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# A Matrix Evaluation Model for Sustainability Assessment of Manufacturing Technologies

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***Abstract*—**Technology assessment is a vital part of decision process in manufacturing, particularly for decisions on selection of new sustainable manufacturing processes. To assess these processes, a matrix approach is introduced and sustainability assessment models are developed. Case studies show that the matrix-based approach provides a flexible and practical way for sustainability evaluation of new manufacturing technologies such as those used in surface coating. The technology assessment of coating processes reveals that compared with powder coating, the sol-gel coating can deliver better technical, economical and environmental sustainability with respect to the selected sustainability evaluation criteria for a decorative coating application of car wheels.

***Keywords*—**Evaluation matrix; sustainable manufacturing; surface coating; technology assessment.



## I. Introduction

TECHNOLOGY assessment (TA) aims at providing knowledge and orientation for acting and decision-making concerning technology and its implementation in society [1]. In sustainable manufacturing, TA is mainly used to provide rational basis and guidance for decision-making about sustainable technologies. For example, TA can be used for analyzing and comparing production possibilities/ alternatives to support decisions on introducing new manufacturing technologies or expanding the use of the existing technologies.

Depending on the purpose of a TA study, technology assessment can be either reactive or proactive. The proactive technology assessment involves the evaluation of technologies that are in their pre-commercial state and not yet readily accepted by the corporate community. In this case, the assessment focuses on study of different alternatives that can bring about the pre-determined goals in an optimal way. With much uncertainty in predicting values of new technologies at the early development stages, proactive TA can present unique challenges, particularly to R&D organizations that emphases technology transfer and commercialization of their scientific outcomes.

The research on TA methodologies has resulted in a number of developments by which new technologies can be assessed to determine future use and diffusion into markets [2]. These may include both the quantitative and qualitative assessment techniques.

In product design and manufacturing domain, the most commonly used assessment methods are quantitative, i.e., the criteria used in assessment are quantifiable and can be measured by metrics, scores, and cardinals. The typical quantitative methods include: quality function deployment [12], decision matrix [3], balanced scorecard, weighted objectives method [4], well-established financial methods for cost-benefit analysis and ROI calculation, as well as the emerging methods in life cycle assessment (LCA) [5] and life cycle costing (LCC) [6]. Although these methods have been successfully applied to many product and process assessment studies with different perspectives, they suffer from a variety of deficiencies when used for proactive TA in manufacturing. For example, most of these methods are designed with a reactive assessment nature rather proactive. They are effective to assess the influence of the existing technologies, but limited in valuing new manufacturing technologies. The difficulty lies in that the consequences of new emerging technologies are highly uncertain and there is little past information on which to base the predictions. Another problem associated with the use of traditional methods in evaluation of sustainable technologies is the lack of a practical and explicit way to define sustainability assessment models for TA.

This paper introduces a matrix approach to proactive TA in sustainable manufacturing. Our focus is to assess the technical, economical and environmental impacts, besides other sustainability factor considerations. This implies that multiple evaluation criteria have to be considered for multi-dimension sustainability assessment. The proposed approach is based on the development of a sustainability evaluation matrix model with a hierarchy of multi-criteria for a given manufacturing technology. Case studies show that the hierarchical matrix models provide a flexible and practical way to define sustainability of manufacturing processes for the use in proactive TA. Furthermore, by using comparative assessment and by involving domain participants and potential users in the TA process, the proposed approach also attempts to overcome the use-stage uncertainty and diffusion-data availability issues in proactive technology assessment.

## II. Related Work

Sustainability manufacturing technology assessment investigates the performance perspectives of manufacturing technologies with respect to multiple sustainability criteria. As the kind of TA highly depends on the technology in question and its stakeholders, it has not been possible to develop a single uniform technology assessment methodology [7]. However, Van den Ende et al. [8] has tried to establish a common framework for conducting TA. In this framework different methods and tools are developed to handle four main types of TA, including the proactive TA to forecast new technological developments and their impacts, and to warn for unintended or undesirable consequences. Among the other prominent TA methodologies, is the constructive technology assessment (CTA) [13] [14]. CTA has been used not only for exploring future technology developments and assessing their potential impacts, but also for making constructive suggestions to adjust the technology under development, thus to broaden its design, development, and implementation processes.

For sustainability assessment of technologies, Foxon et al. suggested use the ecological, economic and social indicators to measure the benefits and disadvantages of technologies [9]. In another study, Pope et al. [10] proposed a modeling concept of 'assessment for sustainability' which seeks to clarify what constitutes sustainability. They also developed corresponding criteria against which an assessment could be performed. A five-step process [15] for undertaking sustainability assessment has been proposed and used in their studies above. Despite all these early efforts, the development of a structured methodology for identification and classification of the most relevant sustainability indicators within a given context appears to be premature, especially for sustainable manufacturing technology assessment in the engineering domain.

## III. The Proposed Approach

### *A. Sustainability Assessment Process*

We have developed a proactive TA process for sustainability assessment of manufacturing technologies. It consists of the following steps.

- To explore technological developments, which strongly depends on the manufacturing domain experts' involvements and contributions;
- To define the TA goals, system boundaries, and sustainability decision criteria covering the technological, economic, environmental and societal requirements;
- To assess potential sustainability impacts of each manufacturing technology with respect to the sustainability criteria defined;
- To value, normalize, weight and aggregate these impacts; and
- To develop alternatives and benchmark them with the technologies under assessment for optimal technological solutions.

The sustainability criteria modeling method and the potential impact assessment method in the proposed TA process above will be elaborated in the following sections.

### *B. Sustainability Criteria Modeling in an Evaluation Matrix*

In our study, sustainability of manufacturing technologies is defined with a set of sustainability criteria along the technical, economic, environmental and societal dimensions. All sustainability criteria are organized in a TA evaluation matrix that is used as a tool to assess the values of technology alternatives against these criteria. The evaluation matrix uses a hierarchical tree structure where:

- A node represents one standardized sustainability criterion identified for every alternative to be assessed;
- An edge indicates a super-sub relationship between two criteria in the hierarchy; and
- A leaf, as the bottom-level node, holds a metric or score to measure the performance of alternative technologies.

In the hierarchy, a higher level criterion takes into account all viewpoints formalized by a set of sub-criteria which is assumed to be operational, coherent and exhaustive [11]. On the other hand, the evaluation of a technology alternative against a higher level criterion node is grounded on the evaluations of all its sub-criteria nodes.

A weight is associated with each higher level criterion. It represents the relative importance of the associated node in relation to other nodes at the same hierarchical level in the tree. In this study, a weight scale of 1~10 is used, with higher weights for more important criteria. All sub-criteria under a node share the weight assigned to their parent node. Fig. 1 illustrates the concepts of and relationships between criteria, sub-criteria and assigned weights in such a hierarchical structure.

### *C. Calculation of Matrix Elements*

Once the considered sustainability factors are organized in the multi-criteria hierarchy structure in Fig. 1, the proactive TA can be conducted to evaluate each technology alternative with respect to the hierarchy of sustainability criteria. This is done by calculating and aggregating node ratings of the tree.

There are two methods for node ratings calculation. One is to use a valuing system to assign a numerical measure as the criterion value of a bottom-level node. The value indicates the performance level of a technology alternative against the criterion at this node. Different valuing systems can be used for this purpose. For example, in one of our case studies, a rating system of (1, 4, 7, 10) is used to assess the alternative's technical performances, where higher values for better performances with respect to the corresponding sustainability criteria. In practice, the semantics of a performance level are usually pre-defined. The definitions are however application-specific.

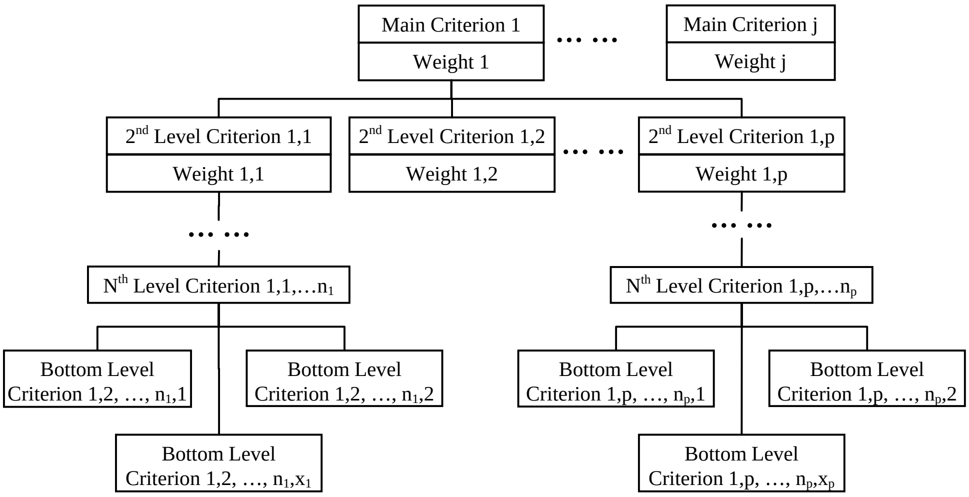


Fig. 1 A hierarchical evaluation structure

Another method for calculating node ratings is to use the metrics associated with each bottom-level node as its criterion value. In this study, the metrics linked with the economic and environmental sustainability criteria are mainly derived from the LCA and LCC analytic tools. Table I shows examples of the LCA and LCC metrics associated with the selected sustainability criteria.

TABLE I
EXAMPLE OF LCA AND LCC METRICS

| Criterion | Metrics |
|---|---|
| Material cost | Material consumption rate<br>Material purchase scale<br>Material scrap rate<br>Part reject rate |
| Tooling cost | % of tool life improvement |
| Savings from process improvement | % of cycle time reduction<br>Number of process steps reduced |
| Greenhouse gas emissions | Quantity of $CO_2$ emission from a mfg. process<br>Quantity of organic emissions |
| Acidification | Quantity of NO emission from a manufacturing process<br>Quantity of $SO_2$ emission |
| Harm to health | Quantity of $PM_{10}$ and $PM_{2.5}$ emissions |

All model elements in Fig. 1 can be represented in an evaluation matrix which is used as the technology assessment model for manufacturing processes in the current study. Table II shows an exemplary evaluation matrix with two hierarchy levels. At the main level, there are three criteria with three different weights, while at the sub level, nine sub-criteria. Two technology options are assessed against these criteria and sub-criteria.

TABLE II
A TECHNOLOGY EVALUATION MATRIX

| Main Criteria ($C_i$) | Sub-Criteria ($C_{ij}$) | Value of Technology Option #1 ($V_{ij}^{(1)}$) | Value of Technology Option #2 ($V_{ij}^{(2)}$) | Weight ($W_i$) |
|---|---|---|---|---|
| $c_1$ | $c_{11}$ | $v_{11}^{(1)}$ | $v_{11}^{(2)}$ | $w_1$ |
| | $c_{12}$ | $v_{12}^{(1)}$ | $v_{12}^{(2)}$ | |
| | $c_{13}$ | $v_{13}^{(1)}$ | $v_{13}^{(2)}$ | |
| | $c_{14}$ | $v_{14}^{(1)}$ | $v_{14}^{(2)}$ | |
| $c_2$ | $c_{21}$ | $v_{21}^{(1)}$ | $v_{21}^{(2)}$ | $w_2$ |
| | $c_{22}$ | $v_{22}^{(1)}$ | $v_{22}^{(2)}$ | |
| $c_3$ | $c_{31}$ | $v_{31}^{(1)}$ | $v_{31}^{(2)}$ | $w_3$ |
| | $c_{32}$ | $v_{32}^{(1)}$ | $v_{32}^{(2)}$ | |
| | $c_{33}$ | $v_{33}^{(1)}$ | $v_{33}^{(2)}$ | |

### D. *Aggregation and Normalization Methods*

An aggregation function*, TA( ),* is defined to calculate all the numerical measures, $v_{ij}^{(k)}$, at each maim criterion level $c_i$ in Table II. The aggregated result provides a quantified assessment to a sustainable technology option. It is calculated by:

$$TA^{(k)} = \sum_{i=1}^{I} w_i \left[\sum_{j=1}^{J} v_{ij}^{(k)} / \sum_{j=1}^{J} Max(v_{ij}^{(k)})\right] / \sum_{i=1}^{I} w_i \,, \qquad (1)$$

where $i = 1, 2,\ldots, I$; $I$ is the number of main criteria; $j = 1, 2,\ldots, J$; $J$ denotes the number of sub-criteria under a main criterion; $k = 1, 2,\ldots, K$; $K$ represents the total number of the technology options being assessed.

To facilitate this aggregation, the $v_{ij}^{(k)}$ measures need to be normalized into a common scale, by using:

$$\textstyle\sum_j max(v_{ij}^{(k)}). \qquad (2)$$

The performance measure of a technology alternative against a main criterion is calculated by aggregating all of the normalized, weighted sub-criteria valuations under the main

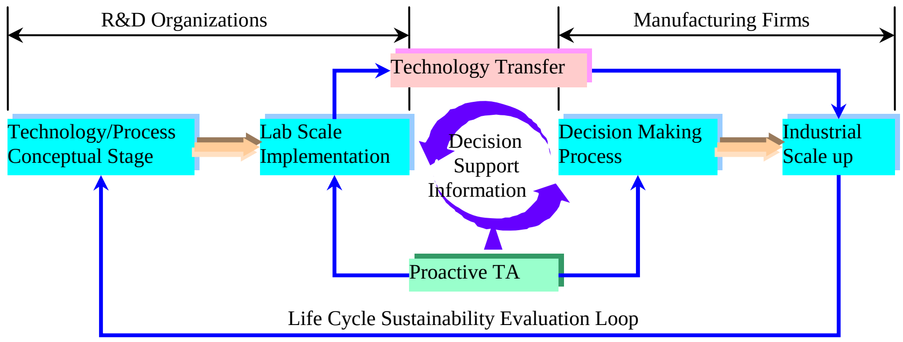


Fig. 2 Proactive TA in manufacturing technology transfer



criterion. Similarly, all the calculated measures at the main criteria level are also normalized corresponding to: $\sum_i w_i$, where $w_i$ is the weight of the $i^{th}$ main criterion.

The final assessment of the technology alternative from the evaluation matrix is the aggregation of the weighted sum of all the sub-criteria evaluations with the non-linear normalizations. Next section will show a case study using the evaluation matrix for technology assessment of a sol-gel coating process and a powder coating process.

## IV. Case Studies: Sustainable Technology Assessment of Coating Processes

The proactive TA approach is used in the following case studies for sustainable technology assessment. A newly developed sol-gel coating technology is assessed and compared with an existing powder coating technology for an automotive decorative application.

### A. *Proactive TA in Technology Transfer*

Sol-gel coating can offer technical advantages over many conventionally applied coatings for automotive components, such as decorative finish for wheels, door/window frames, etc. SIMTech has developed a sol-gel coating process for automotive decorative applications. The lab scale implementation has been completed and a new sol-gel coating process tested. To promote the industrial acceptance of these new technology solutions and to facilitate technology transfer, a TA case study is proposed. Fig. 2 illustrates a process for manufacturing technology transfer which shows the role of TA in the process.

### B. *Sustainability Criteria Design for Coating Process*

The following 3-step process is followed to define the sustainability criteria for the TA evaluation matrix.

- Identifying sustainability criteria from the studied surface coating processes and categorizing the criteria under four sustainability dimensions: technical, economic, environmental and health aspects;
- Quantifying the sustainability criteria with metrics and scores; and
- Organizing them in the TA evaluation matrix.

From this process, the identified technical sustainability criteria mainly cover five aspects: technical feasibility, coating performance, process robustness, process efficiency, and technology maturity. Sub-criteria are defined under each main-level criterion. For example, under the *Technical Feasibility* main criterion, are the four sub-criteria for process feasibility, scale of operations, suitability for clear coating, and suitability for multilayer coating. They are measured by using our earlier defined score-scales in Section III.B. For economic and environmental criteria, the above process generates the results in Table I, in which the economic criteria are quantified by LCC metrics and environmental criteria by LCA metrics. A quantification case study on LCA metrics is given below.

### C. *Environmental Criteria Quantification Case Study*

The quantification of some environmental sustainability criteria in Table I is elaborated here. They are *greenhouse gas emission* mainly influencing climate change and *harm to health* responsible for respiratory (inorganic) effects. The environmental impact quantification follows an ISO standard methodology [5] for LCA. It involves the compilation of environmental intervention data, and the calculation of mass/energy flows and releases.

The environmental interventions ($EnvIV_j$) of the sol-gel coating process are quantified according to the expression of:

$$EnvIV_j = \sum IV_{j,i} X_i, \tag{3}$$

where $IV_{j,i}$ is the $j^{th}$ intervention (i.e. quantified environmental burden per flow) from the $i^{th}$ process step; $X_i$ is a mass or energy flow associated with that process step; $i = 1, 2, \ldots, I$, $I$ is the total number of process steps; $j = 1, 2, \ldots, J$, $J$ is the types of environmental interventions from the system. A commercial LCA software package, GaBi, can be used to provide environmental intervention data $IV_{j,i}$ for calculating $EnvIV_j$ above, if the mass and energy flows, $X_i$, have been specified. Fig. 3 shows the metrics calculation results (in relevant scale) for $CO_2$ emission and organic emissions (group VOC), while Fig. 4 for NO and $SO_2$ emissions over each coating process step. These metric calculations will be used to populate the corresponding evaluation criteria in Table I for technology assessment of the coating processes.

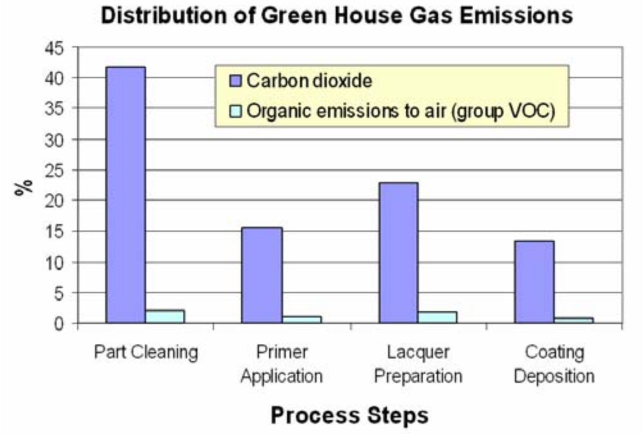


Fig. 3 Emission profile of greenhouse gases released from the processes for power generation, water processing, and sol-gel coating

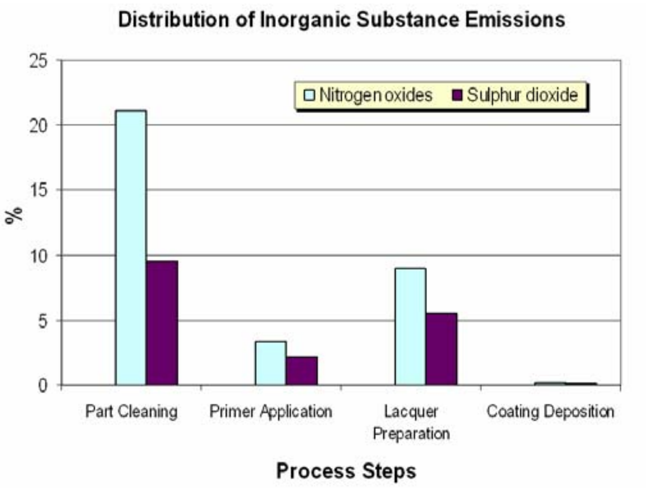


Fig. 4 Emission profile of inorganic substances which are predominantly associated with generation of electricity used in the process

### D. TA Case Study for Coating Processes

Based on the sustainability criteria identified in Section IV.B and in Table I, an evaluation matrix model has been defined for surface coating TA. The model has two hierarchical levels for main criteria and sub-criteria respectively. It is used to assess and compare the sustainability of sol-gel coating and powder coating technologies. Besides the assessment model development, weights are also determined and assigned to each main criterion based on its relative importance. Opinions about the sustainability performances of sol-gel and powder processes in automotive decorative applications are collected from domain participants, incorporated with the inputs from potential technology adopters. By doing so, we try to reduce the uncertainty and implementation risks associated with the technology transfer of the new coating processes.

The coating technology assessment inputs are given in Table III, including the weights assignment and sustainability performance predictions of the sol-gel process. The input data for an existing powder coating process are also listed in the table as a benchmark.

TABLE III
SUSTAINABLE TECHNOLOGY EVALUATION MATRIX

| Main Criteria | Sub- Criteria | Sol-Gel Coating | Powder Coating | Weight |
|---|---|---|---|---|
| Technical Feasibility | Process feasibility | 7 | 10 | 10 |
| | Scale of operations | 10 | 7 | |
| | Suitability for clear coating | 10 | 4 | |
| | Suitability for multilayer coating | 7 | 4 | |
| Coating Performance | … | … | … | 7 |
| Process Robustness | … | … | … | 5 |
| Process Efficiency | … | … | … | 7 |
| Technology Maturity | … | … | … | 3 |
| Material cost | Overspray / scrap rate | 100% | 40% | 10 |
| | Part reject rate | 5% | 5% | |
| Process savings | Number of process steps reduced | 1 | 0 | 8 |
| Acidification ($g/m^2$) | Quantity of NO emission | 0.11 | 0.48 | 5 |
| | Quantity of $SO_2$ emission | 0.09 | 0.039 | |
| Harm to health (mPt) | Quantity of $PM_{10}$ and $PM_{2.5}$ emissions | 172 | 368 | 5 |
| **Assessment Result** | | **75.4%** | **68.4%** | |

The assessment results are represented in a relevant scale in Table III: the higher the assessment result is, the better sustainability the process possesses. For this case study, the sol-gel coating process delivers better technology sustainability than powder process does, with respect to the selected evaluation criteria for a decorative coating application of car wheels.

### E. Beyond Technology Assessment

The results from the coating technology assessment in Table III show that the sol-gel process is more competitive than the powder coating process for the car wheels decorative application. Based on this TA study, the sol-gel process has been selected as a candidate for decorative coating of the case parts. Beyond this, the economic and environmental sustainability metrics at the sub-criteria level in Table III are further assessed. The purpose is to provide more detailed coating performance data to support informed decision-making on adoption of a new coating technology with better economic and environmental sustainability. Using the proposed economic assessment metrics, the critical cost drivers of the sol-gel process have been identified as: overspray rate, material purchase scale, and process reengineering. Control measures are simulated to adjust process parameters to meet the requirements from these critical cost drivers, thus to minimize the total unit cost of the coated case parts. Similarly, by calculating the sol-gel environmental assessment metrics, the process emission hotspots have also been revealed. These include the part cleaning and lacquer preparation of the sol-gel process. As these process-steps contribute most of the inorganic substance emissions and the greenhouse gas emissions, the improvements to these areas, such as water consumption in part cleaning and energy efficiency of lacquer preparation, would help to reduce the environmental load of the sol-gel coating process.

## V. Conclusion

Quantitative justifications on technical, economic and environmental performances of new manufacturing technologies are of critical importance. This is especially true for potential industrial adopters to evaluate technological innovations for implementation. Proactive technology assessment can facilitate this decision process by providing critical information and insights for them to reduce technology implementation risks, thus to facilitate the smooth technology transfer to industry.

A matrix approach to proactive TA has been presented in this paper. The approach has also been tested with coating case studies in sustainability assessment of manufacturing technologies. The proposed TA method overcomes the limitations of the existing approaches by proactively integrating the potential environmental, economic and social impacts into the technological advancement assessment. It also provides detailed methods on how to systematically build the sustainability evaluation matrix and how to derive the matrix calculation results. The TA method and the matrix model developed in this study would therefore enrich the TA methodologies for their use in sustainable manufacturing.

The limitation of the proposed TA method has been identified. This includes the uncertain process parameter's handling and the matrix weighting method enhancement. Our future work will incorporate uncertainty analysis into the proactive technology assessment, and further improve the sustainability weighting calculations in the matrix evaluation model.

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