ORIGINAL PAPER

Sustainability metrics and technical solution derivation for performance improvement of electroplating facilities

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Abstract

The electroplating industry has been highly environmentally regulated due to the use of a 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 evaluate the sustainability performance of facilities and technology candidates, and a holistic solution method for identifying optimal technologies for the system's sustainability performance improvement. We take into account uncertainty in data and the relative improvement of sustainability based on technologies while using the analytical hierarchical process (AHP) for a more systematic and uniform way of determining weighting factors. The methodological efficacy is demonstrated through a case study on five electroplating facilities. The results show the economic, environmental, and social sustainability performances as well as technical solutions for the evaluation of seven technology sets for each facility. The results also show the practical applications of the assessment methodology such as the identification of the misallocation of funds or increases in profitability.

Graphical abstract
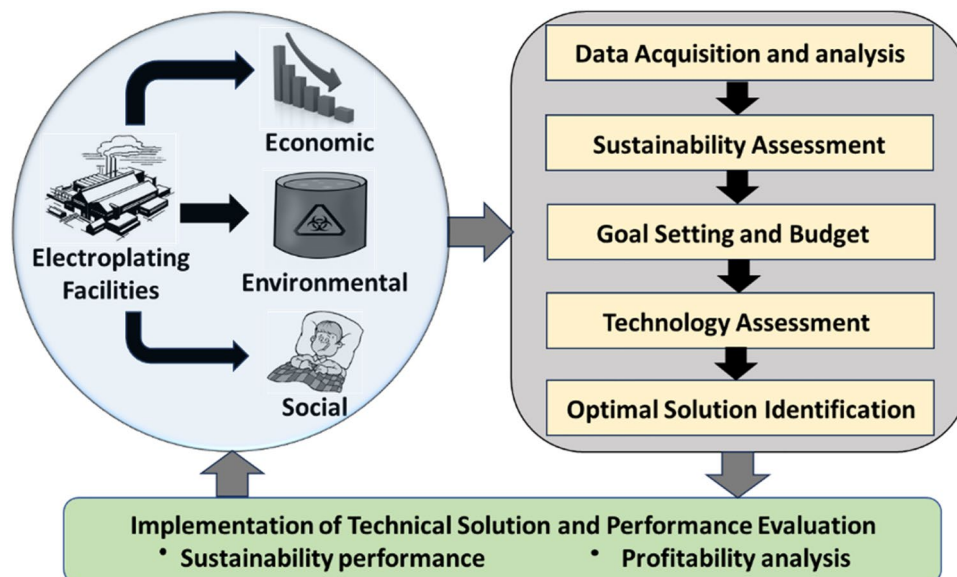
Keywords Sustainability metrics system · Electroplating · Technology assessment · Sustainable manufacturing

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Introduction

The electroplating sector is critical to many manufacturing industries, such as automotive, aerospace, electronics, defense, as well as a variety of Original Equipment Manufacturers (OEMs). This is because finishing on surfaces can have a major effect on the performance, durability, and/or esthetic appearance of workpieces (Lou and Huang 2006). In the USA, there are 4745 metal plating & treating businesses as of 2023 (IBIS World 2023). The sector has been highly regulated by the United States Environmental Protection Agency for decades due to its significant use of a variety of toxic/hazardous chemicals and the generation of large amounts of waste in various forms, which could be extremely harmful to the environment, human health and communities, as well as facilities' financial performance. A recent benchmarking survey on a large number of electroplating facilities also shows that about 80% of the facilities ran at a low profit margin (6% in 2016; 5% in 2017) (Pennington 2018). From the industrial sustainability point of view, these are all sustainability problems that need be holistically studied, and solution strategies be systematically developed.

Electroplating facilities mostly fall under the umbrella of small- and medium-sized manufacturers (SMMs). As shown by Shields and Shelleman (2015), SMMs understand the importance of implementing sustainability principles in business. However, these same authors explain that most of these SMMs, including electroplating facilities, seem to lack a deep understanding of sustainability and seek effective tools for developing strategic goals for short- to long-term sustainable development. In particular, a key challenge identified by these authors was the lack of a structure to integrate sustainability decisions into business planning. Based on this, it is clear that systematic, simple, yet effective sustainability assessment, analysis, and decision-making methodologies are needed.

The central concept of sustainability is triple-bottom-line (TBL)-based, requiring the measurement of economic, environmental, and social sustainability performances. TBL is usually coupled with indicators in three sustainability dimensions. Braccini and Margherita (2018) conducted a TBL-based study on the sustainability of a ceramic manufacturing facility. Wilcox et al. (2016) used TBL as a framework to review water reuse networks. McWilliams et al. (2016) reported a data envelopment analysis through the lens of TBL to determine tradeoffs in decision making. Hernandez-Betancur et al. (2019) applied TBL and the GREENSCOPE methodology to choose indicators, where uncertainty issues were addressed. Gani et al. (2022) studied the influence among indicators with sensitivity analysis.

Early efforts for sustainable electroplating were on environmentally benign manufacturing. Lou and Huang (2000) introduced the concept and fundamentals of so-called profitable pollution prevention (P3), where both economic incentives and environmental cleanness are simultaneously emphasized. Subsequently, a number of P3 technologies were developed for sustainable electroplating including a switchable water allocation network (Zhou et al. 2001), an optimization procedure for cleaning and rinsing (Zhou and Huang 2002), a cyclic hoist scheduling technology (Xu and Huang 2004), a reversed drag out technology (Xu and Huang 2005), a near-zero discharge technology (Xu et al. 2005), an environmentally benign hoist scheduling technology (Kuntay et al. 2006), and an artificial intelligence-based cleaner production evaluation system (Telukdarie et al. 2006). Later, the P3 theory was extended to Collaborative P3 (CP3) by addressing certain issues in the social dimension (Piluso and Huang 2009), and Integrated P3 (IP3) that applied an integrated modeling, analysis, and optimization method for P3 technology applications in electroplating systems (Xiao and Huang 2012). More recently studies include the use of game theory (Yan et al. 2021), petri net modeling (Nait-Sidi-Moh and El-Amraoui 2016), model predictive control methods (Becha et al. 2017), and mixed integer optimization techniques (Wang et al. 2019) to improve electroplating process operation and production. However, these works are lacking in the discussion of comprehensive TBL-based issues. It is necessary for the electroplating industry to have a sustainability metrics system that can be used to evaluate the sustainability performance of electroplating facilities and identify pressing sustainability issues.

The sustainability performance problems identified through TBL-based assessment can be solved by technical and/or nontechnical approaches. Technical approaches are usually about the improvement of existing technologies or the adoption of new ones. This renders a need for technology assessment in the sustainability context and decision making for optimal technology selection. Liu and Huang (2012) introduced a simple, yet systematic methodology for identifying rapidly superior solutions for sustainability performance improvement under uncertainty. The methodology is general enough for the study of sustainability enhancement problems of any size and scope, and its efficacy was demonstrated in a sophisticated study on sustainable development of biodiesel manufacturing.

This paper is focused on bringing all these ideas, from our previous work and others, together in a systematic analysis tailored toward sustainable electroplating. We will introduce a sustainability metrics system developed specifically for the electroplating industry. We will then describe a sustainability enhancement method by resorting to the sustainable technology assessment and decision-making method originally developed by Liu and Huang (2012), extended in this paper

to include relative improvement of technologies and the analytical hierarchical process (AHP) technique for weighting factor determination. We will then apply the methodology to study sustainability performance improvement problems that appeared in five electroplating facilities, where profitability issues are also discussed.

Sustainability metrics system for the electroplating industry

Metal finishers and suppliers have become increasingly interested in evaluating the sustainability performance of their businesses and seeking solutions for sustainable development. Supported by American Electroplaters and Surface Finishers (AESF) Foundation, we have developed a sustainability metrics system for the electroplating sector to perform comprehensive sustainability assessment of their processes, chemicals, products, plants, as well as existing and new technologies. Figure 1 lists the main factors considered in metrics system development. The metrics system consists of three sets of indicators measuring economic, environmental, and social sustainability performance, which is common for other metrics systems, such as that by IChemE (2002).

The indicator set in the economic sustainability category covers aspects related to profit and revenue as both profit and revenue are indicative of profitability in the conventional sense. However, to advance the study of profitability in a holistic manner, one cannot be limited to conventional forms of financial reporting. Indicators describing value added, investment for future growth, and tax must be used. Furthermore, business credibility needs to be measured as well, because production efficiency, product quality, production cost (such as costs for chemicals, energy, and water use) and capital investment are all indicative of the true profitability of a company. Thus, the sub-categories of economic sustainability fall under four major branches: profit, investments, product quality, and technology advancement, as shown in Table 1.
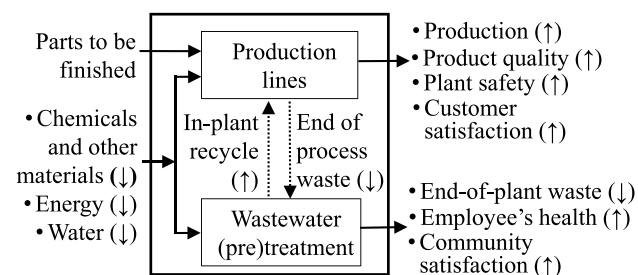

Fig. 1 Main sustainability concerns of an electroplating plant with arrows referring to the direction of change needed for sustainability improvement

A major component of environmental sustainability performance for the metal finishing industry is the effectiveness of waste reduction, particularly source waste minimization using cleaner surface finishing technologies. This is highlighted by the EPA, which found that over 80 percent of the cumulative pounds discharged are attributed to conventional pollutants including total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Many of these pollutants are found in electroplating wastewater (Rajoria et al. 2022), rendering wastewater treatment and production important indicators in the study of environmental sustainability. The EPA also listed a number of energy-related criteria air pollutants (CAP) emissions in the metal finishing industry, which have been considered in indicator development. The ideas of profitable pollution prevention were also used as they can help significantly reduce source waste and greatly reduce the consumption of chemicals, water, and energy in production lines as well as onsite waste treatment facilities. Table 2 shows a list of 19 indicators that can be used to measure the intensities of materials (especially chemicals), water and energy, as well as waste emissions in all forms in plants.

The central focus of social sustainability is on people. Thus, plant safety, employee's health risk, workforce education and training, and stakeholders' satisfaction are always counted for the evaluation of social sustainability. Here stakeholders refer to employees, customers, suppliers, and the neighboring communities and thus satisfies previous definitions of stakeholders determined for thorough sustainability assessment, such as the three categories (manufacturer, user, and society) of stakeholders used by Hapuwatte and Jawahir in their study on closed loop sustainable product design (2021). The indicators of social performance should reflect the company's attitude toward the treatment of its own employees, suppliers, contractors, and customers, and also its impact on society at large. Especially important to the electroplating industry is human health burden. In fact, in one study, 15 out of 53 electroplating companies in Great Britian had workers with urinary nickel concentrations above background concentrations (Beattie 2017). We propose a total of 14 indicators in three subsets shown in Table 3 to measure the social sustainability performance of metal finishing facilities.

Each sustainability indicator is evaluated using, usually, more than one parameter. These parameters could be divided into several types: (1) plant design data, (2) operational data, (3) production and product quality data, (4) EHS (environmental, health, and safety) data, (5) cost/accounting data, and (6) business and management data. The types of parameters for different indicators are listed in Tables 1, 2, and 3.

It is important to note that the indicators presented in this evaluation are not independent. For example,

Table 1 Economic sustainability indicators and parameterization

Sub-category	Indicator	Parameter
E-1: Profit, Value and Tax	E-1–1: Value added ($/y)	Revenue from sales of products before tax Manufacturing cost (including direct production cost, fixed charges, and plant overhead cost)
	E-1-2: Net profit margin (%/$)	Net income (profit) Production cost
	E-1-3: Tax paid as percent of NIBT (%)	Total tax paid annually
	E-1-4: Return on average capital employed (%/y)	Total financial assets Short-term financial obligations
E-2: Investments	E-2-1:Percentage increase in capital employed (%/y)	Capital employed in the current year Past 5-year average of total financial assets
	E-2-2: Investment for employee's education/training	Funds spent for employee (re)training/(re)education Total number of employees
	E-2-3:Investment on new technology ($/y)	Spending for new technology development
E-3: Technology Advancement	E-3-1: Production increment percentage per dollar investment on new technology (%/$-new tech)	Production rate increased after implementing each new technology Amount invested on each new technology
	E-3-2: Product quality improvement percentage per dollar investment on new technology (%/$-new tech)	Final product off-specification rate decreased after implementing new technologies Intermediate product quality off-specification rate decreased after implementing each new technology
	E-3-3: Waste reduction percentage per dollar investment on new technology (%/$-new tech)	Amount of wastewater reduced after implementing each new technology Amount of chemical consumption reduced after implementing each new technology
E-4: Production and Product Quality	E-4-1: Percentage of product delivered on time (%)	Total amount of products produced Products delivered on time
	E-4-2: Product return rate after shipment (%)	Product rejection rate

Table 2 Environmental sustainability indicators and parameterization

Sub-category	Indicator	Parameter
V-1: Materials (excluding fuel and water)	V-1-1: Chemical use in production per value added (lb/$)	Type and amount of each chemical used in production Value added (same as E-1-1)
	V-1-2: Chemical use in waste (pre)treatment per value added (lb/S)	Type and amount of each chemical used in waste (pre)treatment
	V-1-3: Plating solution use per value added (lb/$)	Type and amount of plating solutions used
V-2: Water	V-2-1: Fresh water use in production per dollar of product sales (lb/$)	Amount of fresh water consumed in each production line Annual income from annual sales of products
	V-2-2: Used water reused in production before treatment (%)	Amount of used water reused in production before treatment Amount of fresh water consumed
V-3: Energy	V-3-1: Electricity use per value added (kW/$)	Total amount of electricity used in plant
	V-3-2: Clean energy use among all energy (%)	Total amount of energy used in plant from green or environmentally neutral sources
	V-3-3: Nonproduction energy among all energy consumption (%)	Total amount of energy used in plant Total amount of energy used in production lines
V-4: Waste Generation and Effluents	V-4-1: Spent solutions per value added (lb/$)	Total amount of spent solutions generated in production lines
	V-4-2: Wastewater generated in production per value added (lb/s)	Total amount of wastewater generated in production lines
	V-4-3: Wastewater treatment sludge per value added (lb/$)	Total amount of sludge generated in wastewater treatment facility
	V-4-4: Hazardous waste generated per value added (lb/$)	Types and amounts of hazardous waste generated

Table 3 Social sustainability indicators and parameterization

Sub-category	Indicator	Parameter
L-1: Workplace	L-1-1: Benefits as percentage of payroll expense (%)	Total benefits for employees Total labor cost
	L-1-2: Work related reeducation and/or training (%)	Amount spent on employees' reeducation and retraining
L-2: Safety and Health	L-2-1: Number of accidents in workplace (/y)	Types and numbers of accidents in workplace (in production line or other areas of a plant) Number of employees' health problems (including casualty) caused by the accidents
	L-2-2: Chemical leakage in plant (lb/y)	Types and amount of chemicals emitted in plant and forms Number of employees' health problems (including casualty) caused by chemical leakage
L-3: Society	L-3-1: Number of complaints from local community (/y)	Number of complaints from local community
	L-3-2: Number of complaints from customers (/y)	Number of complaints from customers
	L-3-3: Number of legal actions per value added (/y)	Number of legal actions of a company

freshwater usage definitely has an effect on wastewater generation. The independence of indicators is not considered in this assessment. This is because the only area where the independence of indicators is significant is the results of technology implementation. For example, a technology for lowering freshwater usage would, as a result, also lower wastewater generation. However, these effects are to be detailed and tested by the technology vender and are, thus, included in the evaluation without a need to consider indicator independence.

Sustainability assessment of system and technology

The sustainability metrics system can be used to assess the sustainability performance of any industrial system and to evaluate the performance improvement potentials of technology candidates. A general mathematical framework for the assessments is described in this section.

General assessment formulation

The metrics system shown in Tables 1, 2, and 3 can be used to evaluate the sustainability performance of any type of system (e.g., a process, a plant, a corporation) and technology. The following set of formulas for sustainability assessment proved successful for evaluating various systems such as biodiesel manufacturing under uncertainty (Liu and Huang 2013), technology evaluation under uncertainty (Liu and Huang 2013), vector-based analytics (Moradi-Aliabadi and

Huang 2016a,), and multistage optimization (Moradi-Aliabadi and Huang 2016b) is adopted in this work.

$$E = \frac{\sum_{i=1}^{N_E} a_i E_i}{\sum_{i=1}^{N_E} a_i} \tag{1}$$

$$V = \frac{\sum_{j=1}^{N_V} b_j V_j}{\sum_{j=1}^{N_V} b_j} \tag{2}$$

$$L = \frac{\sum_{k=1}^{N_L} c_k L_k}{\sum_{k=1}^{N_L} c_k} \tag{3}$$

$$S = \frac{\|\langle \alpha E, \beta V, \gamma L \rangle\|}{\|\langle \alpha, \beta, \gamma \rangle\|} = \frac{\sqrt{(\alpha E)^2 + (\beta V)^2 + (\gamma L)^2}}{\sqrt{\alpha^2 + \beta^2 + \gamma^2}} \tag{4}$$

where E, V, L, and S are, respectively, the categorized economic, environmental, social, and overall sustainability; α, β, and γ are the weighting factor associated with the categorized sustainability, representing the importance difference among the three categories of a plant's sustainable development strategy; E_i, V_j, and L_k are individual economic, environmental, and social indicator, respectively; a_i, b_j, and c_k are, respectively, the weighting factor associated with the corresponding economic, environmental, and social sustainability indicator; and N_E, N_V, and N_L are the number of selected economic, environmental, and social indicators, respectively.

To carry out the assessment, all indicators should be normalized such that their values are between 0 (worst) and 1 (best). This normalization is to be carried out using a benchmarking methodology where the data are collected

from similar-sized manufacturing facilities. Thus, when collecting data, each parameter's maximum and minimum values in production, from similar-sized facilities, should be also included. Because of this normalization, the resulting categorized sustainability (*E, V,* and *L*) and overall sustainability (*S*), determined after evaluation, should also be between 0 (worst) and 1 (best). The following equations have been proved successful for normalization in sustainability assessments (Liu and Huang 2013).

$$I = \frac{P - P_{\min}}{P_{\max} - P_{\min}} \tag{5}$$

or

$$I = \frac{P_{\max} - P}{P_{\max} - P_{\min}} \tag{6}$$

where *I* is the normalized indicator value, *P* is the current parameter value, and $P_{\max}$ and $P_{\min}$ are, respectively, the maximum and minimum parameter values. Note that for some indicators, a higher value is better, such as net profit margin, and thus, Eq. 5 should be used to calculate a normalized indicator value, while for others, such as waste generation, a higher value is worse, and thus, Eq. 6 should be used.

A challenging issue in sustainability assessment is the selection of the weighting factor values (i.e., $a_i's$, $b_j's$, and $c_k's$ as well as α, β, and γ). They are commonly selected based on the consensus of a group of decision makers. A more systematic and scientific method, based on expert knowledge and using rigorous mathematics, could be developed by resorting to the analytical hierarchical process (AHP) technique (Saaty 1987). This method is described with an example in "Appendix."

Technology capability evaluation for system performance improvement

To seek a technical solution, the sustainability performance of individual technology candidates and their combinations should be evaluated. The evaluation should be conducted using the same indicators as those used for system's evaluation. The difference between the two assessment results indicates the improvement capacity of each technology set (containing one or more technologies) if adopted, which can be formulated below.

$$\Delta E_i(P|T_j) = \varepsilon_{i,j} E_i(T_j) - E_i(P) \tag{7}$$

$$\Delta V_i(P|T_j) = \zeta_{i,j} V_i(T_j) - V_i(P) \tag{8}$$

$$\Delta L_i(P|T_j) = \eta_{i,j} L_i(T_j) - L_i(P) \tag{9}$$

where $E_i(P)$, $V_i(P)$, and $L_i(P)$ are, respectively, the economic, environmental, and social sustainability performance of system *P* that are evaluated by individual indicators; $E_i(T_j)$, $V_i(T_j)$, and $L_i(T_j)$ are, respectively, the economic, environmental, and social sustainability performance of technology set T_j that are also evaluated by individual indicators; and $\varepsilon_{i,j}$, $\zeta_{i,j}$, and $\eta_{i,j}$ are the indicator-specific coefficients associated with technology set T_j, which should be provided by technology vendor(s), indicating the applicability of the technology set to a specific process *P*.

Note that $\Delta E_i(P|T_j)$, $\Delta V_i(P|T_j)$, and/or $\Delta L_i(P|T_j)$ may be negative, which means using that specific technology set may worsen the system's performance for the measured indicator. The decision makers may want to decide whether the technology set should be further evaluated by other indicators or whether to just remove the technology set from the candidate list.

Evaluation of system's sustainability performance after implementing technologies

For the technology set accepted for further evaluation, the categorized sustainability performance of the system if adopting the technology set can be evaluated as follows:

$$E(P|T_j) = \sum_{i=1}^{N_E} a_i E_i(P|T_j) \tag{10}$$

$$V(P|T_j) = \sum_{i=1}^{N_V} b_i V_i(P|T_j) \tag{11}$$

$$L(P|T_j) = \sum_{i=1}^{N_L} c_i L_i(P|T_j) \tag{12}$$

where

$$E_i(P|T_j) = E_i(P) + \varepsilon_{i,j} E_i(T_j) \tag{13}$$

$$V_i(P|T_j) = V_i(P) + \zeta_{i,j} V_i(T_j) \tag{14}$$

$$L_i(P|T_j) = L_i(P) + \eta_{i,j} L_i(T_j) \tag{15}$$

and the overall sustainability performance of the system after adopting the technology set can be quantified as:

$$S(P|T_j) = \frac{\left\| \langle \alpha E(P|T_j), \beta V(P|T_j), \gamma L(P|T_j) \rangle \right\|}{\| \langle \alpha, \beta, \gamma \rangle \|} \tag{16}$$
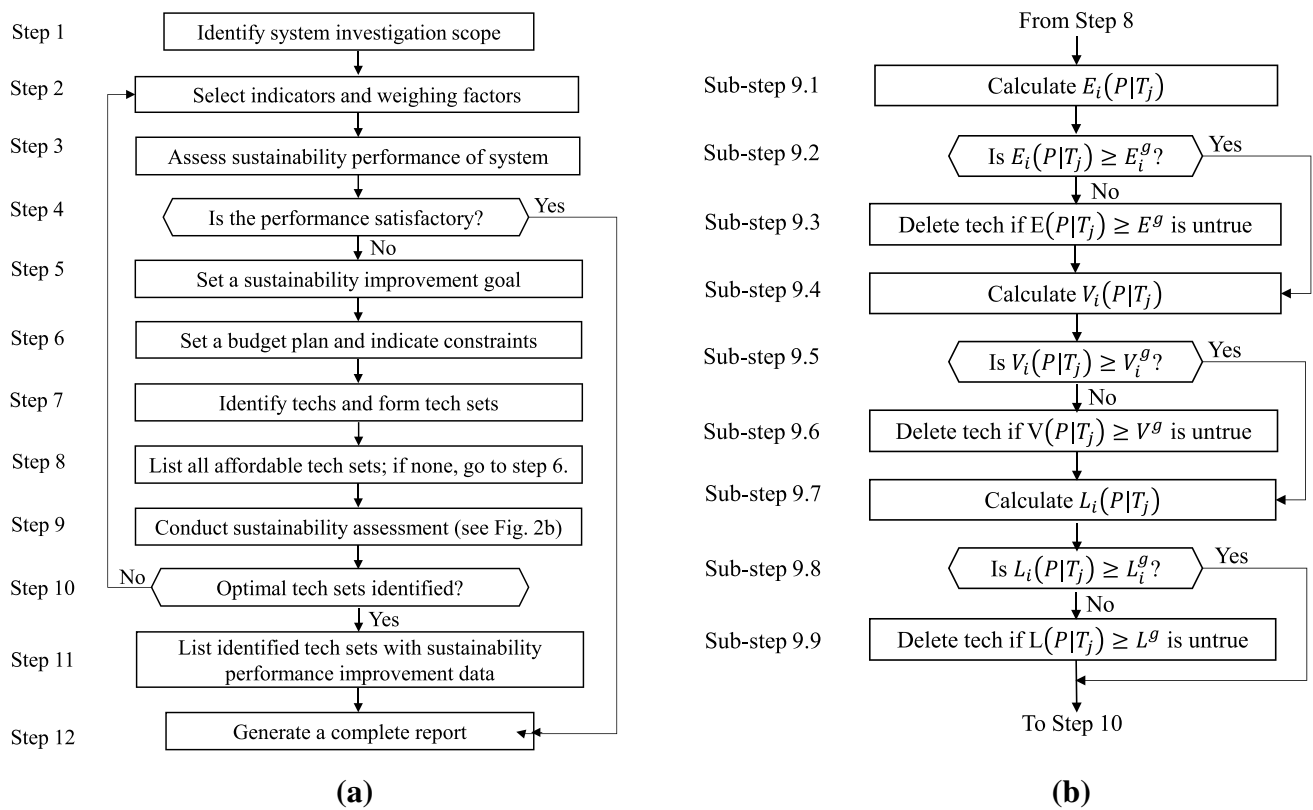
Fig. 2 Flowchart for sustainability assessment and technical solution identification procedure: **a** overall procedure design. **b** sub-steps in Step 9

where α, β, and γ are the weighting factors signifying the relative importance among the economic, environmental, and social sustainability in the company's strategic development plan. Their values can be determined by the AHP technique described in "Appendix."

Technical solution identification procedure

The sustainability assessment formulations presented in the past section are the core of a solution identification method. The method is presented as a general procedure for identifying a solution or solutions that can be adopted by a plant to achieve its preset goals for sustainability performance improvement. For clarity, the 12-step procedure is plotted in Fig. 2.

Step 1 Define a system investigation scope.

Step 2 Select sustainability indicators in each category (i.e., E_i, V_j, and L_k; $i \in N_E$, $j \in N_V$, and $k \in N_L$), and determine the weighting factors associated with individual indicators (i.e., a_i, b_j, and c_k) as well as those associated with the categorized sustainability (i.e., α, β, and γ) using the AHP technique (see "Appendix").

Step 3 Use Eqs. (1) to (4) to assess the sustainability performance of the system, which results in the following values: $E_i(P)$'s, $V_j(P)$'s, and $L_k(P)$'s, as well as $E(P)$, $V(P)$, and $L(P)$.

Step 4 Analyze the assessment result and determine whether the system's performance is satisfactory or not. If yes, go to *Step 12*; otherwise identify the major weaknesses that need be overcome.

Step 5 Set a sustainability performance improvement goal. For those indicators most significant and/or critical to the plant, their target values should be set; they are $E_i^g(P)'s$, $V_j^g(P)'s$, and/or $L_k^g(P)'s$. In addition, the category-specific targets, i.e., $E^g(P)$, $V^g(P)$, and $L^g(P)$, should be set. Note that the targets can be adjusted later as needed.

Step 6 Provide a budget plan and spending limit data by the plant for technology adoption. Note that these can also be adjusted later as needed.

Step 7 Identify technologies potentially useful for sustainability performance improvement. Assume there are N technology candidates for evaluation ($T_1, T_2, …, T_N$). It is likely that the plant will adopt two or more technologies if proved to be more effective for performance improvement. Thus, the N individual technology candidates can form $2^N - 1$ technology sets, each of which contains one, two, …, or even all

N technologies. Obviously, the more technologies that are adopted, the more the plant needs to pay the technology vendors. Thus, the plant needs to discuss with technology vendors for possible discount.

Step 8 Determine affordable technology sets. Based on the budget limit, eliminate all unaffordable technology sets from the $2^N - 1$ sets. The number of remaining sets will be referred to as *M*, where $M \leq (2^N - 1)$. If $M = 0$, then go to *Step 6* for budget change; otherwise, continue.

Step 9 Conduct sustainability assessment of all *M* affordable technology sets (T_i's) individually using the same indicators as those used for evaluating system *P*. Based on the magnitude difference among α, β, and γ that are shown in Eq. (4), the assessment is conducted in the following substeps. For presentation convenience, it is assumed that $\alpha \geq \beta \geq \gamma$.

Sub-step 9-1 Use Eqs. (7) and (10) to evaluate the indicator-specific improvement capacity of each technology set, and obtain the values of $\Delta E_i(P|T_j)$ and $E_i(P|T_j)$.

Sub-step 9-2 Compare $E_i(P|T_j)$ with $E_i^g(P)$. The plant can determine whether T_j should be deleted or not. If it is deleted, then go to *Sub-step 9-4*; otherwise, continue.

Sub-step 9-3 Compare $E(P|T_j)$ with $E^g(P)$. The plant can delete T_j if the preset target(s) cannot be achieved. If it is deleted, the total number of technology sets is reduced by one.

Sub-step 9-4 For the remaining technology sets, use Eqs. (8) and (11) to evaluate the indicator-specific improvement capacity of each technology set, and obtain the values of $\Delta V_i(P|T_j)$ and $V_i(P|T_j)$.

Sub-step 9-5 Compare $V_i(P|T_j)$ with $V_i^g(P)$. The plant can determine whether T_j should be deleted or not. If it is deleted, then go to *Sub-step 9-7*; otherwise, continue.

Sub-step 9-6 Compare $V(P|T_j)$ with $V^g(P)$. The plant can delete T_j if the preset target(s) cannot be achieved. If it is deleted, the total number of technology sets is reduced by one.

Sub-step 9-7 For the remaining technology sets, use Eqs. (9) and (12) to evaluate the indicator-specific improvement capacity of each technology set, and obtain the values of $\Delta L_i(P|T_j)$ and $L_i(P|T_j)$.

Sub-step 9-8 Compare $L_i(P|T_j)$ with $L_i^g(P)$. The plant can determine whether Tj should be deleted or not. If it is deleted, then go to *Step 10*; otherwise, continue.

Sub-step 9-9 Compare the category-specific sustainability performance, $L(P|T_j)$ with the target, $L^g(P)$. The plant can delete T_j if the preset target(s) cannot be achieved. If it is deleted, the total number of technology sets is reduced by one.

Step 10 Go to Step 2 if all the technology sets are deleted and the plant agrees to make some adjustment of the preset goals and/or to reselect indicators with their weighting factors; otherwise, continue.

Step 11 All the remaining technology sets are adoptable as they are not only affordable, but also capable of helping the plant to achieve all the preset goals for performance improvement. The overall sustainability performance of each remaining technology set, i.e., $S(P|T_j)$, should be calculated.

Step 12 Generate a complete report on the solutions for the plant to improve its sustainability performance. This should include: (1) a list of sustainability indicators used, (2) a set of weighting factors used, (3) complete sets of plant data used for assessment, (4) the plant's current sustainability status, (5) the major sustainability weaknesses identified, (6) the plant's goals set for performance improvement and budget commitment, (7) the technologies identified for the plant to achieve its goals, and (8) a detailed analysis about the plant's sustainability performance if the identified technologies are adopted.

Note that the plant may select any technology set as all are satisfactory. It is possible that the plant plans to use some additional criteria, e.g., investment level preference, technology implementation easiness, and management convenience, in their decision-making process.

Table 4 Selected sustainability indicators and weighting factors for case study

Category	Indicator	Weighting factors	
		Symbol	Value
Economic (E)	E_1—Value Added	a_1	0.351
	E_2—Net Profit Margin	a_2	0.351
	E_3—Investment on New Technology	a_3	0.109
	E_4—Product Defect Rate	a_4	0.189
Environmental (V)	V_1—Fresh Water Use in Production per Value Added	b_1	0.062
	V_2—Wastewater Generated in Production per Value Added	b_2	0.153
	V_3—Fraction of Water Recycled within Plant	b_3	0.153
	V_4—Hazardous Waste Generated per Value Added	b_4	0.632
Social (L)	L_1—Number of Complaints from Customers	c_1	0.269
	L_2—Number of Complaints from Local Community	c_2	0.071
	L_3—Human Health Burden per Value Added	c_3	0.660

Table 5 Normalized indicator-specific assessment results of five facilities

Category	Indicator	Indicator-based assessment result				
		Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
Economic (E)	E_1	[0.200, 0.220]	[0.300, 0.335]	[0.050, 0.080]	[0.900, 0.910]	[0.550, 0.558]
	E_2	[0.800, 0.900]	[0.760, 0.776]	[0.100, 0.105]	[0.940, 0.960]	[0.460, 0.500]
	E_3	0.338	[0.127, 0.141]	[0.141, 0.165]	[0.394, 0.451]	[0.403, 0.429]
	E_4	[0.300, 0.364]	0.273	[0.905, 0.909]	[0.864, 0.909]	[0.500, 0.636]
Economic sustainability by Eq. (1)		[0.445, 0.499]	[0.437, 0.457]	[0.239, 0.255]	[0.852, 0.877]	[0.493, 0.538]
Environmental (V)	V_1	[0.233, 0.299]	[0.876, 0.878]	[0.699, 0.712]	[0.035, 0.052]	[0.233, 0.299]
	V_2	[0.417, 0.507]	[0.975, 0.993]	[0.579, 0.597]	0.507	[0.200, 0.236]
	V_3	[0.750, 0.775]	[0.250, 0.300]	0.000	[0.625, 0.675]	0.125
	V_4	[0.433, 0.500]	0.167	0.000	[0.167, 0.333]	[0.133, 0.167]
Environmental sustainability by Eq. (2)		[0.467, 0.531]	[0.347, 0.358]	[0.132, 0.135]	[0.281, 0.395]	[0.149, 0.179]
Social (L)	L_1	[0.792, 0.800]	[0.680, 0.800]	[0.560, 0.600]	[0.520, 0.560]	[0.268, 0.280]
	L_2	[0.408, 0.434]	[0.681, 0.736]	[0.544, 0.566]	[0.308, 0.340]	[0.396, 0.491]
	L_3	[0.447, 0.500]	[0.145, 0.158]	[0.658, 0.711]	[0.316, 0.342]	[0.053, 0.158]
Social sustainability by Eq. (3)		[0.537, 0.576]	[0.327, 0.372]	[0.623, 0.671]	[0.370, 0.401]	[0.135, 0.214]
Overall sustainability by Eq. (4)		[0.486, 0.536]	[0.374, 0.398]	[0.393, 0.421]	[0.560, 0.602]	[0.307, 0.350]

Case study

The sustainability assessment and technical solution identification methodology was applied to investigate the sustainability performance improvement problems with five electroplating facilities.

Sustainability assessment of facilities

Although the facilities have different metal coating types, process configurations and operational settings, production capacities, etc., it is suitable for all of them to be assessed using 11 sustainability indicators in this case study. These include four in the economic category, four in the environmental category, and three in the social category. They are listed in Table 4, where the weighting factors associated with them are also shown. Note that the weighting factors are determined using the AHP technique (see Appendix A,

Table 6 Sustainability goal and budget limit set by 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 Limit (B^{lim})	$50,000	$70,000	$76,000	$125,000	$90,000

where the method is detailed and its application to the determination of all four weighting factors associated with the environmental sustainability for the case study). These data were normalized and then used to conduct indicator-specific and categorized sustainability assessments of each facility (see Table 5). Note that since the collected facility data are all expressed in certain ranges, the assessment results are all presented as interval numbers.

After reviewing the assessment results, the management of each facility can set the goals for sustainability performance improvement (i.e., E^g, V^g, and L^g; note that the overall sustainability goal, S^g, is calculated based on the set goals of the categorized sustainability). In addition, each facility needs set a budget limit for technology adoption (i.e., B^{lim}). The goals and the budget limit set by the facilities are shown in Table 6.

Technologies and capacity assessment

Electroplating facilities have many plating lines within the same facility. However, there exist many technologies for plant performance improvement such that they can be applied to all the lines within the facility and effect the sustainability of the facility as a whole. To illustrate the effectiveness of the methodology, three such technologies are selected here. 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,

Table 7 Effect of technology sets on individual indicators and adoption cost

Category	Indicator	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%]
Environmental (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

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 previous industrial projects regarding wastewater reduction (Huang 2002), chemical-metal zero discharge (Huang 2006), and cyclic hoist scheduling (Xu and Huang 2004). Table 7 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 using interval numbers. As shown in Table 7, the cost for adopting each technology set is also indicated.

Technical solution identification

As shown in Table 5, the five facilities' sustainability statuses, measured using the different indicators, vary widely. After finding the sustainability status, each of these facilities set their goals for performances and budget commitments, which are shown in Table 6. These sustainability statuses and goals were then used in the solution identification method described in the preceding section to derive solution(s) for each facility.

Facility 1

The sustainability assessment for the facility in Table 5 shows that net profit margin (E_2) is the highest performing indicator for economic sustainability (i.e., [0.800, 0.900]). The rest of the economic indicators all showed poor sustainability, with value added (E_1) within the interval of [0.200, 0.220], investment on new technologies (E_3) at 0.338, and product defect rate (E_4) within [0.300, 0.364]. For environmental sustainability, wastewater generation (V_2) and hazardous waste (V_4) both had a sustainability performance around 0.4 to 0.5. The best performing environmental indicator was the amount of water recycled within the facility (V_3) at [0.750, 0.775], and the worst performing indicator was the amount of freshwater used in production (V_1) at [0.233, 0.299]. For social sustainability, the facility performed around average. However, it did show exceptional initiative in its treatment of customers (L_1) which resulted in a sustainability performance in the range of 0.792 and 0.800 for this indicator. In terms of categorical analysis, economic sustainability was the worst performing category in this assessment. But it was not far off from the other two categories, which were all close to average performance. This led to an overall sustainability (S) of 0.484–0.536. The facility needs to identify a suitable technology or technologies for performance improvement in order to achieve the goals shown in Table 6.

In terms of sustainability improvement through technology implementation, the budget limit set by the facility was

Table 8 Technical solution identification for Facility 1 with $50,000 budget and $80,000 budget

Budget	Tech sets		Cost $B(T_i)$	Sustainability after tech application			Overall sustainability $S(P|T_j)$
	No.	Techs		$E(P|T_j)$	$V(P|T_j)$	$L(P|T_j)$	
$50,000	1	{T_1}	$47,000	[0.469, 0.523]	[0.553, 0.629]	Deleted (environ. concern)	
	2	{T_2}	$32,000	[0.461, 0.518]	[0.666, 0.714]	[0.621, 0.660]	Deleted (soc. concern)
	3	{T_3}	$34,000	[0.463, 0.517]	[0.535, 0.604]	Deleted (environ. concern)	
$80,000	**4**	**{T_1,T_2}**	**$75,050**	**[0.485, 0.542]**	**[0.752, 0.812]**	**[0.658, 0.699]**	
	5	{T_1,T_3}	$76,950	[0.488, 0.541]	[0.621, 0.703]	[0.593, 0.646]	
	6	**{T_2,T_3}**	**$62,700**	**[0.480, 0.536]**	**[0.734, 0.787]**	**[0.638, 0.691]**	

Bold rows in the table denote all possible optimal solutions for that facility after technology assessment

Table 9 Technical solution identification for Facility 2 (Budget Limit—$70,000)

No.	Tech Set	Cost for tech set $B(T_i)$	Sustainability after tech application			Overall sustainability $S(P|T_j)$
			$E(P|T_j)$	$V(P|T_j)$	$L(P|T_j)$	
1	{T_1}	$47,000	[0.463, 0.486]	Deleted (econ. concern)		
2	{T_2}	$32,000	[0.455, 0.479]	Deleted (econ. concern)		
3	{T_3}	$34,000	[0.457, 0.478]	Deleted (econ. concern)		
6	**{T_2,T_3}**	**$62,700**	**[0.474, 0.500]**	**[0.601, 0.637]**	**[0.495, 0.545]**	**[0.526, 0.563]**

Bold rows in the table denote all possible optimal solutions for that facility after technology assessment

only $50,000. The result was that only three technologies could be evaluated for their capabilities to improve performance. As shown in Table 8, Tech Sets No. 1 through 3 all met the economic sustainability goal (E^g of 0.510) when using optimistic estimations. However, the environmental sustainability goal (V^g of 0.645) eliminated Set No. 1 and 3. Set No. 2 fell short at social sustainability. It could not meet the social sustainability goal (L^g of 0.690) and was removed from the analysis. This left no technology set that was able to meet the requirements of this facility. In this situation, the management of the facility should make the decision to (1) adjust the social sustainability goal from 0.690 to 0.660 so that Set No. 3 becomes a solution, (2) commit more funds and search for a new solution, or otherwise, and (3) stop the solution search.

In this case, we assumed that the facility increased its budget limit to $80,000. With this change, two solutions, Set No. 4 and 6, were identified (see Table 8). The facility can decide whether the solution with the lower cost is preferable (i.e., $62,700 to adopt Set No. 6) or the one giving a better sustainability performance (~ 2% higher if Set No. 4 is adopted).

Facility 2

The sustainability assessment indicates that the investment on new technology (E_3) is considerably lower than other similar-sized facilities (see Table 5), with a sustainability score of [0.127, 0.141]. It was the worst performing

indicator under the economic analysis for this facility. Value added (E_1), net profit margin (E_2), and product defect rate (E_4) scored [0.300, 0.335], [0.760, 0.776], and 0.273, respectively. The performance for investment on new technology was only slightly worse than the worst performing indicators in environmental sustainability, which were the production of hazardous waste (V_4) at 0.167 and water recycling (V_3) at [0.250, 0.300]. Freshwater usage (V_1) and wastewater generation (V_2) seemed to be areas of focus for this facility in the past, as they scored fairly high at [0.876, 0.878] and [0.975, 0.993], respectively. Alongside these two, this facility showed that it had a good grasp on community and customer satisfaction, as the assessment showed L_1 at [0.680, 0.800] and L_2 at [0.681, 0.736]. The employees' health was a major issue in the facility.

To improve the sustainability performance, this facility decided to invest up to $70,000 for a technical solution. Under this budget limit, only Set No. 1, 2, 3, and 6 were evaluated for possible adoption. As shown in Table 9, however, only Set No. 6 satisfied all the sustainability goals.

Facilities 3 to 5

Each facility had its own strengths and weaknesses in different sustainability aspects. After applying the same technology evaluation methodology, the solutions for these facilities were identified. The technical solution identification for each of these facilities can be found in the supplementary information.

Table 10 Summary of technology selection results for five facilities

Facility	Sustainability performance (current)				Budget B^{lim}	Techs selected	Cost for techs	Sustainability performance (after)			
	$E(P)$	$V(P)$	$L(P)$	$S(P)$				$E(P\|T_j)$	$V(P\|T_j)$	$L(P\|T_j)$	$S(P\|T_j)$
F1	[0.445, 0.499]	[0.467, 0.531]	[0.537, 0.576]	[0.484, 0.536]	$80,000	{T₁,T₂}	$75,050	[0.485, 0.542]	[0.752, 0.812]	[0.658, 0.699]	[0.641, 0.693]
						{T₂,T₃}	$62,700	[0.480, 0.536]	[0.734, 0.787]	[0.638, 0.691]	[0.626, 0.679]
F2	[0.437, 0.457]	[0.347, 0.358]	[0.327, 0.372]	[0.375, 0.398]	$70,000	{T₂,T₃}	$62,700	[0.474, 0.500]	[0.601, 0.637]	[0.495, 0.545]	[0.526, 0.563]
F3	[0.239, 0.255]	[0.132, 0.135]	[0.623, 0.671]	[0.393, 0.421]	$76,000	{T₁,T₂}	$75,050	[0.262, 0.285]	[0.501, 0.544]	[0.746, 0.773]	[0.541, 0.570]
						{T₂,T₃}	$62,700	[0.257, 0.277]	[0.452, 0.479]	[0.745, 0.781]	[0.524, 0.553]
F4	[0.852, 0.877]	[0.281, 0.395]	[0.370, 0.401]	[0.560, 0.602]	$125,000	{T₁,T₂,T₃}	$101,700	[0.873, 0.902]	[0.729, 0.839]	[0.607, 0.663]	[0.744, 0.808]
F5	[0.493, 0.538]	[0.149, 0.179]	[0.135, 0.214]	[0.307, 0.350]	$90,000	{T₂}	$32,000	[0.519, 0.571]	[0.410, 0.441]	[0.369, 0.454]	[0.437, 0.492]
						{T₁,T₂}	$75,050	[0.559, 0.616]	[0.530, 0.590]	[0.428, 0.514]	[0.509, 0.575]
						{T₂,T₃}	$62,700	[0.547, 0.600]	[0.500, 0.548]	[0.414, 0.526]	[0.490, 0.559]

Summary

The information contained in Table 10 summarizes the key results and also contains necessary information for the facility managements to make their decisions. They can also obtain detailed indicator-specific information, if there is a need.

Analysis of technology and technical solution

The identified technical solutions for the five facilities are summarized in Table 10. Among those recommended technology sets, Set No. 6 (i.e., 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.

Figure 3 provides a complete summary of the identified technical solutions' improvements to each facility's sustainability performance in different categories. 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. Figure 3 reveals such a situation. As shown, Tech Set No. 4 (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.

Allocation of funds

Facilities 2 and 3 both show a peculiar trend when it comes to their sustainability assessment results. Both have high scores for net profit margin ([0.800, 0.900] and [0.760, 0.776], respectively), yet low scores for value added ([0.200, 0.220] and [0.300–0.335], respectively) and investment on
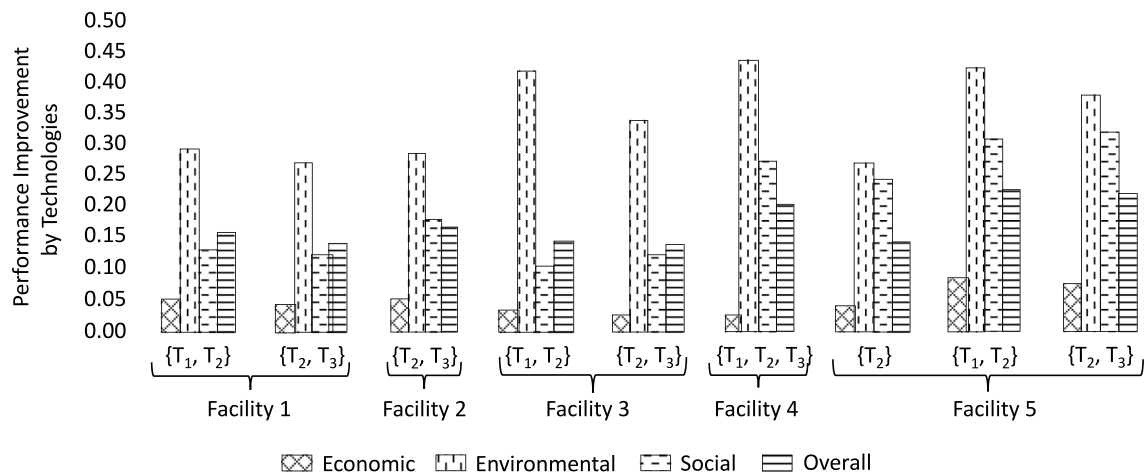
Fig. 3 Sustainability performance improvement by technologies in different facilities
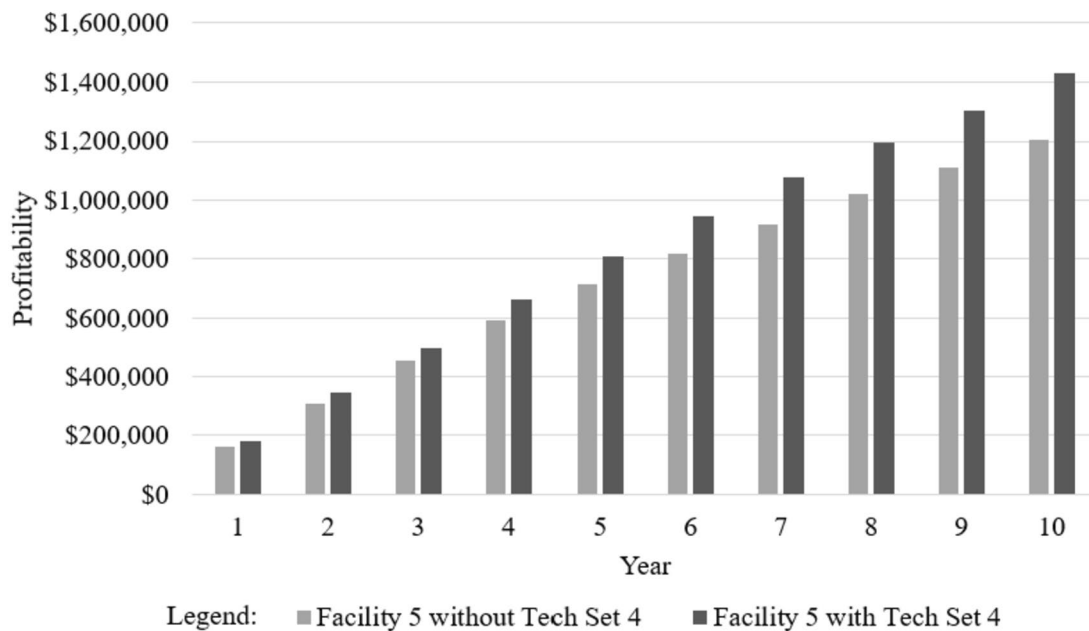

Fig. 4 Profitability improvement for Facility 5 with Tech Set 4, compared to the one without Tech Set 4

new technologies (0.338 and [0.127, 0.141], respectively). Note that the net profit margin accounts for costs related to general expenses and plant overhead, as well as direct production costs only. This discrepancy shows an anomalous amount of funds being spent on direct production. The best course of action for these facilities would be to run a thorough analysis of finances to identify whether there is some sort of misallocation related to their economics. It would also be in their best interests to identify why the investment on technologies is so low compared to other similar-sized electroplating facilities.

Profitability

Table 10 shows the effects of the technology sets after implementation. It is convenient for the facilities to evaluate the profitability gain after adopting the recommended technologies. For instance, Facility 5 saw a major improvement to economic sustainability after implementing Tech Set 4 (i.e., the use of both technologies T_1 and T_2). Here we implement Tech Set 4 to Facility 5 and compare the profitability with Facility 5 without the implementation of Tech Set 4. From the difference in the two facilities, which can be seen in Fig. 4, it becomes clear that Facility 5 with Tech Set 4

always has a better profitability. For the first three years, the profitability is almost equal, however, this is due to the payments to technology vendors for purchasing the technology. After this period, the profitability of facility 5 with Tech Set 4 is clearly increasing at a higher rate. And by the 10th year, the facility using Tech Set 4 has a net present value of $1,430,826. As opposed to the facility without Tech Set 4, which shows a net present value of $1,204,103. This is more than a $225,000 return after 10 years (an average of over $22,500 per year), alongside significantly lowering the amount of waste produced, water used, and product defect rate.

Concluding remarks

The electroplating sector is fairly unique as it deals with high levels of hazardous or toxic waste, which is highly regulated by the EPA. Most facilities in the sector run in a low profit margin, are lacking in terms of research and development capacities, and need to improve various social aspects, such as the relationships with customers and surrounding communities, and workforce training. Thus, one of the urgent needs for the sector is to have tools for conducting sustainability assessment of the facilities and for deriving performance improvement solutions.

In this paper, we have introduced a comprehensive sustainability metrics system and a holistic technical solution identification methodology for the electroplating sector. The methodological efficacy has been demonstrated through a case study on five electroplating facilities. These facilities had various types of sustainability issues identified through sustainability assessment by using a subset of indicators from the metrics system. Then different technical solutions were identified under the facilities' budget, which can help them achieve their sustainability goals. The sustainability metrics system and the technical solution identification methodology are general and can be used by a variety of manufacturing sectors.

Appendix

Weighting factor determination by the analytical hierarchical process

As shown in Table 4, the indicators in each of the three sustainability categories, i.e., the economic sustainability (E), environmental sustainability (V), and social sustainability (L), are assigned different weighting factor values. These values are derived using the analytical hierarchical

Table 11 Relative importance in the AHP method (Saaty 1987)

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

process (AHP) method that was developed by Saaty (1987). Here we take the weighting factors (b_1 to b_4) for the four environmental indicators (V_1 to V_4) as an example to show the derivation.

Step 1 Determine the relative importance of each pair of indicators. Among the four indicators, there are six pairs for relative importance determination: V_i to V_j, ($i > j$, $i = 2, 3, 4$; $j = 1, 2, 3$). The relative importance has a value between 1 and 9, and the meaning of the numbers is shown in Table 11.

Those involved in the decision-making process should determine the relative importance values $\left(a'_{i,j}s\right)$ for pairs of indicators. In this case, assume the values are: $a_{2,1} = 3$ (for V_2 to V_1), $a_{3,1} = 3$ (for V_3 to V_1), $a_{4,1} = 7$ (for V_4 to V_1), $a_{3,2} = 1$ (for V_3 to V_2), $a_{4,2} = 5$ (for V_4 to V_2), and $a_{4,3} = 5$ (for V_4 to V_3).

Step 2 Construction of the relative importance matrix *A*. The dimension of the matrix is determined by the number of indicators, which has a general structure below:

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,N} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,N} \\ \vdots & \vdots & \vdots & \vdots \\ a_{N,1} & a_{N,2} & \cdots & a_{N,N} \end{bmatrix} \tag{A.1}$$

where $a_{i,j}$ is the relative importance of weighting factor V_i to V_j. If $i > j$, the value of $a_{i,j}$ is already determined in Step 1. For $a_{i,i}$, a value of 1 is assigned. If $i < j$, then $a_{i,j} = \frac{1}{a_{j,i}}$. In this case, there are four indicators. Thus, matrix *A* has the following element values.

$$A = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{3} & \frac{1}{7} \\ 3 & 1 & 1 & \frac{1}{5} \\ 3 & 1 & 1 & \frac{1}{5} \\ 7 & 5 & 5 & 1 \end{bmatrix} \tag{A.2}$$

Step 3 Determination of weighting factors. Let *W* be a vector of weighting factors as follows:

$$W = \begin{pmatrix} w_1 & w_2 & \cdots & w_N \end{pmatrix}^T \tag{A.3}$$

It is calculated using the following method.

Number of indicators	1	2	3	4	5	6	7	8	9	10
Consistency index	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Step 3.1 Calculate the vector of roots of individual row-based elements in matrix *A*:

$$M = \left(m_1 \ m_2 \ \cdots \ m_N \right)^T \tag{A.4}$$

where

$$m_i = \left(\prod_{j=1}^{N} a_{i,j} \right)^{\frac{1}{N}} \tag{A.5}$$

In this case,

$$M = \left(0.355 \ 0.880 \ 0.880 \ 3.637 \right)^T \tag{A.6}$$

Step 3.2 Calculate the weighting factors. For the weighting factor vector, *W*, its element values can be calculated using the following formula:

$$w_i = \frac{m_i}{\sum_{j=1}^{N} m_j} \tag{A.7}$$

In this case, the resulting weighting factor values are:

$$W = \left(0.062 \ 0.153 \ 0.153 \ 0.632 \right)^T \tag{A.8}$$

Step 4 Consistency checking. Note that the relative importance of pairs of sustainability indicators individually may cause inconsistency. According to Saaty (1987), the derived vector *W* should be evaluated for its consistency. A consistent evaluation should result in a consistency index equal to or below 0.10, which was considered by Saaty to be the limit at which, if exceeded, the judgements would need re-evaluation. The calculation methodology is shown in the following equations:

Step 4.1 Calculate the eigenvalue of matrix *A*. Let *W* be an eigenvector of matrix *A*, the eigenvalues can be found by solving the equation below:

$$AW = \lambda W \tag{A.9}$$

where λ is an eigenvalue of matrix A. Since matrix A's dimension of NxN, there are N eigenvalues as follows:

$$\lambda = \left(\lambda_1 \ \lambda_2 \ \cdots \ \lambda_N \right)^T \tag{A.10}$$

where

$$\lambda_i = \frac{(AW)_i}{w_i} \tag{A.11}$$

Then, let λ_{Ave} be found the average of all the eigenvalues. This gives:

$$\lambda_{Ave} = \frac{\sum_{i=1}^{N} \lambda_i}{N} \tag{A.12}$$

In this case,

$$\lambda = \left(4.10 \ 4.04 \ 4.04 \ 4.11 \right)^T \tag{A.13}$$

$$\lambda_{Ave} = 4.07 \tag{A.14}$$

Step 4.2 Calculate the consistency ratio, *CR*, as follows:

$$CR = \frac{\lambda_{Ave} - N}{\eta(N - 1)} \tag{A.15}$$

where η is the random consistency index, whose value is related to the number of indicators (see Table 12). In this case, η is 0.9.

The calculation shows that the value of *CR* is 0.027, which is smaller than 0.10. Thus, the weighting factors shown in Eq. (A.8) are consistent.

Facility data for sustainability performance evaluation

The facility data were collected from our previous studies (Song 2016; Xiao and Huang 2012; Xu and Huang 2004; Xu et al. 2005; Yang et al. 1999a, b; Yang et al. 1999a, b), as well as a benchmarking survey for the electroplating sector by the National Center for Manufacturing Sciences (NCMS

Table 13 Facility data for sustainability study

Parameter	Value range		Facility data				
	Best	Worst	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
Sales revenue ($)	$1,300,000	$400,000	[$800,000, $807,000]	[$650,000, $678,500]	[$542,000, $553,000]	[$1,100,000, $1,170,000]	[$900,000, $912,000]
Manufacturing cost ($)	$300,000	$700,000	[$597,000, $600,000]	[$400,000, $411,000]	[$413,000, $417,000]	[$550,000, $615,000]	[$525,000, $533,000]
Net income ($)	$780,000	$240,000	[$480,000, $484,200]	[$390,000, $407,100]	[$325,200, $331,800]	[$660,000, $702,000]	[$540,000, $547,200]
Production cost ($)	$240,000	$741,000	[$460,800, $462,400]	[$374,200, $391,300]	[$309,000, $314,400]	[$629,000, $668,300]	[$527,600, $533,500]
Technology investment ($)	$355,000	$0	$120,000	[$45,000, $50,000]	[$50,000, $58,500]	[$140,000, $160,000]	[$143,000, $152,200]
Product defect rate (%)	4.00%	15.00%	[11.00%, 11.70%]	12.00%	[5.00%, 5.05%]	[5.00%, 5.50%]	[8.00%, 9.50%]
Fresh water consumption (gal/yr)	186,210	4,538,066	[1,078,438, 1,233,014]	[299,566, 323,741]	[299,566, 348,935]	[3,954,272, 4,056,724]	[2,022,071, 2,225,297]
Wastewater generation (gal/yr)	7.61	63.12	[838,785, 1,006,541]	[239,653, 288,482]	[449,349, 520,046]	2,317,144	[2,246,746, 2,361,539]
Amount of water recycling (%)	40%	0%	[30%, 31%]	[10%, 12%]	0%	[25%, 27%]	5%
Hazardous waste generation (kg/yr)	0.01	0.04	[5,000, 5,670]	9,056	5,300	[16,500, 19,425]	[13,125, 13,644]
Customer complaints	0	25	[5, 5]	[5, 8]	[10, 11]	[11, 12]	[18, 18]
Community complaints	0	53	[30, 31]	[14, 17]	[23, 24]	[35, 37]	[27, 32]
Human health burden	120	3000	[620, 693]	[1,100, 1,190]	[288, 350]	[2,035, 2,109]	[1,650, 1,819]

2000). The data in Table 13 were used for sustainability assessment in the case study.

Technical solution identification for facilities 3 to 5.

See Table 14, 15 and 16.

Table 14 Technical solution identification for Facility 3 (Budget Limit—$76,000)

No	Tech set	Cost for tech set $B(T_i)$	Sustainability after tech application			Overall sustainability $S(P|T_j)$
			$E(P|T_j)$	$V(P|T_j)$	$L(P|T_j)$	
1	{T₁}	$47,000	[0.253, 0.272]	[0.251, 0.290]	Deleted (environ. concern)	
2	{T₂}	$32,000	[0.248, 0.268]	Deleted (econ. concern)		
3	{T₃}	$34,000	[0.248, 0.264]	Deleted (econ. concern)		
4	**{T₁,T₂}**	**$75,050**	**[0.262, 0.285]**	**[0.501, 0.544]**	**[0.746, 0.773]**	**[0.541, 0.570]**
6	**{T₂,T₃}**	**$62,700**	**[0.257, 0.277]**	**[0.452, 0.479]**	**[0.745, 0.781]**	**[0.524, 0.553]**

Bold rows in the table denote all possible optimal solutions for that facility after technology assessment

Table 15 Technical solution identification for Facility 4 (Budget Limit—$125,000)

Tech set		Cost $B(T_i)$	Sustainability after tech application			Overall sustainability $S(P|T_j)$
No	Techs		$E(P|T_j)$	$V(P|T_j)$	$L(P|T_j)$	
1	{T_1}	$47,000	[0.861, 0.887]	Deleted (econ. concern)		
2	{T_2}	$32,000	[0.858, 0.885]	Deleted (econ. concern)		
3	{T_3}	$34,000	[0.858, 0.885]	Deleted (econ. concern)		
4	{T_1,T_2}	$75,050	[0.866, 0.895]	[0.650, 0.751]	[0.576, 0.612]	Deleted (soc. concern)
5	{T_1,T_3}	$76,950	[0.867, 0.895]	[0.470, 0.605]	Deleted (environ. concern)	
6	{T_2,T_3}	$62,700	[0.864, 0.892]	[0.619, 0.718]	[0.562, 0.614]	Deleted (soc. concern)
7	**{T_1,T_2,T_3}**	**$101,700**	**[0.873, 0.902]**	**[0.729, 0.839]**	**[0.607, 0.663]**	**[0.744, 0.808]**

Bold rows in the table denote all possible optimal solutions for that facility after technology assessment

Table 16 Technical solution identification for Facility 5 (Budget Limit—$90,000)

Tech set		Cost $B(T_i)$	Sustainability after tech application			Overall sustainability $S(P|T_j)$
No	Techs		$E(P|T_j)$	$V(P|T_j)$	$L(P|T_j)$	
1	{T_1}	$47,000	[0.533, 0.583]	[0.268, 0.328]	Deleted (environ. concern)	
2	**{T_2}**	**$32,000**	**[0.519, 0.571]**	**[0.410, 0.441]**	**[0.369, 0.454]**	**[0.437, 0.492]**
3	{T_3}	$34,000	[0.521, 0.567]	Deleted (econ. concern)		
4	**{T_1,T_2}**	**$75,050**	**[0.559, 0.616]**	**[0.530, 0.590]**	**[0.428, 0.514]**	**[0.509, 0.575]**
5	{T_1,T_3}	$76,950	[0.561, 0.611]	[0.358, 0.435]	[0.238, 0.346]	Deleted (soc. concern)
6	**{T_2,T_3}**	**$62,700**	**[0.547, 0.600]**	**[0.500, 0.548]**	**[0.414, 0.526]**	**[0.490, 0.559]**

Bold rows in the table denote all possible optimal solutions for that facility after technology assessment

Author contributions Y-H contributed to conceptualization; Y-H and A-S provided methodology; A-S collected data; A-S and R-P carried out calculations; Y-H, A-S, and R-P performed writing—review and editing; Y-H performed overall project supervision and funding acquisition; and all authors have read and agreed to the published version of the manuscript.

Data availability All data used are presented in the manuscript or appendix.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval In this specific research project, it does not apply since it is not considered that there are ethical conflicts.

Consent to participate All authors consent to participate in the research project.

Consent for publication All authors consent to publish the article in question.

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