RESET FORM

WAYNE STATE UNIVERSITY

SPONSORED PROGRAM ADMINISTRATION

DATE: November 4, 2019

LETTER OF INTENT TO ENTER INTO A CONSORTIUM AGREEMENT

Title of Application: Development of a Sustainability Metrics System and a Technical Solution Method for Sustainable Surface Finishing

Proposed Period of Performance: 01/01/20 to 12/31/22

Total Proposed Amount: $ 75,000.00

Recipient Investigator(s): Yinlun Huang

Legal Entity Name and Address: Wayne State University/5057 Woodward Avenue, 13th Floor

Sub-Recipient Investigator(s):

Legal Entity Name and Address:

DUNS Numbers: WSU - 001962224; Other Party -

Prime Sponsor: AESF Foundation

Are Animals Applicable to proposed project ☐ Yes ☑ No

Are Humans Applicable to proposed project ☐ Yes ☑ No

SECTION A – PROPOSAL DOCUMENTS

The following documents are included in our proposal and were prepared in compliance with the prime sponsor's solicitation guidelines

- ☑ Statement of Work
- ☑ Budget
- ☑ Budget Justification
- ☐ Other proposal documents as required by the solicitation
- ☐ Federally negotiated rate agreement (if applicable)

SECTION B – CERTIFICATIONS

1. Facilities & Administrative (F&A) Rates included in the proposal have been calculated based on :

   - [ ] Our federally negotiated F&A rate
   - [x] Other Rate (Please explain)
   - [ ] Not Applicable (No F&A cost)

2. Conflict of Interest – Please select one of the following:

   - [x] My organization **DOES HAVE** a PHS-compliant Financial Conflict of Interest (FCOI) policy and my organization will rely on this policy and associated procedures to comply with PHS Conflict of Interest regulation.

Yes [x] or No [ ] We are registered as an organization with a PHS-compliant FCOI policy with the FDP Clearinghouse: http://thefdp.org/.

   - [ ] My organization **DOES NOT HAVE** a PHS-compliant Financial Conflict of Interest (FCOI) policy.

Yes [x] or No [ ] My organization agrees to rely on Wayne State's University's FCOI policy and procedures to comply with PHS Conflict of Interest regulations.

Note: Organizations checking this option are required to follow WSU's FCOI policies: http://research.wayne.edu/coi/index.php

3. Assurance

By signing this application, I certify (1) to the statements contained in the list of certifications* and (2) that the statements herein are true, complete and accurate to the best of my knowledge. I also provide the required assurances* and accept the obligation to comply with Public Health Services terms and conditions if a grant is awarded as a result of this application. I am aware that any fake, fictitious, or fraudulent statements or claims may be subject me to criminal, civil or administrative penalties.

Debarment, Suspension, and Other Responsibility Matters

Organization certifies by signing this Application that neither it nor its principals are presently debarred, suspended, proposed for debarment, declared ineligible or voluntarily excluded from participation in this transaction by any federal department or agency.

Please Print the name and contact information of the Authorized Representative

Sophia Johnson-Parks
Grant and Contract Officer

Signature of Authorized Sub Recipient Representative

Sophia Johnson Parks

Signature Date:

11/5/19

5057 Woodward, Suite 13202 ◊ Detroit, Michigan 48202-4050 ◊ 313-577-3726 OFFICE ◊ 313-577-5055 FAX

CONSORTIUM/CONTRACTUAL ARRANGEMENTS

Explain the programmatic, fiscal, and administrative arrangements to be made between the applicant organization and the consortium organization.

Programmatic:

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.

To meet the industrial need, we propose this research project, aiming 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 technical solutions for performance improvement.

Fiscal:

This proposal is for $75,000 ($25,000/year for 3 years). Direct costs per year are $24,500 per year with $500 in administrative costs, as limited by sponsor directives.

Administrative:

The award will follow the administrative requirements as detailed in the contract documents from the AESF Foundation.

The applicant and all proposed consortium participants understand and agree to the following statement: The appropriate programmatic and administrative personnel of each organization involved in this grant application are aware of the agency's consortium agreement policy and are prepared to establish the necessary inter-organizational agreement(s) consistent with that policy.

PROPOSAL SUMMARY FORM

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

PRINCIPAL INVESTIGATOR: Prof. Yinlun Huang, Department of Chemical Engineering and Materials Science, Wayne State University, Detroit, Michigan 48202

OVERVIEW. 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.

OBJECTIVE: To meet the industrial need, we propose this research project, aiming 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 technical solutions for performance improvement.

WORK PLANNED: During the project, we plan to work closely with the industry. In the end of the 1st project year, we plan to introduce the first version of the sustainability metric system, with some basic case studies on metrics application, at a SUR/FIN conference. Industrial feedback should be valuable for upgrading the metrics system. In the 2nd SUR/FIN conference, we will present a new version of the sustainability metrics system, a general method for metrics application using real plant data as well as selected new technologies. In the 3rd project year, we will complete the development a powerful sustainability performance improvement method for decision support to plants for identification of critical sustainability problems and technical solution methods under various conditions, such as budget constraint, profit assurance, regulations, etc. These will be presented in the 3rd SUR/FIN conference. We will also work with the AESF to explore a possibility to organize a training workshop for industrial practitioners to learn how to use the sustainability metrics systems and the technical solution methods to analyze and improve their plants' sustainability performance.

SIGNIFICANCE TO THE NASF. The NASF's mission is to: (1) advance an environmentally and economically sustainable future for the finishing industry, and (2) promote the vital role of surface technology in the global manufacturing value chain. The mission statement delivers a very important message. That is, surface finishing sustainability is the industry's commitment, and the development and utilization of advanced technologies should be a key approach to the industry's endeavor for sustainable development. The proposed project should be the earliest effort on the development of a sustainability metrics system specifically for the metal finishing industry. A successful execution of the project should lead to a creation of such a metrics system for scientifically guided sustainability assessment. Using the developed sustainability analysis method, companies should be able to compare their past and current performance in different sustainability categories, and identify bottleneck(s) in each in a systematic way. The analysis should also result in a comprehensive evaluation of some valuable ideas/plans not only for companies to take actions, but also to suppliers (e.g., chemical suppliers) and technology vendors who may need to evaluate their products/technologies' capacity for sustainability performance enhancement.

1. OVERVIEW

The metal finishing industry is critical to many manufacturing industries, such as automotive, aerospace, electronics, defense, as well as a variety of OEMs. This is because the finish on a surface can have a huge effect on the performance, durability, and/or aesthetic appearance of the parts that are used by them. In the U.S., the metal finishing industry is composed of possibly 2,000–2,500 metal finishing facilities, mostly very small (100 employees or less) and independently owned. Over the past two decades, low-cost imports from overseas and other globalization trends have significantly impacted the industry. According to an EPA report in 2007, job loss was in the range of 25-30% between 2000 and 2003, with a corresponding reduction in sales of approximately 40%. [1] A very recent benchmarking survey on a large number of electroplating facilities by Pennington shows that about 80% of the facilities ran at a low profit margin (6% in 2016; 5% in 2017). [2] The industry has been also highly regulated by EPA for decades due to its significant use of numerous toxic/hazardous chemicals and the generation of huge amounts of waste in various forms; this could be very harmful to the environment, human health and communities, as well as facilities' financial performance. From the industrial sustainability point of view, these are all *sustainability* problems that should be holistically studied and solution strategies be systematically developed. [3]

The metal finishing industry has made significant progress in multiple fronts to improve environmental performance over the past decades. In 2000, NCMS published a comprehensive survey on six key environmental variables of 132 metal finishing facilities, covering more than 30 different metal finishing processes. [4] That document also contains some practical guidance for helping facilities to learn how to compare with others in business, how the best environmental performers did it, what kind of equipment they used, how they ran their processes, and how they locked in their advantage. In 2017, NCMS executed an EPA funded project - P2 Research and Implementation for Michigan Metal Finishers. Out of 600 shops nationwide, they received surveys from 31 metal finishing facilities. According to a preliminary project summary shared by Chalmer of NCMS, "almost all of the facilities did significantly better" "in wastewater discharged per sales dollar than would have been expected from the average performance of shops in 1998." However, "the results for sludge generation and for electricity usage are mixed." [5] The preliminary report does not include other types of information that is needed for a complete analysis of the economic, environmental and social performance of those facilities, as that may be beyond the project scope, the same as the NCMS report in 2000. [4]

2. RESEARCH NEED, OBJECTIVE, AND SIGNIFICANCE

Research need. 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. More and more companies have already adopted *voluntary* sustainability measures to better manage their businesses and respond to stakeholders in an increasingly transparent, more-connected world. The metal finishing industry, however, is obviously behind others in response to the challenging needs for sustainable development. As most metal finishing facilities are (very) small, they usually don't have a deep understanding of the concept and principles of sustainability. In general, the companies don't know their facilities' sustainability status, and are lack of needed knowledge, experience, tools, and funds to identify, analyze, and improve sustainability performance in their facilities. They may also worry about whether company's profitability would be negatively affected, while pursuing sustainability.

In recent years, more and more metal finishers and suppliers presented their views, methods and techniques that covered different aspects of sustainability at national platforms, such as the SUR/FIN. But the industry as a whole does not have even the first version of sustainability metrics system for the metal finishing companies to consider a possible adoption for performing basic sustainability assessment on their processes, chemicals, products, plants, as well as existing and new technologies. There exists basically no method, guideline, or tool to assist companies in evaluation of their strategic plans for sustainability performance improvement, while ensuring profitability.

Objective. To meet the industrial need, we propose this research project, aiming 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 technical solutions for performance improvement.

Significance to the NASF. This project should be the earliest effort on the development of a sustainability metrics system specifically for the metal finishing industry. A successful execution of the project should lead to a creation of such a metrics system for scientifically guided sustainability assessment. Using the developed sustainability analysis method, companies should be able to compare their past and current performance in different sustainability categories, and identify bottleneck(s) in each in a systematic way. The analysis should also result in a comprehensive evaluation of some valuable ideas/plans not only for companies to take actions, but also to suppliers (e.g., chemical suppliers) and technology vendors who may need to evaluate their products/technologies' capacity for sustainability performance enhancement.

Relationship to NASF Goals. The NASF, representing the interests of businesses and professionals throughout the surface coatings industry, states that its mission is to: (1) advance an environmentally and economically sustainable future for the finishing industry, and (2) promote the vital role of surface technology in the global manufacturing value chain. [6] This mission statement delivers a very important message. That is, surface finishing sustainability is the industry's commitment, and the development and utilization of advanced technologies should be a key approach to the industry's endeavor for sustainable development. The sustainability metrics system, if proven to be valuable after test use in a few companies, should be adequate for dissemination among metal finishing facilities. It should be also a good education material for workforce training in the metal finishing industry. Thus, this project should contribute very positively to achieve NASF's strategic goals.

3. PROPOSED RESEARCH AND TECHNICAL APPROACH

The main research tasks include the development of a sustainability metrics system and a sustainability analysis and enhancement method. A prototype software tool will be developed where all developed methodologies will be embedded. Case studies will be conducted in the end.

3.1 Development of a Sustainability Metrics System

The metrics system will be developed by resorting to sustainability science and engineering fundamentals. Sustainability is a triple-bottom-line-based concept and practice. It emphasizes long-lasting economic, environmental, and social development. Thus, a sustainability metrics system must consist of indicators in all the three categories.

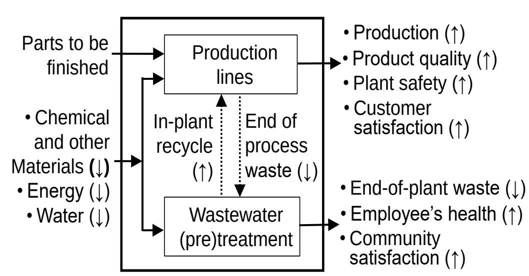


Fig. 1. Sketch of a metal finishing plant with sustainability concerns.

Deep understanding of plant-centric sustainability aspects is a key for the development of an effective sustainability metrics system. Figure 1 lists a number of main factors that must be taken into account. It is known that profitability is the most for company's sustainable development. The indicators in the economic sustainability category should cover those related profit and revenue. These are also related to production efficiency, product quality, production cost (such as costs for chemicals, energy, and water use) and capital investment. Some of these are shown in Fig. 1, where the arrow direction associated with each parameter indicates the preference from the sustainability point of view.

Table 1. Draft list of economic sustainability indicators

Profit, Value and Tax
• Value added ($/y)
• Value added per direct employee ($/y)
• Net profit margin (%/$)
• Net profit per direct employee ($/y)
• Tax paid as percent of NIBT (%)
• Return on average capital employed (%/y)
Investments
• Percentage increase in capital employed (%/y)
• Percentage of new employees (%/y)
• Percentage of training vs payroll expense (%)
• Investment for employee's education/training
• Investment on new technology ($/y)
Production and Product quality
• Percentage of product delivered on time (%)
• Product defect rate during production (%)
• Product return rate after shipment (%)

Environmental sustainability performance for the metal finishing industry is always evaluated by the effectiveness of waste reduction, particularly source waste minimization using cleaner surface finishing technologies. It has shown that profitable pollution prevention (P3) technologies that are developed by the PI [7-21] can be used to not only significantly reduce source waste, but also greatly reduce the consumption of chemicals, water, and energy in production lines as well as onsite waste treatment facility, thus making the production more profitable. Some of the key parameters are listed in Fig. 1.

Plant safety, employee's health risk, workforce education and training, and stakeholders' satisfaction are always counted for the evaluation of social sustainability. Here stakeholders include not only employees and customers, but also suppliers, distributors and business partners, as well as local community. Some of the parameters are also shown in Fig. 1.

Based on the above basic analysis, we propose the following three sets of indicators as a starting point for the development of a sustainability metric system.

Economic sustainability indicator set. Profitability is a key indicator of the success of any metal finishing company. However, the indicator set should not be limited to just from conventional financial reporting; it should include those describing value added aspects, investment for future growth, as well as tax. Furthermore, business credibility should be measured by manufacturing performance and product quality. Table 1 shows a draft list of indicators in three sub-sets of totally 14 indicators.

Environmental sustainability indicator set. EPA has published a good number of environmental studies of the metal finishing industry over the past few decades. In plants, workpieces are plated using a variety of metals, including top regulated pollutants: cadmium, chromium, copper, nickel, silver, and zinc. [22] EPA found that over 80 percent of the cumulative pounds discharged are attributed to conventional pollutants including TSS, TDS, COD, and BOD. EPA also conducted assessment of the current state of the metal finishing industry, including an

Table 2. Draft list of environmental sustainability indicators

Material (excluding fuel and water)
Chemical use in production per value added (lb/$)
Chemical use in production per dollar of sales (lb/$)
Chemical use in waste treatment per value added (lb/S)
Plating solution use per value added (lb/$)
Plating use per dollar of sales (lb/$)
Other material use per dollar of sales (lb/$)
Water
Fresh water use in production per dollar of sales (lb/$)
Used water reused in production before treatment
Fraction of water recycled within plant (%)
Energy
Electricity use per dollar of sales (kW/$)
Natural gas and oil use per dollar of sales (MMBtu/$)
Clean energy use among all energy (%)
Non-production energy among all energy consumption (%)
Waste Generation and Effluents
Spent solutions per value added (lb/$)
Wastewater generated in production per value added (lb/s)
Wastewater treatment sludge per value added (lb/$)
Hazardous waste generated per value added (lb/$)
Non-hazardous waste generated per value added (lb/$)
Human health burden (carcinogenic) per value added (/$)

updated industry profile, descriptions of new and traditional process technologies, and techniques, potential new pollutants of concern, advances in wastewater treatment technologies, and strategies used to achieve zero liquid discharge. [23] EPA listed a number of energy-related Criteria Air Pollutants (CAP) emissions in the metal finishing industry. Thus, the environmental sustainability indicator set should well cover those concerns. Table 2 shows a draft 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.

Table 3. Draft list of social sustainability indicators

Workplace
Benefits as percentage of payroll expense (%)
Work related training (%)
Employee turnover (resigned+redundant / employed) (%)
Promotion rate (promotions / employed) (%)
Working hours lost as percent of total hours worked (%)
Safety and Health
Number of process safety review (/y)
Number of accidents in workplace (/y)
Chemical leakage in plant (/y)
Human health burden (carcinogenic) per value added (/$)
Society
Number of stakeholder meetings (/y)
Indirect community benefit ($/y)
Number of complaints from local community (/y)
Number of complaints from customers (/y)
Number of legal actions per value added (/y)

Social sustainability indicator sets. It is commonly agreed that good social performance of a company is important in ensuring its license to operate over the longer term. The central focus of social sustainability is on people. Thus, the indicators of social performance should reflect the company's attitude to treatment of its own employees, suppliers, contractors, and customers, and also its impact on society at large. Here we propose a total of 14 indicators in three sub-sets shown in Table 3 to measure the social sustainability performance of metal finishing facilities.

3.2 Development of a Guideline for Indicator Selection and Data Collection

Tables 1 through 3 list a total of 47 indicators in 10 sub-sets of the three sustainability categories. This list will be refined based on the feedback from metal finishers in the first two years of the project period. However, the current draft list and a refined list would be still considered long in terms of the number of indicators, and thus companies may feel difficult to use and thus lose interest in adoption. It must be point out that the proposed metrics system can be viewed as a superset of indicators. Each individual metal finishing company can select part of the indicators to conduct a self-motivated assessment. The main benefit for a company is that through assessment, it can compare fairly the company's current sustainability performance with its past or other company's using the same indicators.

Indicator selection. In this project, we will develop a general guideline for metal finishing companies to select indicators. The basic principles for selection would be as follows: (1) since sustainability is triple bottom line based, a certain number of indicators from each of the three tables must be selected, (2) at least one indicator from each subset of each table should be selected, (3) if possible, more indicators should be selected as this will make sustainability assessment more comprehensive, (4) if the company wants to add its own indicator(s) to the list, that should be acceptable, but make sure to place the added indicator in an appropriate sub-set of a right sustainability category, and (5) if a selected indicator requires some information related to suppliers, customers, and/or communities, early communications with them will be needed.

Data acquisition and analysis. A necessary condition in indicator selection is data accessibility, reliability and sufficiency; otherwise, the evaluation of indicator values will be either impossible or unmeaningful. In this project, we will generate a guideline for indicator-specific data acquisition in each the economic, environmental and social sustainability categories. These include data types and acquisition frequency, data processing (i.e., collection and analysis of data including historical ones, data selection from a pool, and data interpretation), and data utilization for indicator value calculation. Note that some data types could be used by more than one sustainability indicator. Also note that for each parameter, the collected data must be in a certain range from the smallest to the largest. The data range for each should be all kept for normalizing each sustainability indicator value. This will be described in the description of the next project task.

3.3 Development of Systematic Sustainability Assessment and Analysis Methods

In the past years, the PI developed a systematic sustainability assessment method that has been successfully used for biodiesel manufacturing systems and automotive nanopaint development and application. [24-27] The method will be adopted here, with necessary modifications, for the assessment of metal finishing sustainability. The framework of the method is briefly described below.

Assessment formulation. Let the economic, environmental, and social sustainability indicator sets be denoted as sets *E*, *V*, and *L*, respectively; they are composite indices. The overall sustainability indicators, named as set *S*, is defined below.

$$S=\{E,\quad V,\quad L\}, \tag{1}$$

where $E=\{E_i \mid i=1,2,\cdots,N_E\}$ is the set of economic sustainability indicators; $V=\{V_i \mid i=1,2,\cdots,N_V\}$ is the set of environmental sustainability indicators; $L=\{L_i \mid i=1,2,\cdots,N_L\}$ is the set of social sustainability indicators; N_E, N_V, and N_L are, respectively, the total number of the economic, environmental, and social sustainability indicators selected for application. For convenience and consistency in sustainability assessment, every indicator will be normalized to a value between 0 (indicating the worst performance) and 1 (the best performance).

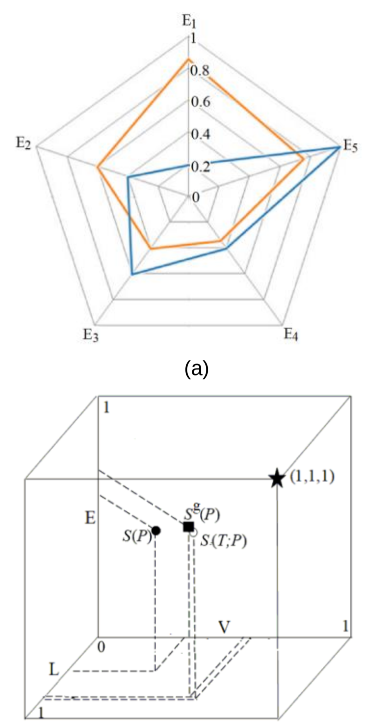
As shown, in each sustainability category (*E*, *V*, or *L*), there are a number of indicators. For instance, the economic sustainability is evaluated based on the values of N_E indicators. Note that a metal finishing company may value the importance of the indicators differently. Thus, we will permit assignment of different weighting factors for different indicators, each of which is in the range of 1 (for the least important indicator) to 5 (for the most important), and set 3 as a default value. This will allow a company to assign a weighting factor to each indicator based on their understanding of the importance of each indicator in the assessment. Therefore, we propose the following formulas for evaluating the economic sustainability (*E*), environmental sustainability (*V*), and social sustainability (*L*), where a_i, b_i, and c_i are weighting factors in a value range from 1 to 5:

$$E=\frac{\sum_{i=1}^{N_E} a_i E_i}{\sum_{i=1}^{N_E} a_i}, \tag{2}$$

$$V=\frac{\sum_{i=1}^{N_V} b_i V_i}{\sum_{i=1}^{N_V} b_i}, \tag{3}$$

$$L=\frac{\sum_{i=1}^{N_L} c_i L_i}{\sum_{i=1}^{N_L} c_i}. \tag{4}$$

The overall sustainability performance of the system, *S*, will be evaluated using the composite indices, *E*, *V*, and *L*, with weighting factors to be assigned again by the company; that is,



(b)

Fig. 2. Scheme for assessment result presentation: (a) economic sustainability, and (b) overall sustainability.

$$S = \frac{\left\|(\alpha E, \quad \beta V, \quad \gamma L)\right\|}{\left\|(\alpha, \quad \beta, \quad \gamma)\right\|}, \tag{5}$$

where α, β, and γ are the weighting factors also in the range of 1 to 5. Because of the normalization of *E*, *V*, and *L*, *S* is also normalized between 0 (completely unsustainable) and 1 (completely sustainable).

Guideline for performance analysis. The above assessment formulation can be used to evaluate the sustainability performance of a system of any scope; the system can be defined as a production line or lines if process sustainability is a major concern; as a product if product sustainability is a main interest; new technologies if they need to be evaluated for adoption for plant sustainability performance improvement; or the entire plant if business sustainability is to be assessed). The above formulation can be used for any particular year, either in the past, current, or the near future. [28, 29]

Radar chart. We propose to use a radar chart to show categorized sustainability status. Figure 2(a) displays an example of the assessment results of the economic sustainability, where five economic sustainability indicators ($E_1 – E_5$) are used in the assessment. The two pentagons (orange and blue colored) represent the assessment results of two cases, such as for two different years of a plants or for a plant to compare with the best practice. This type of chart can help the user to gain a visually clear understanding in performance comparison. This type of radar chart will be used for showing comparative performance of the environmental and social sustainability as well.

Sustainability cube. In addition to the radar chart, we also propose the use of a sustainability cube shown in Fig. 2(b), where the three edges are assigned for different composite indices (*E*, *V*, and *L*). Each edge has a value range from 0 to 1. The corner marked 0 represents the overall sustainability (S) of value of 0, meaning completely unsustainable, while its opposite corner, with the coordinate of (1, 1, 1) represents the overall sustainability (*S*) of value of 1, meaning completely sustainable. In the cube, there are three points, marked $S(P)$, $S^g(P)$, and $S(T;P)$, which designated for, respectively, the current sustainability status of the plant, the sustainability goal set for the plant, and the achieved plant performance after adopting some technologies. In the figure, the dotted lines are originated from the specific values of E, V, and L in different cases.

Both the radar chart and the sustainability cube should be the schemes easy to use by users when comparing different cases.

Rapid identification of sustainability weaknesses. If the performance of any categorized sustainability (i.e., *E*, *V*, and/or *L*) is unsatisfactory, the analysis method can provide some critical information through sorting the indicator-specific assessment results. This will be accomplished by performing the following operation, where the environmental sustainability is taken as an example:

$$\text{Sort}^{\text{des}}(V) = \left\{ V_i \mid i \in N_V \right\}, \tag{6}$$

$$\text{Sort}^{\text{des}}(V) = \left\{ b_i V_i \mid i \in N_V \right\}. \tag{7}$$

Equation (6) gives a list of the environmental sustainability index values in descending order, while Eq. (7) gives a list of the weighted index values also in descending order. Those in the end of the list represent poorer or poorest performance, and the corresponding index numbers are also shown. In this way, the company can easily identify the weak area(s) that they may want to find ways to improve by taking either some technical or managerial actions(s). It should be pointed out that Eq. (7) is for applications in which the company has already assigned different weighting factors to indicators. For instance, if the values of indicators V_2 and V_7 are equal to 0.8 and 0.4, respectively, and if b_2 and b_7 are set to 1 and 5, respectively, then by Eq. (6), the process parameter used for evaluation by the 7th indicator shows a clearly poorer performance than that by the 2nd indicator. However, in the sorted list by Eq. (7), the weighted value of the

2nd indicator (1 x 0.8) is much smaller than that of the 7th indicator (5 x 0.4). Therefore, the improvement of the value of the 2nd indicator is needed; however, its contribution to sustainability performance is very small because of the small weighting factor. This type of information could be valuable for the user.

3.4 Development of an Optimal Sustainability Performance Improvement Methodology

If the sustainability performance is unsatisfactory, the company need to decide what the strategy for performance improvement should be, what and when actions should be taken, what the effectiveness of the actions could be, whether the actions will be affordable, and will the company's profitability be negatively affected. These are very important but also very challenging questions for any company.

Over the past few years, the PI has studied some very challenging sustainability improvement problems, and developed advanced methodologies by resorting to sustainability science and engineering principles; these have been successfully applied to the problems appeared in biodiesel plants, regional strategic planning for biodiesel manufacturing, and nanocoating design and manufacturing. [30-34] In this project, the PI plans to "customize" them to a methodology that will be fully applicable to solving metal finishing sustainability problems. The major steps included in such a methodology is proposed below.

Step. 1. Apply the formulations in Eqs. (2) to (5) to a plant, and generate the following assessment results, $E(P)$, $V(P)$, $L(P)$, and $S(P)$, where P is designated for process, product, or plant – a scope determined by the plant decision maker.

Step 2. Use Eqs. (6) and (7) so that the decision maker can readily identify a number of weaknesses.

Step 3. The plant needs to search for technology candidates (within the plant and/or from technology vendors) that are possibly applicable for removing or mitigating the weaknesses, and collect the technical and cost information.

Step 4. Apply the same sustainability indicators for plant assessment to all M technology candidates and generate the following results: $E_i(T_k); i \in N_E$, $V_i(T_k); i \in N_V$, and $L_i(T_k); i \in N_L$, where $k \in M$. In addition, the cost for using each technology, $C(T_k)$, is recorded.

Step 5. Use the result from Step 4 to generate the following three sets of data about the capacities of the technology candidates for sustainability performance improvement, i.e.,

(a) Individual technology's capacity (indicator specific):

$$\Delta E_i(T_k;P) = E_i(T_k) - E_i(P) \quad (8)$$

$$\Delta V_i(T_k;P) = V_i(T_k) - V_i(P) \quad (9)$$

$$\Delta L_i(T_k;P) = L_i(T_k) - L_i(P) \quad (10)$$

(b) Individual technology's capacity (all indicators based):

$$\Delta E(T_k;P) = \frac{\sum_{i=1}^{N_E} a_i \Delta E_i(T_k;P)}{\sum_{i=1}^{N_E} a_i} \quad (11)$$

Table 4. Technology capacity in sustainability performance improvement

Sustainability category and cost for technology use	Improvement by individual tech			
	T_1	T_2	⋯	T_M
Econ. sust. improvement	$\Delta E(T_1;P)$	$\Delta E(T_2;P)$	...	$\Delta E(T_M;P)$
Environ. sust. improvement	$\Delta V(T_1;P)$	$\Delta V(T_2;P)$	...	$\Delta V(T_M;P)$
Soc. sust. improvement	$\Delta L(T_1;P)$	$\Delta L(T_2;P)$	...	$\Delta L(T_M;P)$
Overall sust. Improvement	$\Delta S(T_1;P)$	$\Delta S(T_2;P)$	...	$\Delta S(T_M;P)$
Cost for technology use ($)	$C(T_1)$	$C(T_2)$	...	$C(T_M)$

$$\Delta V\left(T_k;P\right)=\frac{\sum_{i=1}^{N_V} b_i \Delta V_i\left(T_k;P\right)}{\sum_{i=1}^{N_V} b_i} \tag{12}$$

$$\Delta L\left(T_k;P\right)=\frac{\sum_{i=1}^{N_L} c_i \Delta E_i\left(T_k;P\right)}{\sum_{i=1}^{N_L} ac_i} \tag{13}$$

The above information can be summarized in Table 4, where the cost data ($C(T_i)$) for adopting each technology is also listed.

Step 6. Identify an optimal set of technologies. It is very possible that to achieve a company's sustainability goal, multiple technologies may be selected. We propose the following approach to identify an optimal technology set. With M technology candidates, there are maximum 2^M-1 different combinations (sets), such as $\{T_1\}$, $\{T_1, T_2\}$, $\{T_1, T_2, T_3\}$, $\cdots$. Obviously, the more the technologies in a set, the more costly for a company. Thus, depending on the company's budget, most of the combinations should be removed from the list. We number these technology sets as $T^\alpha; \alpha=1,2,\cdots,\left(2^M-1\right)$. New sustainability performance evaluation after adopting technologies:

$$E\left(T^\alpha;P\right)=\sum_{i=1}^{N_E} \Delta E_i\left(T^\alpha;P\right)+E\left(P\right) \tag{14}$$

$$V\left(T^\alpha;P\right)=\sum_{i=1}^{N_V} \Delta V_i\left(T^\alpha;P\right)+V\left(P\right) \tag{15}$$

$$L\left(T^\alpha;P\right)=\sum_{i=1}^{N_L} \Delta L_i\left(T^\alpha;P\right)+L\left(P\right) \tag{16}$$

$$S\left(T^\alpha;P\right)=\frac{\left\|\left(\alpha E\left(T^\alpha;P\right),\quad \beta V\left(T^\alpha;P\right),\quad \gamma L\left(T^\alpha;P\right)\right)\right\|}{\left\|\left(\alpha,\quad \beta,\quad \gamma\right)\right\|} \tag{17}$$

Note that the information obtained from Eqs. (14)-(17), together with the data from Step 1, can be added to the sustainability cube shown Fig. 2(b). If a company has already set a sustainability goal, represented by $E^g(P)$, $V^g(P)$, $L^g(P)$, and thus $S^g(P)$, these data can be also added to the sustainability cube. The figure provides a clearly view of the plant's current sustainability status, the status after using technologies, as well as a comparison with a company goal.

The effectiveness of technology sets in application can be further evaluated through calculating sustainability improvement percentages in the following way:

$$E^{imp}\left(T^\alpha;P\right)=\frac{\sum_{i=1}^{N_E} \Delta E_i(T^\alpha;P)}{E\left(P\right)} \tag{18}$$

$$V^{imp}\left(T^{\alpha};P\right)=\frac{\sum_{i=1}^{N_V}\Delta V_i(T^{\alpha};P)}{V\left(P\right)}, \tag{19}$$

$$L^{imp}\left(T^{\alpha};P\right)=\frac{\sum_{i=1}^{N_L}\Delta L_i(T^{\alpha};P)}{L\left(P\right)}, \tag{20}$$

$$S^{imp}\left(T^{\alpha};P\right)=\frac{S\left(T^{\alpha};P\right)-S\left(P\right)}{S\left(P\right)}. \tag{21}$$

Table 5. Sustainability status after applying new technologies

Tech.	Econ. Sust.	Envion. Sust.	Social. Sust.	Overall Sust.	Cost ($)
T_1	$\left(E\left(T_1;P\right);E^{imp}_{T_1;P}(\%)\right)$	$\left(V\left(T_1;P\right);V^{imp}_{T_1;P}(\%)\right)$	$\left(L\left(T_1;P\right);L^{imp}_{T_1;P}(\%)\right)$	$\left(S\left(T_1;P\right);S^{imp}_{T_1;P}(\%)\right)$	$C\left(T_1\right)$
T_2	$\left(E\left(T_2;P\right);E^{imp}_{T_2;P}(\%)\right)$	$\left(V\left(T_2;P\right);V^{imp}_{T_2;P}(\%)\right)$	$\left(L\left(T_2;P\right);L^{imp}_{T_2;P}(\%)\right)$	$\left(S\left(T_2;P\right);S^{imp}_{T_2;P}(\%)\right)$	$C\left(T_2\right)$
⋮	⋮	⋮	⋮	⋮	⋮
T_M	$\left(E\left(T_M;P\right);E^{imp}_{T_M;P}(\%)\right)$	$\left(V\left(T_M;P\right);V^{imp}_{T_M;P}(\%)\right)$	$\left(L\left(T_M;P\right);L^{imp}_{T_M;P}(\%)\right)$	$\left(S\left(T_M;P\right);S^{imp}_{T_M;P}(\%)\right)$	$C\left(T_M\right)$
T_i,T_j	$\left(E\left(T_{i,j};P\right);E^{imp}_{T_{i,j};P}(\%)\right)$	$\left(V\left(T_{i,j};P\right);V^{imp}_{T_{i,j};P}(\%)\right)$	$\left(L\left(T_{i,j};P\right);L^{imp}_{T_{i,j};P}(\%)\right)$	$\left(S\left(T_{i,j};P\right);S^{imp}_{T_{i,j};P}(\%)\right)$	$C\left(T_{i,j}\right)$
⋮	⋮	⋮	⋮	⋮	⋮

The above information will be summarized in Table 5. The decision maker can sort the table in several ways. For instance, if the economic sustainability is most important, then he/she can sort the table based on the second column data in descending order. If the cost is the most important factor, then sort based the last column data in ascending order. In the resulting sorted tables, the top lines are the best options for the decision maker to consider adoption.

3.5 Development of a software tool

The proposed methodology described in the preceding section will be fully embedded in a MATLAB based prototype software tool, which is named SAEMF (Sustainability Assessment and Enhancement for Metal Finishing). The major modules of the tool is depicted in Fig. 3. There will be a user friendly interface that manages communication with a user and computation and data processing within the system.

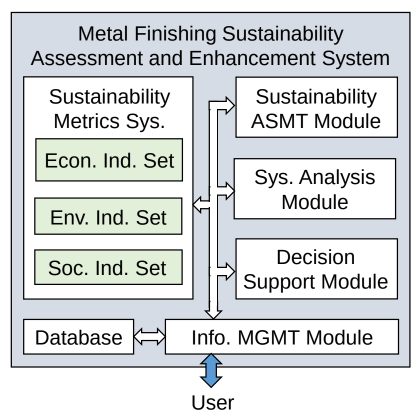


Fig. 3. Basic structure of a metal finishing sustainability enhancement system.

A major operational procedure for a user to use the tool is as follows:

Step 1. The tool guides the user to select sustainability indicators from an indicator menu that is provided by the tool.

Step 2. The tool displays a list of parameters that are directly related to the calculation of the selected indicators. The user needs to respond to the tool whether he/she can collect reliable data for each listed parameter. If no data can be collected, the tool will inform the user which selected sustainability indicator(s) will be removed from the list. If the user agrees, then go to Step 3; otherwise, the user needs to make effort to collect data.

Step 3. The tool guides the user to input data based on the agreeable parameters. Note that for some parameters, there could be more than one data point needed; it is possible that some parameters need many data in order to make data analysis statistically meaningful.

Step 4. The tool guides the user to input additional information, such as budget constraints for investment, workforce training, the minimum profit margin to maintain, technology candidate data, etc.

Step 5. The tool performs sustainability assessment and analysis, and then develop sustainability enhancement strategies. The results will be organized in tables and plots, with necessary short texts for explanation.

Step 6. The user needs to review the tool's output. He/she may repeat the analysis from Step 1.

3.5 Case Studies

The developed methodology and tool will be tested through a number of case studies. The PI has the following plan for this task:

(1) The PI has collected a large amount of information and data from the following sources: (a) those based on the PI's collaboration with a few electroplating facilities over years, (b) publically accessible data from EPA, DOE, and US Census Bureau reports and databases, and (c) open literature and publications, including NCMS' Benchmarking Metal Finishing published in June 2000.

(2) The PI will seek new collaboration with metal finishing plants. The collaboration will be mutually beneficial, as for the PI, his methodology and tool can be tested, and for the collaborating plants, they may gain a much better understanding of the plant sustainability performance and possible solutions for performance enhancement.

(3) The PI will also seek collaboration with technology vendors. Again, this will be mutually beneficial. For the vendors, they may have a comprehensive assessment of the sustainability performance of their technologies and can gain some better understanding about possible acceptance by metal finishing facilities.

The case studies will be published in referred journal and presented at the national/international conferences, such as SURFIN, AIChE national meetings.

4. PROJECT TASKS AND TIMELINES

In the end of the 1st project year, we plan to present the first version of the sustainability metric system, with some basic case studies on metrics application, at a SUR/FIN conference. Industrial feedback should be valuable for upgrading the metrics system. During the 2nd SUR/FIN conference, we will present a new version of the sustainability metrics system, a general method for metrics application using real plant data as well as selected new technologies. In the 3rd project year, we will complete the development of a powerful sustainability performance improvement method for potential users to investigate critical sustainability problems under various conditions, such as budget constraint, profit assurance, regulations, etc. These will be presented in the 3rd SUR/FIN conference. We will also work with the AESF to explore a possibility of organizing a training workshop for industrial practitioners to learn how to use the sustainability metrics systems and the tool. The following is a proposed project schedule.

Table 6. Project schedule

Task		**Year 1**	**Year 2**	**Year 3**
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

5. RELATED RESEARCH AND WORK EXPERIENCE

The PI's research on engineering sustainability has been advanced from Pollution Prevention (P2) in 1993, to Profitable Pollution Prevention (P3) in 2000, Collaborative P3 (CP3) in 2008, and Integrated P3 (IP3) in 2012, all with applied study on metal finishing problems. Since 2008, the PI has extended his research to fundamental study on sustainability science and multiscale sustainable engineering. These are briefly described below.

Pollution Prevention (P2) - Focusing on Source Waste Minimization. The PI initiated his research on Design for Waste Minimization using process synthesis methods and artificial intelligence techniques after joining Wayne State in 1993. His first NSF award was the project, "Artificial Intelligence Based Process Synthesis Methodology for In-Plant Waste Minimization" in 1994. A year later, he became one of the first group of awardees of the NSF/EPA joint program **-** "*Technology for a Sustainable Environment (TSE) Initiative*", with the project, "Intelligent Decision Making and System Development for Comprehensive Waste Minimization in the Electroplating Industry". He developed novel methodologies for source reduction through integrated process design and control where waste source and flow were quantified and managed. His accomplishment was highlighted in the NSF/EPA's TSE program reports (e.g., https://archive.epa.gov/ncer/science/tse/web/html). His research attracted industrial support from AESF, Hughes Aircraft, and surface finishing companies. Industrial applications led to significant source reduction of chemical, water, energy, and thus waste.

Profitable Pollution Prevention (P3) - Emphasizing Economic Benefit While Achieving Source Waste Minimization. Comprehensive investigation of P2 showed that (1) a large number of P2 technologies were in fact for *post-process* application (i.e., to deal with the waste streams generated from processes), and (2) many P2 technologies were very costly in adoption. This raised a major question: is it possible to develop P2 technologies that could generate profit as well? The PI studied the fundamental principles of in-process-oriented P2, and introduced what he called P3 concept and theory, by which quantitative relationships among chemical/water/energy, production rate, product quality, waste minimization, and profitability should be established. He found that the source waste reduction and profit goals could be achieved simultaneously in many cases. He successfully developed eight P3 technologies for the electroplating industry, four of which (for chemical cleaning optimization, water used/reused network design, stage-wised chemical allocation network design, and the reversed electroplating solution recovery system design and operation) were implemented in plants. Michigan Department of Environmental Quality and two plants organized two state-wide technology demonstrations. Impressive achievements include the reduction of fresh water and wastewater by 27.3% and certain hazardous chemical by 92%, while the ratio of annual profit to total annualized cost for using the technologies reached ~20:1 and ~17:1 in two plants (all environmental and economic benefits were calculated by plants). His successful industrial applications led to the recognition of the 2009 Michigan Governor's Green Chemistry Award and the 2010 AIChE Sustainable Engineering Research Excellence Award.

Collaborative P3 (CP3) and Integrated P3 (IP3) - Promoting Synergistic Effort among Participating Industrial Entities and Integrated Use of P3 Technologies for Maximum Benefits. To maximize environmental and economic benefits, collaboration among participating entities, within one or more companies, or sectors in supply chain, are crucial. The synergy and collaboration among entities are one aspect of social sustainability. The PI's study indicates that further development of innovative P3 technologies should include not only those for environmentally benign design and operation, source reduction, production efficiency improvement, but also safety assurance, environmental health, etc. This could encounter challenges about how to apply a group of P3 technologies. In this regard, he advanced P3 to Collaborative P3 (or CP3) and Integrated P3 (or IP3), which requires multi-dimensional system modeling and analysis and decision-making using large scale systems theory. The developed methods and tools have also been successfully applied to a number of auto-manufacturing focused industrial problems, involving surface coating systems (both metal and polymeric coatings), chemical suppliers, and other OEMs that were strongly funded by the Federal agencies and industries.

Sustainability Science and Engineering – Towards Triple-Bottom-Line-Balanced Development. CP3/IP3 contain limited elements of environmental, economic, and social sustainability. To fully address industrial and environmental sustainability problems and derive effective solutions for short-to-long term sustainability, fundamental research on sustainability science and engineering methods is needed. Since 2008, The PI's research has been focused the following areas: sustainability assessment and decision making under uncertainly, sustainable manufacturing, integrated material-product-process design and sustainability analysis and technology sustainability. In recent years, he introduced the concept and fundamentals of multiscale sustainability. He defined two types of multiscale sustainability problems: Type 1 – the systems with sustainability concerns on molecular property, nanoparticle-related health and environmental impact, to the concerns on material/energy efficiency, emission, waste handling, safety, etc., during product/process design and manufacturing stages; and Type 2 – the systems of the scales from process design and production to distributed energy manufacturing in a large geographical region. The methodologies for multiscale sustainable system design and manufacturing have been used to perform hierarchical system modeling, comprehensive sustainability analysis, and multiscale decision making under uncertainty. He has also introduced a mathematical framework of sustainability controllability and observability, and a mathematical framework of life-cycle-based sustainability decision making using large-scale systems theory and uncertainty theory. The developed methods and tools have been successfully used to investigate the problems with distributed biofuel manufacturing, nanopaint/nanocoating manufacturing, recovery of pressure-based mechanical energy in chemical plants, and sustainable surface finishing.

6. REFERENCES

[1] U.S. EPA, Energy Trends in Selected Manufacturing Sectors: Opportunities and Challenges for Environmentally Preferable Energy Outcomes, Final Report, Washington, D.C., March 2007.

[2] Pennington, T., "2018 Top Shops Benchmarking Survey: Electroplating Data Show Profit Correlations," Products Finishing Magazine, April 1, 2018.

https://www.pfonline.com/articles/2018-top-shops-benchmarking-survey-electroplating-data-show-profit-correlations

[3] Huang, Y., William Blum Memorial Lecture – Surface Finishing Sustainability, SUR/FIN Conf., Cleveland, OH, June 9-11, 2014.

[4] NCMS, Benchmarking Metal Finishing, Report 0076RE00, Ann Arbor, MI, June 2000.

[5] Chalmer, P., PRIM Survey Data – Preliminary Summary and Analysis, NCMS, Ann Arbor, MI, June 2018.

[6] https://nasf.org/aboutnasf/, accessed Sept. 28, 2019.

[7] Lou, H. H. and Y. Huang, "Profitable Pollution Prevention: Concept, Fundamentals, and Development," J. of Plating and Surface Finishing, 87(11), 59-66, 2000.

[8] Xiao J. and Y. Huang, "Technology Integration for Sustainable Manufacturing: An Applied Study on Integrated Profitable Pollution Prevention in Surface Finishing Systems," I&EC Research, 51(35), 11434-11444, 2012.

[9] Piluso, C. and Y. Huang, "Collaborative Profitable Pollution Prevention: An Approach for the Sustainable Development of Complex Industrial Zones with Uncertain Information," Clean Technologies and Environmental Policy, 11(3), 307-322, 2009.

[10] Li, X., H. H. Lou, J. Xiao, and Y. Huang, "Surface Coating Thickness Distribution in Electrodeposition: A Case Study on Copper Plating of Tube Inner Surface," J. of Applied Surface Finishing / Plating & Surface Finishing, 95(3), 39-47, 2008.

[11] Kuntay, I., K. Uygun, Q. Xu, and Y. Huang, "Environmentally Conscious Hoist Scheduling in Material Handling Processes," Chem. Eng. Comm., 193, 273-293, 2006.

[12] Lou, H. H. and Y. Huang, Electroplating, in Encyclopedia of Chemical Processing, S. Lee (ed.), Vol. 2, pp. 839-848, Taylor & Francis, New York, NY, 2006.

[13] Xu. Q., A. Telukdarie, H. H. Lou, and Y. Huang, "Integrated Electroplating System Modeling and Simulation for Near Zero Discharge of Chemicals and Metals," Ind. & Eng. Chem. Research, 44(7), 2156-2164, 2005.

[14] Telukdarie, A., C. Brouchart, and Y. Huang, "A Fuzzy-Logic-Based Approach to Cleaner Production Evaluation for Surface Finishing Plants," J. of Plating & Surface Finishing, 92(5), 50-55, 2005.

[15] Xu. Q. and Y. Huang, "Design of an Optimal Reversed Drag-out Network for Maximum Chemical Recovery in Electroplating Systems," J. of Plating & Surface Finishing, 92(6), 44-48, 2005.

[16] Lou, H. H. and Y. Huang, Profitable Pollution Prevention in Electroplating: An In-Process Focused Approach, in Toward Zero Discharge: Innovative Methodology and Technologies for Process Pollution Prevention, T. K. Das (ed.), pp. 476 - 491, Wiley-Interscience, NY, 2005.

[17] Zhou, Q. and Y. Huang, "Hierarchical Optimization of Cleaning and Rinsing," J. Plating and Surface Finishing, 89(4), 68-71, 2002.

[18] Zhou, Q., H. H. Lou, and Y. Huang, "Design of a Switchable Water Allocation Network Based on Process Dynamics," Industrial and Engineering Chemistry Research, 40(22), 4866-4873, 2001.

[19] Lou, H. H. and Y. Huang, "Qualitative and Quantitative Analysis for Environmentally Benign Electroplating Operations," in Green Engineering, Anastas, Heine, and Willamson (ed.), ACS Symposium Series No. 766, Chapter 5 (pp. 42-61), Oxford Press, NY, 2001.

[20] Yang, Y. H., H. R. Lou, and Y. Huang, "Optimal Design of a Water Reuse System in an Electroplating Plant," J. of Plating and Surface Finishing, 86(4), 80-84, 1999.

[21] Yang, Y. H., Lou, H. R. and Y. Huang, "Synthesis of an Optimal Wastewater Reuse Network," Int. J. of Waste Management, 20(4), 311-319, 2000.

[22] US SPA, Preliminary Review of the Metal Finishing Category, EPA 821-R-18-003, Washington, D.C., April 2018.

[23] U.S. EPA, The 2014 Annual Effluent Guidelines Review Report, EPA-821-R-15-001, Washington, D.C., July 2015.

[24] Piluso, C., J. Huang, Z. Liu, and Y. Huang, "Sustainability Assessment of Industrial Systems under Uncertainty: A Fuzzy-Logic-Based Approach to Short-to-Mid-Term Predictions,"Ind. Eng. Chem. Res., 49(18), 8633-8643, 2010.

[25] Xiao J. and Y. Huang, "Technology Integration for Sustainable Manufacturing: An Applied Study on Integrated Profitable Pollution Prevention in Surface Finishing Systems," I&EC Research, 51(35), 11434-11444, 2012.

[26] Liu, Z. and Y. Huang, "Sustainable Distributed Biodiesel Manufacturing under Uncertainty: An Interval-Parameter-Programming-Based Approach," Chemical Engineering Science, 93, 429-444, 2013.

[27] Song, H., J. Xiao, and Y. Huang, "Multiscale Modeling and Optimization of Nanoclearcoat Curing for Energy Efficient and Quality Assured Coating Manufacturing," for the special issue on Sustainable Chemical Manufacturing (Y. Huang and T.F. Edgar, eds), Industrial and Engineering Chemistry Research, 55(12), 3351-3359, 2016. DOI: 10.1021/acs.iecr.5b03167.

[28] Song, H., N. Bhadbhade, and Y. Huang, "Sustainability Assessment and Performance Improvement of Electroplating Process Systems," in Sustainability in the Design, Synthesis, and Analysis of Chemical Engineering Processes (G. Ruiz-Mercado and H. Cabezas, eds.), Chapter 10 (pp. 227-248), Elsevier, 2016.

[29] Moradi Aliabadi, M. and Y. Huang, "Vector-Based Sustainability Analytics: A Methodological Study on System Transition toward Sustainability," Industrial and Engineering Chemistry Research, 55(12), 3239-3252, 2016.

[30] Jayswal, A., X. Li, A. Zanwar, H. H. Lou, and Y. Huang, "A Sustainability Root Cause Analysis Methodology and Its Application," Computers and Chemical Engineering, 35(12), 2786-2798, 2011.

[31] Liu, Z. and Y. Huang, "Technology Evaluation and Decision Making for Sustainability Enhancement of Industrial Systems under Uncertainty," AIChE J., 58(6), 1841-1852, 2012.

[32] Liu, Z. and Y. Huang, , "Sustainability Enhancement under Uncertainty: A Monte Carlo Based Simulation and System Optimization Method," Clean Technologies and Environmental Policy, 17(7), 1757-1768, 2015.

[33] Moradi Aliabadi, M. and Y. Huang, "Multistage Optimization for Chemical Process Sustainability Enhancement under Uncertainty," ACS Sustainable Chemistry and Engineering, 4(11), 6133-6143, 2016.

[34] Moradi Aliabadi, M. and Y. Huang, "Decision Support for Achieving Manufacturing Sustainability: A Hierarchical Control Approach," ACS Sustainable Chemistry and Engineering, 6(4), 4809–4820, 2018.

BUDGET

A	Salary	Year 1	Year 2	Year 3	Total
A.1	PI: Dr. Yinlun Huang (0.1 sum mon)	$2,165	$2,219	$2,275	$6,659
A.2	Graduate Assistant (4.5 acad. mons)	$9,375	$9,609	$9,850	$28,834
	Sub-total Salaries and wages	$11,540	$11,828	$12,125	$35,493
B	**Fringe Benefits**				
B.1	PI: (P6 fringe rate @ 10.8%)	$234	$240	$246	$719
B.2	GRA (fringe rate @ 15.1%)	$1,416	$1,451	$1,487	$4,354
	Sub-total Fringe Benefits	$1,650	$1,691	$1,733	$5,073
	Total Salary and Fringes	$13,190	$13,519	$13,858	$40,567
C	**Travel**				
C.1	Travel: Domestic	$2,500	$2,150	$2,000	$6,650
	Total Travel	$2,500	$2,150	$2,000	$6,650
D	**Other Direct Costs**				
D.1	Materials & Supplies	$1,400	$1,201	$700	$3,301
D.2	Publication Costs	$200	$200	$100	$500
D.3	Computer Services	$210	$150	$271	$631
D.4	GRA Tuition	$7,000	$7,280	$7,571	$21,851
	Total Other Direct Costs	$8,810	$8,831	$8,642	$26,283
	TOTAL DIRECT COSTS (ALL)	$24,500	$24,500	$24,500	$73,500
E	**Fee for grant administration**	$500	$500	$500	$1,500
	TOTAL PROJECT COSTS	**$25,000**	**$25,000**	**$25,000**	**$75,000**

BUDGET JUSTIFICATION

A. Salary:

The PI will be at 0.1 summer months per year. He will be responsible for the entire project, including the accomplishment of the proposed research and development activities, including supervision of students.

One GRA will be appointed for 4.5 months per academic year.

B. Fringe Benefits:

Based on university standard rates, according to position classification, the fringe benefits are determined as 10.8% for the PI's summer effort, and 15.1% for the GRA.

C. Travel:

The funds will be used for the PI and students to attend the SURFIN and other domestic conference to present project results and discussion with industrial practitioners.

D. Other Direct Costs

D.1 In the first project year, the PI will purchase a notebook computer for the project (both software tool development and presentation in industry and national conferences). For the second and the third years, the funds will be used for a printer and other materials.

D.2 The budget will be used for publications.

D.3 The budget will be used for printer cartridge, computer memory, etc.

D.4 For the GRA's one semester tuition

E. Fee for grant administration:

AESF Foundation allows annual charge of $500 for the university to administer the grant

YINLUN HUANG, PROFESSOR
Director, Laboratory for Multiscale Complex Systems Science and Engineering
Department of Chemical Engineering and Materials Science
Wayne State University, Detroit, Michigan 48202

PROFESSIONAL PREPARATION

Zhejiang University, China	Chemical Eng. / Control Eng.	B.S. 1982 / M.S. Study, 1984-86
Kansas State University	Chemical Engineering	Ph.D., 1992; M.S., 1988
University of Texas at Austin	Chemical Engineering	Post-Doc., 1992–93

APPOINTMENTS

- Professor (2002–present), Assoc. Professor (1998–2002), Asst. Professor (1995–98), Asst. Professor Research (1993–95), Dept. of Chem. Eng. & Mat. Sci., Wayne State University (WSU)
- Director, Sustainable Engineering Grad. Certificate Prog., WSU (2008–present)
- Director, Grad. Prog. of Chem. Eng. and Grad. Prog. of Mat. Sci. & Eng., WSU (1996–2019)
- Founding Chair, Sustainability@Wayne – A University-wide OVPR Seminar Series (2012–2019)

PUBLICATIONS (<u>10 most relevant to the proposed project)</u>

1. Moradi Aliabadi, M. and Y. Huang, "Decision Support for Achieving Manufacturing Sustainability: A Hierarchical Control Approach," *ACS Sust. Chem. & Eng*., 6(4), 4809–4820, 2018.
2. Song, H., N. Bhadbhade, and Y. Huang, "Sustainability Assessment and Performance Improvement of Electroplating Process Systems," in Sustainability in the Design, Synthesis, and Analysis of Chemical Engineering Processes (G. Ruiz-Mercado and H. Cabezas, eds.), Chapter 10 (pp. 227-248), Elsevier, 2016.
3. Li, J., R. Uttarwar, and Y. Huang, "CFD-Based Modeling and Design for Energy-Efficient VOC Emission Reduction in Surface Coating Systems," Clean Technologies and Environmental Policy, 15(6), 1023-1032, 2013.
4. Xiao J. and Y. Huang, "Technology Integration for Sustainable Manufacturing: An Applied Study on Integrated Profitable Pollution Prevention in Surface Finishing Systems," Industrial and Engineering Chemistry Research, 51(35), 11434-11444, 2012.
5. Piluso, C. and Y. Huang, "Collaborative Profitable Pollution Prevention: An Approach for the Sustainable Development of Complex Industrial Zones with Uncertain Information," Clean Technologies and Environmental Policy, 11(3), 307-322, 2009.
6. Liu, Z., J. Xiao, and Y. Huang, "Proactive Product Quality Control: An Integrated Product and Process Control Approach to MIMO Systems," Chemical Engineering Journal, 149, 435-446, 2009.
7. Moradi-Aliabadi, M. and Y. Huang, "Multistage Optimization for Chemical Process Sustainability Enhancement under Uncertainty," *ACS Sust. Chem & Eng.*, 4(11), 6133, 2016.
8. Moradi Aliabadi, M. and Y. Huang, "Vector-Based Sustainability Analytics: A Methodological Study on System Transition toward Sustainability," *Ind. & Eng. Chem. Res.*, 55(12), 3239, 2016.
9. Liu, Z. and Y. Huang, "Sustainability Enhancement under Uncertainty: A Monte Carlo Based Simulation and System Optimization Method," *Clean Tech. & Env. Pol.*, 17(7), 1757, 2015.
10. Li, X., H. H. Lou, J. Xiao, and Y. Huang, "Surface Coating Thickness Distribution in Electrodeposition: A Case Study on Copper Plating of Tube Inner Surface," J. of Applied Surface Finishing / Plating & Surface Finishing, 95(3), 39-47, 2008.

SYNERGISTIC ACTIVITIES

1. <u>Professional Leadership Roles</u>: (i) Project Director, NSF RCN-SEES: Smart Manufacturing Advances in Research and Technology Coordination Network (2012–17), involving 14 domestic universities, 6 foreign universities, and 11 national organizations and university research centers/institutes; (ii) AIChE: International Committee Chair (2014-2016); AIChE Sustainable

Engineering Forum: Award Committee Chair (2018-19); Tech. Advisor (2011-17); International Committee Chair (2010-11); Forum Chair (2008–09); Nomination Chair (2007); Membership Chair (2003-05); Founding Chair, Sustainable Engineering for Chemical Engineers (SEChE) Committee, (2012-present); Chair, Process Research and Innovation, Process Development Div. (2003-05); (iii) ACS: Chair, Green Chemistry and Green Engineering Subdivision, I&EC. (2010); (iv) AESF Foundation: Member, Board of Trustees; Chair, Scholarship Board (2007-present).

2. Chair/Co-Chair/Co-Organizer of Sustainability and Process/Product System Engineering Conferences: (i) the 1st to 7th International Congresses on Sustainability Science & Engineering in the U.S. (2009, 2011, 2013 and 2018), Hungary (2015), China (2016), and Spain (2017); (ii) the 1st to 5th International Conferences on Sustainable Chemical Product and Process Engineering in China, 2007, 2010, 2013, 2016 and 2019 (all sponsored by the US National Science Foundation); (iii) NSF Workshop on Sustainable Manufacturing: Urgent Research Needs and Multidisciplinary Collaboration, Arlington, VA, August 2015; (iv) U.S. NSF-China NSF Workshop on Sustainable Manufacturing, Wuhan, China, March, 2014; (v) Int'l Conf. on Sustainability and Safety, Singapore, June 2018; (vi) more than 60 other international/national conferences, symposiums and their plenary and technical sessions, 1997-.
3. Editorial: Assoc. Editor of *Smart and Sustainable Manufacturing Systems* (2015-); Member of Editorial Board, *ACS Sustainable Chemistry and Engineering* (2012–), *Clean Technologies and Environmental Policy* (2007–); *J. of Nano Energy and Power Research* (2010–); *Chinese J. of Chemical Engineering* (2011–); Co-Chair, Editorial Advisory Board, *J. of Applied Surface Finishing* (2006–07); Guest Editor for the special issues of *IECR* (on Sustainable Manufacturing, 2016), *CTEP* (on the Issues of Water, Manufacturing, and Energy Sustainability, 2015), *ACS Sustainable Chemistry and Engineering* (on Sustainable Chemical Product and Process Engineering, 2014), and *Chi. J. ChE* (on Sustainable Chemical Product and Process Engineering, 2008), and Journal Referee for more than 50 journals.
4. Plenary/Keynote Speeches on Sustainability: AIChE Annual Meeting – Sustainability Forum's Plenary, Oct. 28-Nov. 2, 2018 & Oct. 29-Nov. 3, 2017; 9th US-China ChE Conf., Beijing, China, Oct. 15-19, 2017; European CAPE Forum, Athens, Greece, Sept. 6-8, 2017; NASF SUR/FIN Sustainability Summit, Atlanta, GA, June 19-21, 2017; PSE2015/ESCAPE25, Copenhagen, Denmark, May 31-June 4, 2015; RENESENG Workshop, Copenhagen, Denmark, May 27-31, 2015; 4th International Congress on Sustainability Science and Engineering, Balatonfured, Hungary, May 26-29, 2015; SUR/FIN Conf., Cleveland, June 9-11, 2014; 4th Int'l Forum on Sustainable Manufacturing, Lexington, KY, Sept. 12, 2014; Smart Manufacturing and Green Chemistry Workshop, Gaithersburg, MD, June 16-17, 2014; 3rd Int'l. Conf. on Sustainable Chemical Product and Process Eng., Dalian, China, May 27-31, 2013; 2nd World Cong. on Sustainability Eng., Pittsburgh, PA, Oct. 29, 2012; AIChE Annual Nat'l Mtg., Nov. 7-12, 2010; Keynote Speech on Industrial Sustainability, SUR/FIN Conf., Grand Rapids, MI, June 13-17, 2010;. The UNESCO Int'l Workshop on Eng. Education for Sustainable Development, Beijing, China, Oct. 31-Nov. 2, 2006; 7th World Cong. on Recovery, Recycling, and Reintegration, Beijing, China, Sept. 25-29, 2005; and many others.
5. Awards: Elected Fellow of NASF (2017); AIChE Sustainability Education Award (2016); Elected Fellow of AIChE (2014); NASF Scientific Achievement Award, National Association of Surface Finishing (2013); AIChE Research Excellence in Sustainable Engineering Award (2010); Michigan Green Chemistry Governor's Award (2009); Fulbright Scholar, U.S. Dept. of State (2008-09); Charles H. Gershenson Distinguished Faculty Fellow, WSU (2005); Outstanding Graduate Mentor Award, WSU (2001); Career Development Chair Award, WSU (2000); Teaching Excellence Award, College of Engineering, WSU (1999); Presidential Research Enhancement Awards, WSU (2011, 2003); Eminent Engr., Tau Beta Pi - WSU Chapter (1999); DAAD Fellow, Germany (1996); Advisor of 25 Student Best Paper Awards at international/national conferences and national professional society's student scholarships.