bmatrix} = \frac{\rho_{AHP}}{\alpha_{AHP}} \tag{14}$$

$$\lambda_{Ave} = \frac{\sum_{i=1}^{N} \lambda_i}{N} \tag{15}$$

$$CI = \frac{\lambda_{Ave} - N}{N - 1} \tag{16}$$

$$CR = \frac{CI}{\eta} \tag{17}$$

where $\vec{\rho}_{AHP}$ is the vector resulting from multiplying the eigenvector to the AHP matrix; λ_i is the estimate for the eigenvalue from the i-th row; λ_{Ave} is the average of the eigen value estimates; CI is the consistency index; CR is the consistency ratio; η is the Saaty consistency index denominator.

Example. We have tested the calculation for four environmental vectors, V_1 to V_4, using the formulas listed above. Table 2 shows the relative importance value between each pair of indicators. Using the method, the following matrix and vectors are obtained:

$$M_{AHP,Env} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{3} & \frac{1}{7} \\ 3 & 1 & 1 & \frac{1}{5} \\ 3 & 1 & 1 & \frac{1}{5} \\ 7 & 5 & 5 & 1 \end{bmatrix} \tag{18}$$

Table 2. Relative Importance Assignment for Four Environmental Indicators

Indicators	V_1	V_2	V_3	V_4
V_1	1	1/3	1/3	1/7
V_2	3	1	1	1/5
V_3	3	1	1	1/5
V_4	7	5	5	1

$$M_{NR,Env} = \begin{bmatrix} 0.355 \\ 0.880 \\ 0.880 \\ 3.637 \end{bmatrix} \tag{19}$$

The weighting factors, b_1 to b_4, for environmental indicators V_1 to V_4, are derived below, which are the same as those shown in the table on page 4.

$$B_{AHP} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0.62 \\ 1.53 \\ 1.53 \\ 6.32 \end{bmatrix} \tag{20}$$

We also obtained the results for the consistency ratio as follows:

$$\vec{\lambda}_{AHP} = \begin{bmatrix} 4.10 \\ 4.04 \\ 4.04 \\ 4.11 \end{bmatrix} \tag{21}$$

$$\lambda_{Ave} = 4.0725 \tag{22}$$

$$CI = 0.024 \tag{23}$$

$$CR = 0.027 \tag{24}$$

Since the consistency ratio value (CR) is below 0.1, the weighting factors shown in Eq. (21) are consistent. The implementation of the AHP-based weighting factor derivation is general for any type of sustainability problems.

B.4 Presentation Activities

In this period, the PI and his students presented three papers as follows, each of which has a focus on sustainable metal finishing:

Huang, Y., "Life-Cycle-Based Multiscale Sustainability: Challenges and Opportunities in the Era of Industry 4.0," plenary speech at the AIChE Annual National Meeting in Phoenix, AZ, Nov. 13-18, 2022.

Siddiqui, A., M. Moghadasi, and Y. Huang, "Plant-Wide Digital Twinning of Surface Finishing for Sustainable Manufacturing," Paper No. 86c, presented at the AIChE Annual National Meeting, Phoenix, AZ, Nov. 13-18, 2022.

Siddiqui, A. and Y. Huang, "Technology Assessment and Impact Analysis for Life Cycle-Based Sustainability Improvement," Paper No. 613a, presented at the AIChE Annual National Meeting, Phoenix, AZ, Nov. 13-18, 2022.

C. PLAN FOR THE 12TH 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.