2020 AESF Research Project (No. R-121)

13TH QUARTERLY PROGRESS REPORT
Reporting Period: 04/01/2023 – 06/30/2023

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Submission Date: July 15, 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 – 03/31/2024

A. STUDENT PARTICIPATION

Abdurrafay Siddiqui and Mahboubeh Moghadasi, two PhD students in the PI's group, conducted research in this reporting period. They are financially supported mainly by Wayne State University's Graduate Teaching Assistantship Program, and partially by National Science Foundation and this AESF research project.

In addition, Ryan Kitelinger, an undergraduate student of chemical engineering at Florida Institute of Technology, is hired for the PI's another NSF grant, which is for supporting him to conduct 10-week research in the PI's lab during the Summer Academy of Sustainable Manufacturing at Wayne State University, which started on June 1, 2023.

B. SUMMARY OF PROJECT ACTIVITIES

Under the PI's supervision, the student research activities are summarized below:

Abdurrafay Siddiqui: Continuously develop a computer-aided tool, namely ISAE (Industrial Sustainability Assessment and Enhancement) tool. The tool development of different phases was reported in the 7th, 8th, 9th, and 11th quarterly reports. In this reporting period, Abdurrafay implements a technology assessment and selection methodology and tests it through a case study.

Mahboubeh Moghadasi: Focus on the development of a set of digital twins (DTs) using the physics-informed neural network (PINN) technology. She has been making impressive progress in learning PINN fundamentals, writing computer codes using Python – a high-level, general-purpose programming language, and simulating a PINN-based cleaning-rinsing system model set. We intend to make the PINN model much more robust than the fundamental models we developed before, as the PINN model will have its key model parameters continuously updated based on real-time dynamic data.

Ryan Kitelinger: Lean the fundamentals of electroplating and engineering sustainability through literature survey, and conduct computer simulation of a cleaning-rinsing model set. The student presents his work during the PI's lab group's meetings and the Summer Academy at Wayne State once a week. The student has shown his strong interest in electroplating and his ability of using chemical engineering fundamentals to study electroplating sustainability problems, including how to identify opportunities for reducing chemical and water consumption, while the cleaning and rinsing quality can be guaranteed.

Conference attendance and presentation. The PI and his two PhD students attended the SUR/FIN Conference in Cleveland, OH, June 6, 2023. We presented the following two papers: (1) Siddiqui, A. and Y. Huang, "Industrial Sustainability Assessment and Enhancement (ISAE) Tool", and (2) Moghadasi, M. and Y. Huang, "Digital Twin-Based Dynamic Sustainability Assessment of Electroplating Facilities". The two students discussed their research with industrial practitioners during the conference, which were very beneficial to them.

Note: Both PhD students submitted their individual research progress reports to the PI, one on the ISAE tool development and a case study (13 pages), and the other on PINN development (18 pages). However, the PI decides to report the ISAE tool development and case study in this report. The PINN part will be reported in the next quarterly report, which will contain more research results in the following months.

C. ISAE Tool Development and Case Study

We have been continuously enhancing the computer-aided tool, named Industrial Sustainability Assessment and Enhancement (ISAE). In this reporting period, we have enhanced the tool further by implementing the sustainability assessment of technologies and the technology selection methodology, and then tested the tool's capability for plant sustainability performance improvement.

Technologies and data. We selected two technologies, which we developed before: Tech 1 – an environmentally benign cleaning rinsing and technology that can reduce chemical and water consumption in a cleaning-rinsing system, and Tech 2 – a water reuse technology to minimize wastewater generation in plating lines. Table 1 shows the selected sustainability indicators and the facility data collected for sustainability indicator evaluation. The data was collected from the National Center for Manufacturing Sciences' Benchmarking Metal Finishing (NCMS, 2000) and the PI's early publications. The data are then normalized for the use of ISAE, which are summarized in Table 2.

Table 1. Sustainability Indicators and Data for Case Study

Sustainability Indicator	Value Range		Facility	Tech. 1	Tech. 2
	Best	Worst			
Economic					
Value Added ($)	500,000	100,000	225,000	240,000	235,000
R&D Expenditure as Percentage of Sales (%)	15%	5%	7%	10%	9%
Investment on Education per Employee Training Expenses ($/$)	0.55	0.3	0.43	0.48	0.46
Charitable Gifts as a Percentage of New Income Before Tax (%)	7%	0%	3%	3%	3%
Environmental					
Total Raw Materials Used per Unit Value Added (Kg/$)	20	90	45	45	45
Net Water Consumed per Unit Value Added (Kg/$)	3	64	30	25	15
Hazardous Solid Waste per Unit Value Added (Kg/$)	0.01	0.04	0.04	0.04	0.04
Fraction of Raw Material Recycled within Company (%)	40%	0%	10%	10%	20%
Human Health Burden per Unit Value Added (t/$)	0.0012	0.005	0.0031	0.0034	0.0037
Social					
Benefits as a Percentage of Payroll Expense (%)	14%	5%	7%	7%	7%
Working Hours Lost as a Percentage of Total Hours Worked (%)	12%	25%	17%	20%	14%
Indirect Community Benefit per Unit Value Added ($/$)	0.3	0.06	0.19	0.22	0.25

Table 2. Normalized Indicator Values of the Facility and the Two Technologies

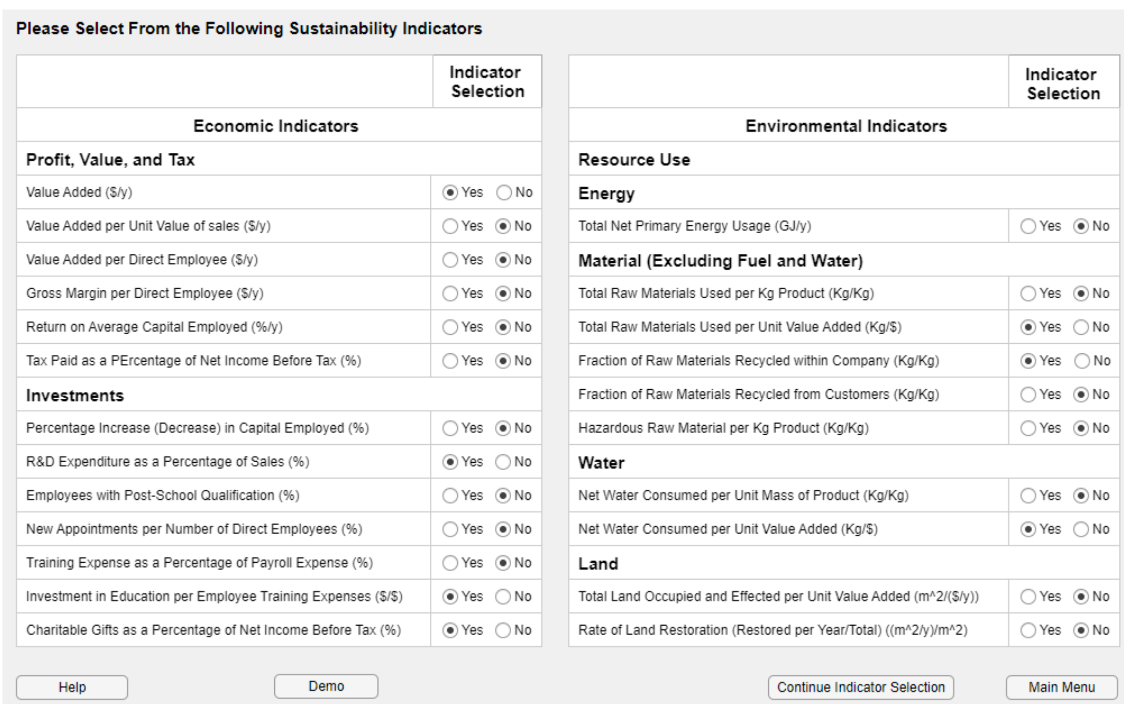
Sustainability Indicator	Facility	Tech. 1	Tech. 2
Economic			
Value Added ($)	0.31	0.35	0.34
R&D Expenditure as Percentage of Sales (%)	0.20	0.50	0.40
Investment on Education per Employee Training Expenses ($/$)	0.52	0.72	0.64
Charitable Gifts as a Percentage of New Income Before Tax (%)	0.43	0.43	0.43
Environmental			
Total Raw Materials Used per Unit Value Added (Kg/$)	0.64	0.64	0.64
Net Water Consumed per Unit Value Added (Kg/$)	0.56	0.64	0.80
Hazardous Solid Waste per Unit Value Added (Kg/$)	0.00	0.00	0.00
Fraction of Raw Material Recycled within Company (%)	0.25	0.25	0.50
Human Health Burden per Unit Value Added (t/$)	0.50	0.42	0.34
Social			
Benefits as a Percentage of Payroll Expense (%)	0.22	0.22	0.22
Working Hours Lost as a Percentage of Total Hours Worked (%)	0.62	0.38	0.85
Indirect Community Benefit per Unit Value Added ($/$)	0.54	0.67	0.79

User interface and functions. The home screen of the ISAE tool is shown in Fig. 1. The tool has three clickable bottoms, named "Assessment" (for conducting sustainability assessment), "Analysis" (for performing sustainability analysis based on the assessment result), and "Decision Making" (for deriving solutions for sustainability performance improvement).

Fig. 1.The home screen of the ISAE tool.

Sustainability indicator selection. As the first task for using the tool, a user needs to select a set of economic, environmental, and social indicators. The selected indicators will be used for evaluating (i) the sustainability performance of an electroplating facility, and (ii) the two listed technologies' capacity for performance improvement.

As shown in Table 1, a total of 12 indicators are listed, including 4 economic indicators, 5 environmental indicators, and 3 social indicators. Thus, in Fig's. 2 and 3, these 12 indicators are selected (see the selection of "Yes" that is associated with each individual indicator).



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 | Demo | Continue Indicator Selection | Main Menu

Fig. 2. Selection of economic and environmental (the 1st part) indicators.

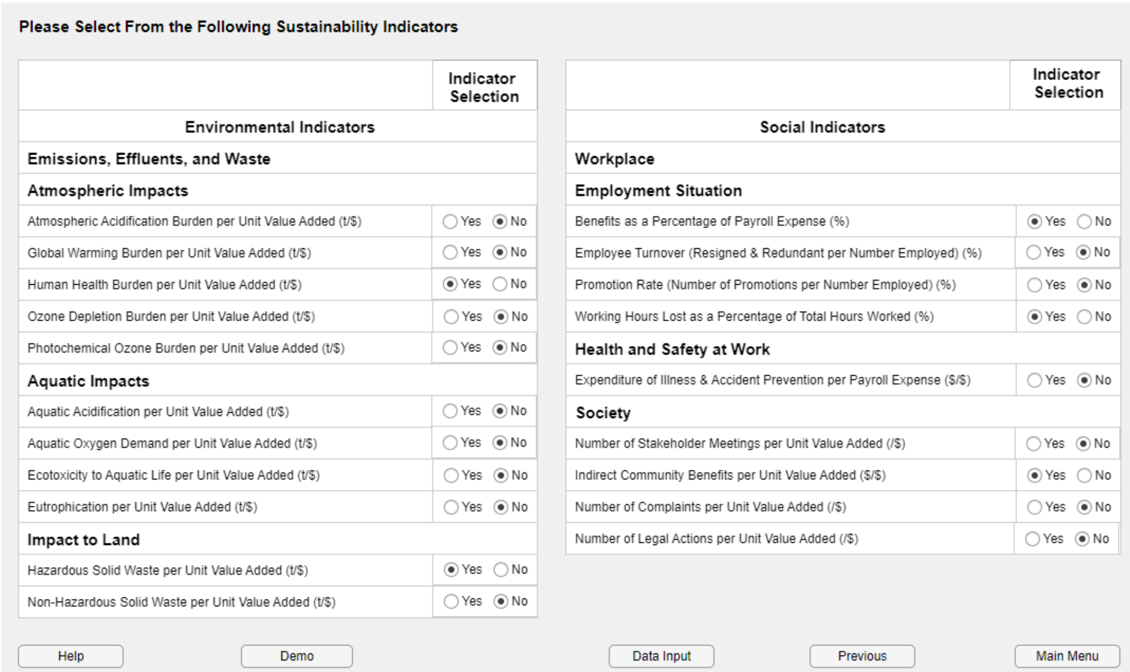


Fig. 3. Selection of environmental (the 2nd part) and social indicators.

Data input of sustainability assessment. Once the indicators are chosen, the next step is to input the normalized sustainability assessment results shown in Table 2 into the ISAE tool (by clicking on the “Assessment” tab shown in Fig. 1). Figures 4 and 5 show the data input for the electroplating facility being studied.

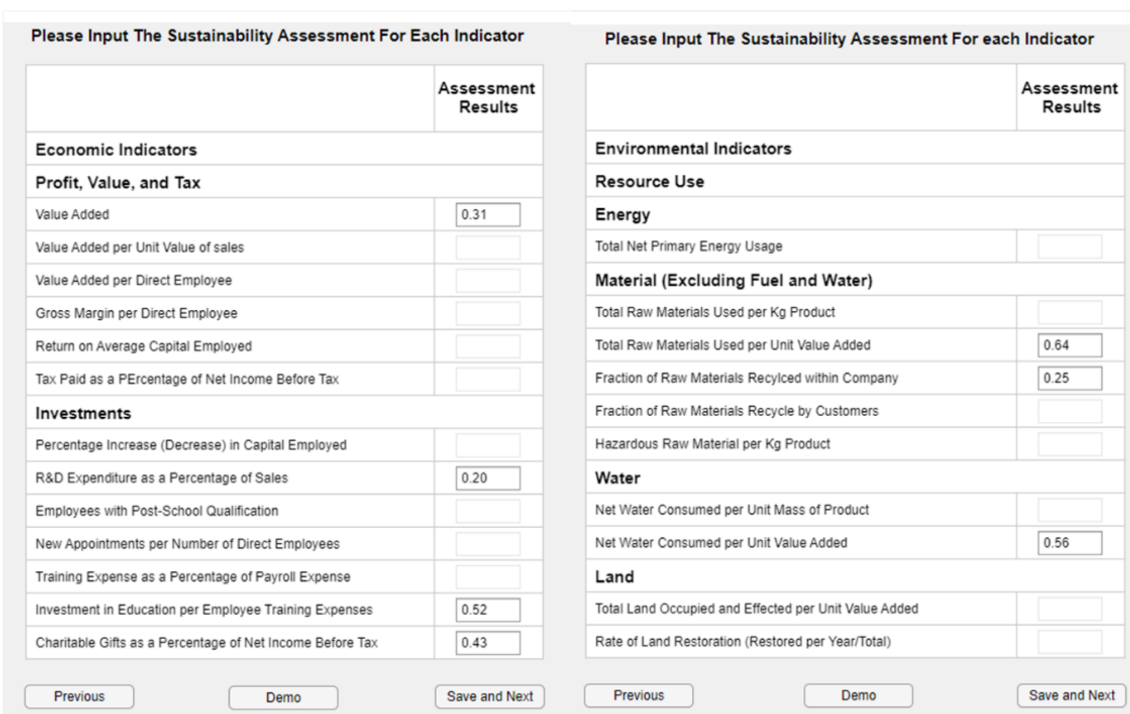


Fig. 4. Data input for the selected economic and environmental (the 1st part) indicators.

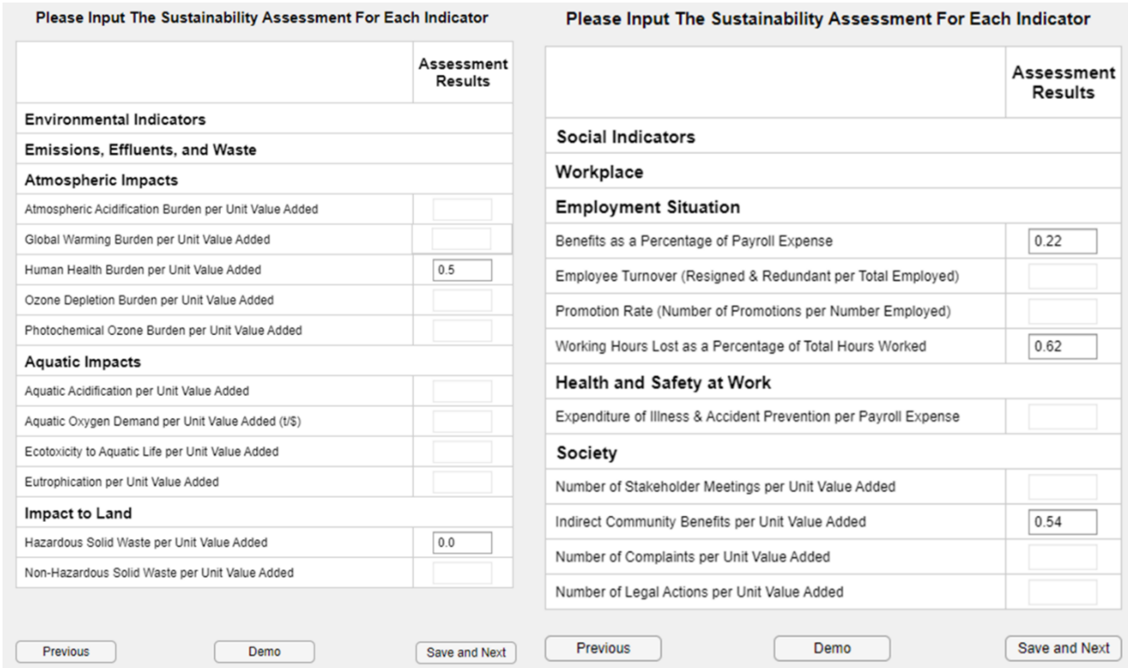


Fig. 5. Data for the selected environmental (the 2nd part) and social indicators.

Data input of the cost for technology adoption. After inputting the assessment results shown in Table 2, the user needs to click on the "Decision Making" tab to let the ISAE tool analyze the technologies and select the best one, but this requires input of additional information. The user is prompted to input the number of technologies and the budget of each technology if adopted. Figure 6 shows a window for input the cost data of the adoption of each of the two technologies, which are $47,000 for Tech. 1 and $32,000 for Tech. 2.

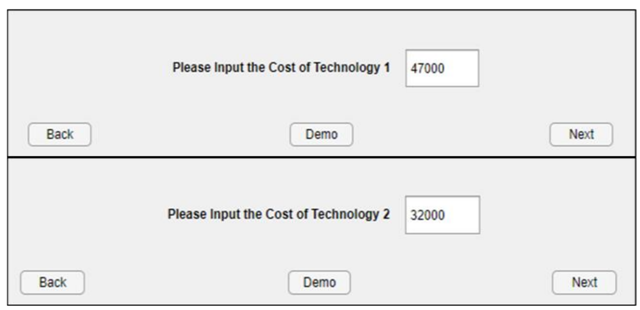


Fig. 6. Input of the cost data for Techs 1 and 2.

Data input of the facility's budget commitment and sustainability goal. In order to identify a technical solution for a facility's sustainability performance improvement, the user must let the ISAE tool know the following: (1) the budget commitment by the facility, and (2) the facility's expectation of the sustainability performance improvement, after known the current sustainability performance of the facility. In this case, the budget committed is $80,000, and the economic, environmental, and social sustainability goals are set to 0.55, 0.50, and 0.60, respectively. Figure 7 demonstrates a tool's interface for the users to enter these data. Note that the figure also shows a set of other data: 0.37 as the "Current Economic Sustainability", 0.39

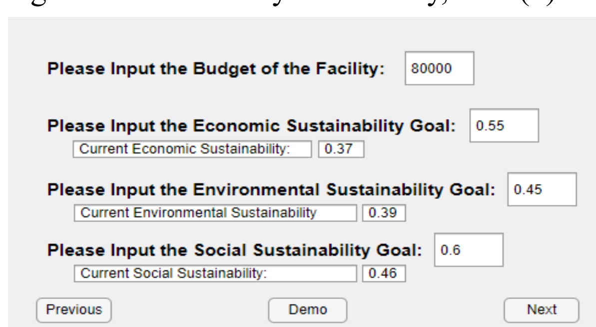
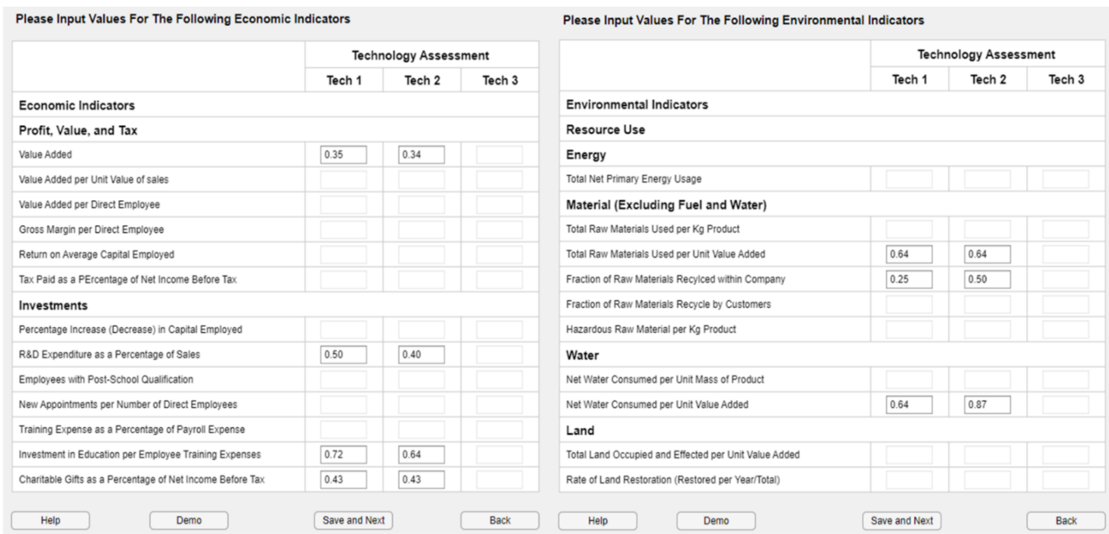


Fig. 7. Sustainability goal and budget input.

as the “Current Environmental Sustainability”, and 0.48 as the “Current Social Sustainability”. These data were calculated by the ISAE tool, based on the indicator-based sustainability assessment results shown in Table 2 (see the data in the column titled “Facility”. The calculation method was reported in the 3rd quarterly report submitted in Jan. 2021.

Data input of the technology’s sustainability improvement capacity. In Table 2, the right two columns contain the indicator-based sustainability performance improvement capacity of each of the two technologies. The calculation method was reported in the 8th quarterly report submitted in April 2022. The method needs to be implemented in the tool later. Figures 8 and 9 show the data input into the tool.


Please Input Values For The Following Economic Indicators

	Technology Assessment		
	Tech 1	Tech 2	Tech 3
Economic Indicators			
Profit, Value, and Tax			
Value Added	0.35	0.34	
Value Added per Unit Value of sales			
Value Added per Direct Employee			
Gross Margin per Direct Employee			
Return on Average Capital Employed			
Tax Paid as a PErcentage of Net Income Before Tax			
Investments			
Percentage Increase (Decrease) in Capital Employed			
R&D Expenditure as a Percentage of Sales	0.50	0.40	
Employees with Post-School Qualification			
New Appointments per Number of Direct Employees			
Training Expense as a Percentage of Payroll Expense			
Investment in Education per Employee Training Expenses	0.72	0.64	
Charitable Gifts as a Percentage of Net Income Before Tax	0.43	0.43	

Help Demo Save and Next Back

Please Input Values For The Following Environmental Indicators

	Technology Assessment		
	Tech 1	Tech 2	Tech 3
Environmental Indicators			
Resource Use			
Energy			
Total Net Primary Energy Usage			
Material (Excluding Fuel and Water)			
Total Raw Materials Used per Kg Product			
Total Raw Materials Used per Unit Value Added	0.64	0.64	
Fraction of Raw Materials Recylced within Company	0.25	0.50	
Fraction of Raw Materials Recycle by Customers			
Hazardous Raw Material per Kg Product			
Water			
Net Water Consumed per Unit Mass of Product			
Net Water Consumed per Unit Value Added	0.64	0.87	
Land			
Total Land Occupied and Effected per Unit Value Added			
Rate of Land Restoration (Restored per Year/Total)			

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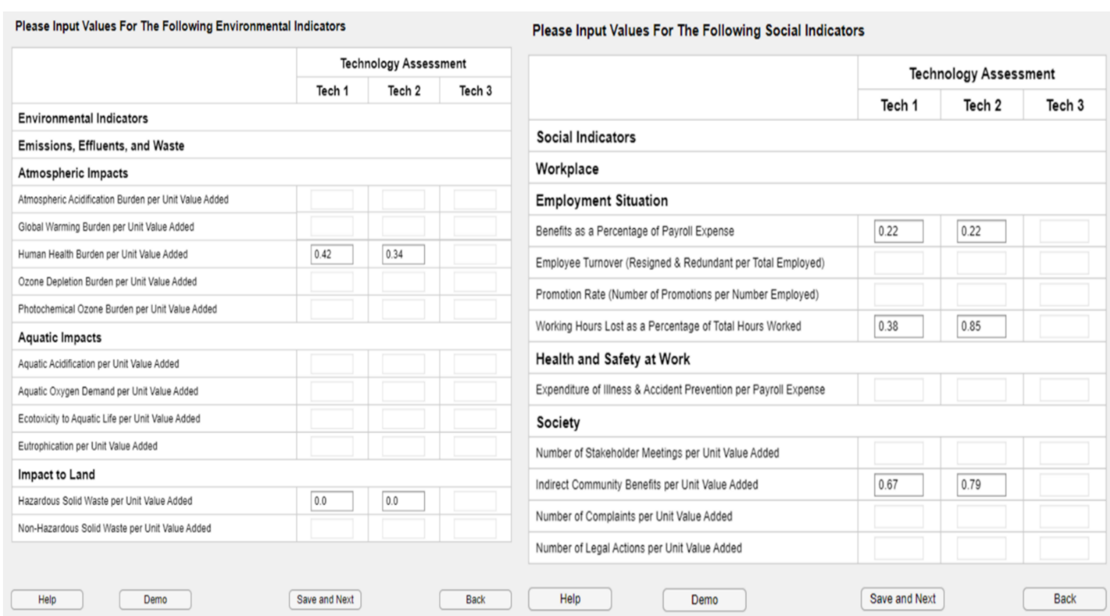
Fig. 8. Data input for the selected economic and environmental (the 1st part) indicators.


Please Input Values For The Following Environmental Indicators

	Technology Assessment		
	Tech 1	Tech 2	Tech 3
Environmental Indicators			
Emissions, Effluents, and Waste			
Atmospheric Impacts			
Atmospheric Acidification Burden per Unit Value Added			
Global Warming Burden per Unit Value Added			
Human Health Burden per Unit Value Added	0.42	0.34	
Ozone Depletion Burden per Unit Value Added			
Photochemical Ozone Burden per Unit Value Added			
Aquatic Impacts			
Aquatic Acidification per Unit Value Added			
Aquatic Oxygen Demand per Unit Value Added			
Ecotoxicity to Aquatic Life per Unit Value Added			
Eutrophication per Unit Value Added			
Impact to Land			
Hazardous Solid Waste per Unit Value Added	0.0	0.0	
Non-Hazardous Solid Waste per Unit Value Added			

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Please Input Values For The Following Social Indicators

	Technology Assessment		
	Tech 1	Tech 2	Tech 3
Social Indicators			
Workplace			
Employment Situation			
Benefits as a Percentage of Payroll Expense	0.22	0.22	
Employee Turnover (Resigned & Redundant per Total Employed)			
Promotion Rate (Number of Promotions per Number Employed)			
Working Hours Lost as a Percentage of Total Hours Worked	0.38	0.85	
Health and Safety at Work			
Expenditure of Illness & Accident Prevention per Payroll Expense			
Society			
Number of Stakeholder Meetings per Unit Value Added			
Indirect Community Benefits per Unit Value Added	0.67	0.79	
Number of Complaints per Unit Value Added			
Number of Legal Actions per Unit Value Added			

Help Demo Save and Next Back

Fig. 9. Data input for the selected environmental (the 1st part) and social indicators.

Technical solution identification. After the input of all necessary information, the tool will do computations and output the results with the following possibilities: one or more solutions identified, or no solution. In this case, one solution is identified, i.e., both two technologies must be used, and the total cost is $77,000. The achieved economic, environmental, and social sustainability performances are 0.58, o.49, and 0.63, respectively, which are better than the preset goals listed in Fig. 6, i.e., 0.55 for economic, 0.45 for environmental, and 0.60 for social. The result is shown in Fig. 10, where a sustainability cube plotted provides the sustainability performance of the facility before and after technology adoption. It also reports that Tech. 1 or Tech. 2 alone is incapable of helping the facility to achieve preset sustainable goals.

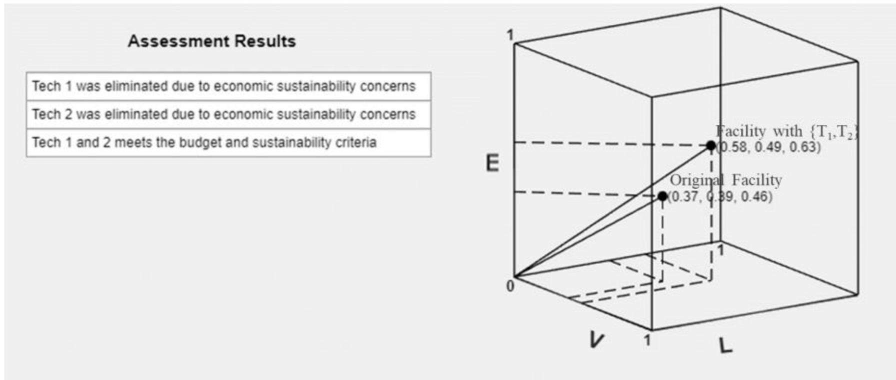

Fig. 10. Report on technical solution identification.

Discussion. As stated, the ISAE tool for solution derivation can lead to the generation of two types of reports:

(1) Successful solution identification, which means one or two solutions are identified. Detailed information of each solution includes the technology name(s) and sustainability performance data (before and after technology adoption), and the cost for technology adoption. The case study described above is a successful example.

(2) No solution identified. It will report the reasons for no solution, which may include, e.g., the low commitment of funds for technology adoption, technology's incapability of achieving the preset economic, or environmental, or social sustainability goal(s). In the case study, we encountered these types of problems. These included: (a) an initial lower budget commitment of $60,000, and (2) an environmental sustainability goal of 0.50. With the report from the ISAE tool, we readjusted the budget to $80,000, and the goal for environmental goal to 0.45.

D. REFERENCES

Gong JP, Lou KG, Huang Y (1997) Dynamic modeling and simulation for environmentally benign cleaning and rinsing. Plat. Surf. Finish. 84:63-70.

NCMS (National Center for Manufacturing Sciences) (2000) Benchmarking metal finishing (No. 0076RE00). Ann Arbor, MI.

Yang YH, Lou HR, Huang Y (1999) Optimal design of a water reuse system in an electroplating plant. Plat. Surf. Finish. 86:80-84.

E. PLAN FOR THE NEXT QUARTER

We plan to report our new progress on the tool development and on new case studies. In addition, we will report our research on the digital twin study with application of the Physics-Informed Neural Network (PINN) technology for an electroplating system.