Integrating Sustainable Manufacturing Assessment into Decision Making for a Production Work Cell

Hao Zhang[1], Karl R. Haapala[1]*

[1] Industrial Sustainability Laboratory, School of Mechanical, Industrial, and Manufacturing Engineering, 204 Rogers Hall, Oregon State University, Corvallis, OR 97331

*Corresponding Author: Email: karl.haapala@oregonstate.edu, Phone: (541)737-3122, Fax: (541)737-2600

Abstract

Sustainability has been the focus of intense discussions over the past two decades, with topics surrounding the entire product life cycle. In the manufacturing phase, research has often focused solely on environmental impact assessment or environmental impact and cost analysis in its assessment of sustainability. Few efforts have investigated sustainable production decision making that addresses the three pillars of sustainability concurrently; which requires engineers and managers to consider economic, environmental, and social impacts. An approach is developed to assess broader sustainability impacts by conducting economic assessment, environmental impact assessment, and social impact assessment at the work cell level. Assessment results are then integrated into a sustainable manufacturing assessment framework, along with a modified weighting method based on pairwise comparison and an outranking decision-making method. The approach is illustrated for a representative machining work cell producing stainless steel knives. Economic, environmental, and social impact results are compared for three production scenarios by applying the sustainable manufacturing assessment framework. The case study finds that cutting tool cost is the largest contributor to production costs for the investigated work cell. The level of environmental and social impact varies according to cycle time. Sensitivity analysis is conducted to examine the robustness of the results.

Keywords: Sustainable manufacturing; Manufacturing work cell; Life cycle assessment; Decision making

1. Introduction

The world market has enabled manufacturers to trade globally and even position their factories in other countries for strategic advantages (e.g., access to supply chains and lower labor costs). With a changing environment and increasing concern for the human-ecology system, manufacturers recognize the advantages of taking responsibility for reducing industrial energy use and wastes (Rusinko, 2007). Gradually, more environmental and social protection policies have been enacted by the government, which has prompted manufacturers to consider environmental impact and social impact in production (Barrett, 1994). At the same time, personal and business consumers are demanding more sustainable products, prompting companies to develop their own sustainability indices and targets to reduce market risk. The idea of sustainable manufacturing has emerged over the past 40 years (Haapala et al., 2013). It can be defined as producing products in a way that minimizes environmental impacts and takes social responsibility for employees, the community, and consumers throughout a product’s life cycle, while achieving economic benefits. It is crucial that decision makers within and across industries work together to develop approaches that support industrial sustainability (Jegatheesan et al., 2009). Sustainable manufacturing performance originates from the shop floor and, thus, engineers must be aware of the attendant economic, environmental, and social issues, as well as the methods and tools to address them.

Several methods and tools have been developed to analyze the sustainability performance of a manufacturing system. Life cycle costing (LCC) analyzes costs from a product life cycle perspective, which provides a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item (Asiedu and Gu, 1998). Life cycle assessment (LCA) offers a holistic tool encompassing all environmental exchanges (i.e., resources, energy, emissions, and wastes) occurring over the product life cycle (Klöpffer et al., 2007). Environmentally-focused manufacturing process modeling has investigated various operations (e.g., Dalquist and Gutowski, 2004; Gediga et al., 1998; Gutowski et al., 2006; Haapala et al., 2004; Jeswiet and Nava, 2009; Masanet and Horvath, 2004; Helu et al., 2012; Kong et al., 2013; and Munoz and Sheng, 1995), to support LCA studies. Recent global efforts have reinforced manufacturing-focused LCA (Kellens et al., 2012a, 2012b). Rajemi et al. (2010) developed a model for optimizing a machining process (turning) on the basis of energy consumption, while Pusavec et al. (2010) compared a novel machining process (cryogenic and high pressure jet assisted) to conventional machining for a broad set of sustainability metrics. While several efforts have been undertaken to include social assessment into LCA (e.g., Dreyer et al., 2006; Hutchins and Sutherland 2008; Lee et al., 2010; Jørgensen et al., 2010; Hutchins et al., 2013; and O'Brien et al., 1997), currently, there is no commonly accepted method. Social LCA guidelines developed by UNEP follow the structure of LCA (Benoît et al., 2010), but an operational methodology is needed in order to be applied to manufacturing systems.

Engineers on the manufacturing shop floor face a variety of challenges, including optimizing production systems, complying with environmental laws and regulations, and addressing operator physical safety and mental concerns. Research into sustainable manufacturing decision making has focused on reducing environmental impacts and production costs since as early as the 1980s. Malakooti and Deviprasad (1987) developed an interactive multiple criteria approach and decision support systems (DSS) for metal machining operations. The analytic hierarchy process (AHP) (Avram et al., 2010), Markov processes (Milacic et al., 1997), and pairwise comparison analysis (Basu and Sutherland, 1999) have all been explored to support sustainable manufacturing decision making. Hersh (1999) posited that sustainable decision-making research is required in a number of different areas including the development of improved models for decision making and problem classification, the development of improved user interfaces, and DSS based on different types of decision-making models. Greater understanding should be gained regarding the types of decision makers, organizations, and situations to determine the most appropriate approaches. Romaniw (2010) argued that detailed assessments are still lacking, which are necessary for robust decision making at each stage of product life.

While research efforts have been conducted into each sustainability domain, existing frameworks, methods, and tools for integrating such assessments into manufacturing decision making for process improvement are lacking. The research herein addresses several of the existing deficiencies by developing an approach to integrate sustainable manufacturing assessment into decision making to assist engineers in conducting process planning at the work cell level. Prior work focused on the assessment of an individual part feature (Zhang and Haapala, 2012), while this work examines a set of operations and setups.

2. Methodology

The approach developed as a part of this research integrates economic assessment, environmental impact assessment, and social assessment to evaluate the sustainability of a manufacturing work cell. Assessment results are further integrated into a decision-making methodology. Pairwise comparison is utilized in weighting of metrics. Compared with other weighting methods, pairwise comparison can most appropriately assist engineers in making both subjective and objective judgments (Böhm et al., 2008). Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) is used for ranking alternatives, which allows a decision maker to evaluate the scores for different alternatives. PROMETHEE is applied here because of its simplicity and applicability in various work cell situations, which often have a discrete solution set that needs to be quickly explored.

Figure 1 describes the approach for sustainability assessment of a production work cell. A work cell is composed of equipment, utilities, labor, required materials, and supplies. The horizontal flows shown in the figure represent the primary input and output flows for the work cell. The inputs of the work cell include physical flows and information flows. Process conditions (information flows) include process settings (e.g., machining parameters) and working environment parameters (e.g., lighting and heating levels). Outputs of the work cell include the processed part, solid and liquid waste, which may be associated with economic, environmental, and social impacts.

(Figure 1 near here)

The vertical flows in the figure depict the information flows where assessment tools and decision making are involved. Economic, environmental, and social impacts are analyzed. The results are integrated using an alternative ranking multi-criteria decision-making process and improved process settings can be identified and chosen as a new working condition.

2.1 Sustainability assessment of a production work cell

The following describes the details of applying three tools in sustainability assessment and multi-criteria decision making for a production work cell. Economic, environmental, and social assessment are first described, and then the decision-making approach is introduced.

2.1.1 Economic assessment

Economic assessment covers four work cell aspects: facility costs, labor costs, material costs, and utility costs. In order to compare options, decision makers are required to identify and quantify appropriate metrics. Economic metrics are computed on a cost per part basis. Cost per part can represent a factory's economic goal, which is to gain maximum profit based on limited orders. Economic metrics can also be computed on a cost per time period. This happens when the work of a work cell is not affected by the lack of product orders (i.e., it is fully utilized). The result of cost assessment can be a single value (e.g., in dollars). It can also be multiple values in different categories, which gives more detailed information for cost analysis of specific materials. This work uses the former approach to assist ranking of alternatives and the latter for contribution analysis.

2.1.2 Environmental assessment

Life cycle assessment (LCA) can be applied to analyze the environmental impacts of the work cell. LCA includes four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Curran, 2006). By identifying the quantity of materials and energy use for different processes in the work cell based upon a defined functional unit, practitioners can associate the input and output materials and energy use with environmental impact categories for scenario-based comparisons. Goal and scope definition identifies what is being studied and why, as well as the processes/activities that are involved in the work cell and the functional unit. Life cycle inventory (LCI) analysis involves creating an inventory of flows within the work cell, including raw material, energy, releases, and any resources related to the work cell processes. Life cycle impact assessment (LCIA) evaluates the significance of environmental impacts identified in the life cycle inventory. In this phase, the LCI results are characterized to produce a number of impact indicators. Interpretation evaluates the accuracy of the results from the life cycle inventory (LCI) and life cycle impact assessment (LCIA) activities, for example through sensitivity analysis. Thus, while LCA was devised primarily as a product evaluation method, its utility for conducting process and systems-level analysis is evident for assisting sustainable manufacturing assessments.

2.1.3 Social assessment

Assessment of social sustainability at the work cell level has more challenges than economic and environmental sustainability because prior research has focused on the organization level rather than a small production unit. Social LCA (SLCA) provides a framework for analyzing the social impact of a system (Benoît et al., 2010). When SLCA is applied to a work cell, the framework requires modification of scope and boundary. The metrics are also limited to specific aspects at the work cell level instead of considering social impacts of all levels.

Similar to LCA, the goal and scope definition with SLCA aims to describe the study (Benoît et al., 2010). In this phase, a practitioner identifies the purpose of the study, the system assessed, and the users of the results. The work cell may be composed of multiple sub-processes, so social impact of the work cell is also limited due to its size and functionality. Hence, practitioners need to clearly understand the relationship between the work cell and other functional units within the system. Since society is an interrelated system, it is without any question that a work cell’s performance does affect social impact at a higher level, for example impacting the community and society through worker health and safety. However, more readily measurable, less uncertain, and more manufacturing relevant social impact metrics for a work cell are at a considerably lower level (e.g., wages, injuries, and workload), which have a direct effect on the workers.

In the life cycle inventory phase of SLCA, the system is modeled, data is collected, and results are obtained. Once the work cell system boundary is defined, practitioners need to collect relevant social data. Data collection for a screening-level analysis can be conducted through literature review and web search. Site-specific data collection may be carried out through a social audit that may involve (Benoît et al., 2010):

- Review of documentation
- Participative methodologies
- Directed and semi-directed interviews
- Focus groups
- Questionnaires and surveys

Collecting social impact data is not an easy task for a work cell because not all the data can be retrieved from records, and the validation of collected data is difficult. Practitioners would need to address these uncertainties in the interpretation phase.

For social impact assessment, stakeholders can be categorized into following types: worker, consumer, local community, society, and value chain actors (Benoît et al., 2010). In this phase, practitioners need to select appropriate metrics for assessment. Each inventory result is then assigned to a specific stakeholder category and impact subcategory. The method of quantifying each metric developed herein is to evaluate the difference between the local performance standard (P_{local}), e.g., average operator wage, and the work cell performance (P_j), e.g., wage for the operator position under study. Social impact measures are then normalized into relative values which sum to 1 for all scenarios analyzed. The normalized value (a_{ij}) is calculated using Equation 1.

$$a_{ij} = \frac{P_{ij} - P_{local,ij}}{\sum_{j=1}^{m} P_j - P_{local,ij}} \quad (1)$$

In this equation, a_{ij} is the normalized value of i^{th} metric and j^{th} alternative. There are n metrics and m alternatives. The total social impact, I_{3_j}, of each alternative (j) can then be calculated as (Eq. 2):

$$I_{3\_j} = \sum_{i=1}^{n} a_{ij} \quad (2)$$

After cost assessment, environmental impact assessment, and social assessment are conducted, impact metrics and associated results are then to be used to assist decision making.

2.2 Decision making for work cell sustainability

Multi criteria decision making (MCDM) methods can provide support to engineers making sustainable work cell design decisions. With MCDM, results from economic, environmental, and social assessments can be integrated and weights can be assigned to compare metrics. In this section, a mathematical method, which is based on the analytic hierarchy process and PROMETHEE method is developed, where AHP is used to assist in assignment of weights and PROMETHEE is used to assist in ranking of alternatives. The steps of the method are described below.

Step 1: Metric definition

Engineers and other decision makers must address many factors in sustainable manufacturing decision-making problems. Therefore, it is necessary to categorize the metrics and simplify the problem to be analyzed. Here, the metrics are categorized into three levels (Figure 2).

(Figure 2 near here)

The top level shows the overall decision-making problem, which is to improve work cell sustainability performance by evaluating each alternative, j. The middle level encompasses the three sustainability domains. Each metric is shown in the bottom level for each of the sustainability domains, where k is the domain identifier (k of 1=economic, 2=environmental, and 3=social). The set of n metrics are defined for each domain based on a discussion of all decision makers involved. Normally, metric selection should consider decision makers' goals as well as regulations and company policies. Through this process, a set of metrics should be generated, ready to be assigned weights.

Step 2: Weight assignment

Pairwise comparison was developed by Thurston (1927) to study preferences, attitudes, and social choice. In order to give a proper weight for each metric, a pairwise comparison of importance between n metrics needs to be conducted by the decision maker, who will judge $(n^2-n)/2$ times which will increase the consistency of judgment in case any error is made. The judgment shall be followed by the guideline of Table 1, which provides fundamental scale of absolute numbers for a judgment result.

(Table 1 near here)

The eigenvector of the matrix M_k, the comparison matrix of judgment result, is the weights of all the metrics in the comparison vector, $W_k = (w_{1k}, w_{2k} \ldots, w_{nk})^T$, where k is the domain identifier (Eq. 3).

$$M_k = \begin{bmatrix} \frac{w_{1k}}{w_{1k}} & \frac{w_{1k}}{w_{2k}} & \cdots & \frac{w_{1k}}{w_{nk}} \\ \frac{w_{2k}}{w_{1k}} & \frac{w_{2k}}{w_{2k}} & & \\ \vdots & & \ddots & \vdots \\ \frac{w_{nk}}{w_{1k}} & & \cdots & \frac{w_{nk}}{w_{nk}} \end{bmatrix} \quad (3)$$

In general the eigenvalue λ_k can be used to determine if M_k is a consistent matrix, because $\lambda_k = n$ when matrix M_k is consistent, and $\lambda_k > n$ when the matrix is not consistent. A consistency index (CI) is defined to evaluate the inconsistency as (Eq. 4):

$$CI = \frac{\lambda_k - n}{n-1} \quad (4)$$

The random index (RI) is the average value of CI for random matrices using the Saaty scale (Saaty, 1980). Various authors have computed and obtained different RIs depending on the simulation method and the number of generated matrices (Alonso and Lamata, 2006). Saaty and Uppuluri (1980) simulated an experiment with 500 and 100 runs, respectively, and obtained the RI values for matrix sizes ranging from 1-15 (Table 2).

(Table 2 near here)

The consistency identifier (CR) is the ratio of CI and RI (Eq. 5), which indicates the acceptability of the judgments made by the decision maker.

$$CR = CI/RI \quad (5)$$

When $CR < 0.1$, the consistency of the matrix is acceptable, and when $CR \geq 0.1$ the matrix needs revision (Saaty, 1980). In other words, when $CR \geq 0.1$, the decision maker must apply new judgments by reconducting the pairwise comparison.

After evaluating the bottom level metrics (Figure 2), decision makers then evaluate middle level metrics and make a comparison among the economic, environmental, and social domains of sustainability. The comparison result provides the weight (w_k) for each of the three domains. An integrated weight (w_t), which is the result from the domain weight (w_k) and metric weight ($w_{k,n}$) in a certain domain, is calculated using Eq. 6.

$$w_t = w_{k,n} * w_k \quad (6)$$

Step 3: Alternative ranking

The PROMETHEE method proposed by Brans and Vincke (1985) uses the outranking principle, which allows preferable alternatives to rank higher than others, outranking methods exhibit ease of use and low complexity (Pohekar and Ramachandran, 2003). The preference function *P* translates the difference between the evaluations obtained for the two alternatives (*a* and *b*) in terms of a particular criterion, into a preference degree ranging from 0 to 1 (Eq. 7).

$$P(A_a, A_b) = G(f(A_a) - f(A_b)) \tag{7}$$

For each alternative *a*, belonging to the set *A* of alternatives, $\pi(A_a, A_b)$ is an overall preference index of *a* over *b*, taking into account all *n* criteria (Eq. 8).

$$\pi(A_a, A_b) = \sum_{i=1}^{n} [w_t * \pi(A_a, A_b)] \tag{8}$$

Then, alternatives are ranked in both positive and negative flow. The overall preference index, $\pi(A_a, A_b)$, is given for alternative *a* over alternative *b*. A positive outranking score can be calculated by summing up the overall preference values of alternative *a* over all the other *m-1* alternatives (Eq. 9).

$$\varnothing^{+}(A_a) = \frac{1}{m-1} \sum_{b=1}^{m-1} \pi(A_a, A_b) \tag{9}$$

Similarly, a negative outranking score represents how much alternative A_a is not preferred compared with all the other alternatives. The negative outranking score can be calculated using Eq. 10.

$$\varnothing^{-}(A_a) = \frac{1}{m-1} \sum_{b=1}^{m-1} \pi(A_a, A_b) \tag{10}$$

The value of positive ranking flow signifies how much each alternative outranks the others. The larger $\varnothing^{+}(A_a)$ is, the better the alternative. A similar principle applies to the negative outranking flow: the smaller $\varnothing^{-}(A_a)$ is, the better the alternative.

In the end, a net ranking score $\varnothing(A_a)$ represents the integration of both positive ranking preference and negative ranking preference for alternative A_a. The net score $\varnothing(A_a)$ can be calculated using Eq. 11.

$$\varnothing(A_a) = \varnothing^{+}(A_a) - \varnothing^{-}(A_a) \tag{11}$$

The net ranking provides the final ranking and basis for a recommendation to the decision maker.

3. Application of the approach

To demonstrate this approach for sustainable manufacturing decision making, the case of a work cell for machining a stainless steel knife is presented in the following sections.

3.1 Case background

The hypothetical company located in northwest Oregon considered in this study produces stainless steel knives. First, knife blanks are laser cut from a stainless steel sheet. Second, knives are sent to a grinding work cell to create the basic blade geometry. Next, the knives move through two machining work cells (Machining Cell 1 and Machining Cell 2) to process the inner and outer profiles. Thereafter, the machined knives are heat-treated and sharpened. Finally, the knives are packed and shipped to retailers. The company is evaluating its production to improve processes from a sustainability perspective.

(Figure 3 near here)

In order to create a smooth surface and precise dimensions for one of its models, Knife X (Figure 3), Machining Cell 1 processes the inside surface of the lanyard hole and a portion of the handle. Machining Cell 2 processes the remainder of the handle and the blade spine. The production engineer will undertake a sustainable manufacturing assessment by focusing on Machining Cell 1. The study begins with the setting of peripheral milling parameters (speed and feed), which affect the surface quality, as well as several other sustainability metrics.

3.1.1 Work cell description

The work cell investigated in this study, Machining Cell 1, includes two CNC milling centers (M1 and M2), a coordinate measuring machine (CMM), a chamfer mill, and one operator. The milling centers are operated under a power condition of 208 volts and 40 amps. Energy use varies depending on machine utilization. The CMM draws 2.5 kW during operation. In this study, due to the limitations of available information, it is assumed that CMM consumes 2.5 kW during idle time as well. The chamfer mill draws 1.5 kW when it is chamfering and is turned off when idle. Each operator works 22 days per month and has an eight-hour shift, including one hour of breaks. In this case, the total effective production time (t_{mo}) is 154 hours per month (Table 3).

(Table 3 near here)

The operator starts by setting up ten knife blanks (n_{blanks}) into the milling fixture, which takes about three minutes and includes checking the CMM report, setting the programs, and loading the knife blanks. Then, the operator initiates the milling sequence. The mill operates at a feed of 618 μin./min. and the speed of 1937 in./min. During machining, the operator works on other processes (e.g., loading or unloading knives for the other CNC, inspection, and chamfering). After the knives are machined, the operator selects one for inspection to assess part quality. The inspection process takes about three minutes using the CMM. If the inspected dimensions deviate from the standard, the operator will change the tool based on the report from CMM. The lanyard holes are then chamfered, which takes about one minute. It is assumed that all the operations are standardized, and operators strictly follow the process. Cutter change time is neglected because tool change happens after several cycles and takes about one minute. Figure 4 shows the general process flow for Machining Cell 1.

(Figure 4 near here)

3.1.2 Knife characteristics

The blank for Knife X is laser cut from a 0.124 inch (3.15mm) thick sheet of 154CM stainless steel alloy. Subsequent peripheral milling requires a high performance endmill and appropriate cutting feedrate and speed to achieve a desirable surface finish, since 154CM is a premium grade stainless steel which offers great corrosion resistance with good toughness and edge quality (Benchmade, 2011). The Knife X lanyard hole under consideration has a 0.75 in. (19.1 mm) diameter. The hole is first laser cut to a diameter (d_1) of 0.73 in. (18.5 mm). A two-end, four-flute, 5/32 in. (3.97mm) TiAlN-coated carbide endmill is used to conduct the two inch outer profile machining operation. A rough machining operation then enlarges the hole to a diameter (d_2) of 0.74 in. (18.8 mm). The hole is further enlarged to the final diameter (d_3) of 0.75 in. (19.05 mm) with a finish machining operation using the same type of tool (Figure 3).

An automatic tool change occurs after outer profile machining and rough machining. As operators have different standards on judging tool wear, for the case of this illustration, in order to standardize the tool life and work cell process in this study, the mill will not be adjusted for tool wear compensation, rather the end mill is assumed to have worn beyond its limits once the machined surface finish is no longer acceptable. It should be noted that tool wear compensation can help prolong tool life in actual production, but tool life varies depending upon the tool compensations made by different operators. To support this study, machining energy data was collected by conducting a set of experiments on a CNC milling center. Due to limitations, some data is collected from other sources. Tool life is estimated based on the number of test holes machined with the diameter dimension measured using a CMM and the surface finish quality judged by operators. While less subjective, use of hole diameter was found to be a poor measure of tool life, since poor surface finish was exhibited at acceptable diameters.

3.1.3 Machining experiments

Machining experiments were conducted to assist in identifying milling feed and speed settings. The experimental design defined high and low feeds and high and low speeds to define four corners (A1-A4) of the exploration space, as well as a centerpoint (A5). See Table 4.

(Table 4 near here)

It was found that A3 resulted in an unacceptable surface finish and A2 and A4 provided acceptable surface finish, but tool life was shorter than for A1 and A5. Therefore, A1 and A5 were selected as candidate settings for rough and finish machining settings. Since A5 provided a better surface finish than A1, A5 is preferred for finish machining in an A1-A5 combination. Therefore, three scenarios (Table 5) of machining conditions are to be investigated using the integrated sustainable manufacturing decision-making approach (S1: A1-A5, S2:A1-A1, and S3:A5-A5).

(Table 5 near here)

With the material, energy, and time information compiled for the work cell cycle for the scenarios, they can be evaluated by applying the sustainability assessment approach previously introduced.

3.2 Application of the integrated approach

In the assessment, cost analysis, LCA, and SLCA are applied to assess the sustainability of the three scenarios to machine the lanyard hole and profile for Knife X. Thereafter, the results are integrated into multi-criteria decision making, and sensitivity analysis is performed to examine how uncertain factors may affect the results. The basis for comparison is the impact of processing one knife at each process setting, which is the functional unit for this study. The system boundary encompasses the work cell system, including utilities (Figure 5). Impacts of prior material processing are not accounted for in this study.

(Figure 5 near here)

3.2.1 Cost assessment

Production costs for machining include labor cost, stainless steel cost, coolant cost, tool cost, and energy cost. To determine labor cost (C_{labor}), the operator's wage includes a $4,200 monthly base wage (C_{base}) with benefits, and includes a monthly bonus (C_{bonus}) calculated based on the number of knives machined. The minimum production quantity ($Q_{minimum}$) is 12,600 knives per month. The operator will receive a $0.50 bonus for each knife produced beyond the target quantity. The labor cost per knife can be calculated as follows (Eq. 12):

$$C_{labor} = [C_{base} + (Q_{actual} - Q_{minimum})*C_{bonus}]/Q_{actual} \quad (12)$$

In this case study, it is assumed that the cost of stainless steel for the knife is allocated to all work cells, thus the cost for the volume removed in Machining Cell 1 is accounted for in the cost assessment. Stainless steel cost ($C_{material}$) is calculated as follows (Eqs. 13 and 14):

$$C_{material} = V_{steel} * r_{steel} \quad (13)$$

$$V_{steel} = [\pi*(d_3^2-d_1^2)/4+L*d]*h_{blank} \quad (14)$$

where r_{steel} is stainless steel cost per unit volume and V_{steel} is the volume of steel removed, based on hole area removed, the length of the profile cut, L, the depth of the profile cut, d, and the knife blank thickness, h_{blank}. Tool cost is calculated based on the results from the machining tests described above. Each two-end endmill is purchased at a price of $20 ($C_{endmill}$ = $10). The tool cost for processing one knife (C_{tool}) can be calculated as follows (Eq. 15):

$$C_{tool} = (t_{rough} *C_{endmill}/L_{tool\_rough})+(t_{finish}*C_{endmill}/L_{tool\_finish})+(t_{profile}*C_{endmill}/L_{tool\_profile}) \quad (15)$$

where L_{tool_rough} is tool life under rough cutting conditions, L_{tool_finish} is tool life under finish cutting conditions, $L_{tool\_profile}$ is profile machining tool life, and t_i is the cutting time for each operation, i.

The milling center is equipped with a coolant system to improve machinability. The tank has a 95 gallon (360 L) capacity (V_{base}). The coolant loss rate (r_{loss}) is assumed to be 10% of annual coolant use (Gutowski et al., 2006). Coolant will be changed every 6 months ($t_{coolant}$). The coolant needed to process one knife ($V_{coolant}$), when considering the amount of make-up coolant (V_{makeup}), is calculated as follows (Eqs. 16 and 17):

$$V_{coolant} = (V_{base} + V_{makeup})/(t_{coolant}*Q_{actual}) \quad (16)$$

$$V_{makeup} = V_{base}*r_{loss}/(1 - r_{loss}) \quad (17)$$

The total coolant cost ($C_{coolant}$) includes the cost of new coolant and make-up coolant (Eq. 18), where the unit coolant cost ($r_{coolant}$) is $21.60/gallon ($81.76/L) .

$$C_{coolant} = V_{coolant}*r_{coolant} \quad (18)$$

The coolant cost results in Table 6 show that S3 has the highest cost and S2 has the lowest coolant cost per knife. The energy cost (C_{energy}), including equipment energy use, heating, and lighting, is calculated knowing energy use rates and machining time per hole. The industrial electricity cost rate ($r_{electricity}$) is assumed to be 6.73¢/kWh for Oregon (USEIA, 2012). Thus, the energy cost of machining one hole is (Eq. 19):

$$C_{energy} = r_{electricity}*(P_{i\_idle}*t_{i\_idle} + P_{i\_work}*t_{i\_work}) \quad (19)$$

where P_{i_idle} is power drawn by the machine during non-cutting time for process *i*; t_{i_idle} is the non-cutting time for process *i*; P_{i_work} is the power drawn during cutting for process *i*, and t_{i_work} is cutting time for process *i*.

The heating energy is assumed based on recent research investigating non-process energy use of industrial facilities, which have an average heating power intensity (P_{heat}) of 30.59 W/m^2 (Bawaneh, 2011). The work cell is assumed to be 10.5 ft. (3.2 m) in length and width. The heating energy per knife (E_{heat}) is based on the work cell area ($A_{workcell}$), monthly working time (t_{mo}), monthly production quantity (Q_{actual}), and heating power intensity (P_{heat}).

$$E_{heat} = t_{mo} * P_{heat} * A_{workcell} / Q_{actual} \quad (20)$$

To estimate lighting energy use, the Oregon lighting control requirement ($P_{lighting}$) of 1.24 W/ft^2 (13.35 W/m^2) is used as the lighting density in the workspace (Oregon and ICC, 2010). Lighting energy ($E_{lighting}$) consumed per knife can be calculated with Eq. 21.

$$E_{lighting} = t_{mo} * P_{lighting} * A_{workcell} / Q_{actual} \quad (21)$$

Cost for processing one knife in the work cell ($C_{workcell}$) is used as a metric for evaluating the performance of each scenario, as shown in Eq. 22.

$$C_{workcell} = C_{labor} + C_{tool} + C_{coolant} + C_{energy} + C_{material} \quad (22)$$

The calculated cost results for each scenario are shown in Table 6.

(Table 6 near here)

It should be reiterated that only costs associated with Machining Cell 1 are accounted for here (e.g., the raw material cost of material removed is allocated to Machining Cell 1), and not the total cost of producing the knife. Next, environmental impacts are estimated for the three scenarios by applying the same boundary.

3.2.2 Environmental impact assessment

Environmental impact assessment is conducted following the framework of life cycle assessment (LCA). Impact results are reported for each of the three scenarios being considered. A life cycle inventory (LCI) is completed for each of the processes within the work cell system boundary (Table 7). Several sources of impact are involved in machining, e.g., energy use, tools, coolant, and chips. In order to complete the LCI, some assumptions are made. First, process and material databases in the LCA software used (SimaPro) do not include 154CM stainless steel, but 440B stainless steel has similar constituents and is used to model the impacts of 154CM. Second, the cutting fluid is modeled as water (90%) and vegetable oil (10%) (Silliman, 1992). Next, the cutting tool is modeled as its individual constituents, i.e., cobalt, tantalum carbide, and tungsten carbide, based on (Jaharah et al., 2009).

(Table 7 near here)

To determine environmental impacts, the ReCiPe Endpoint (H) method with World ReCiPe H/A weighting is selected, because of its categorization of impact. LCI data are imported to LCA software (SimaPro), which generates the environmental impact results shown in Table 8. The results are consistent with the assumption that feed and speed variations affect energy use, tool life, and, consequently, environmental impacts.

(Table 8 near here)

3.2.3 Social impact assessment

Social assessment follows the UNEP Social LCA framework, which involves goal and scope definition, life cycle inventory, impact assessment, and interpretation (Benoît et al., 2010). The social impact of the work cell is limited to a small boundary because of its comparatively low impact to external stakeholders. Thus, the focus of the impact assessment is on the worker, rather than the community and society, and the goal of the assessment is to analyze how different conditions affect the operator in Machining Cell 1. The social LCA framework categorizes social impact into eight categories, i.e., wage, working hours, workload, injuries, community engagement, local employment, and technology development (Benoît et al., 2010) . Work cell operating conditions contribute directly to three social impact categories, i.e., wage, workload, and injuries, while they have little effect on the other categories. In this research, the performance of each category is determined by considering the difference between work cell conditions and a local standard. In this case, Oregon work policies are used as a standard for comparison. Social impact measures are normalized to relative values which sum to one for each scenario, which is illustrated in Eq. 3.1.

For all the three scenarios, wages are higher than the local standard (Table 9). Therefore, wages have a positive social impact, and the normalized values (calculated by Eq. 1) are negative by convention. The normalized wage impact would be zero if the work cell wage is equal to the local standard wage ($51,856 per year) for machining operators (Stevenson et al., 2011).

(Table 9 near here)

The second social metric, workload, here measured as cycle time, is directly related to changes in production rate. In Table 10, it can be seen that all the three scenarios outperform the standard workload. The assumption is made that standard work cell cycle time ($t_{standard}$) is based on a production rate that will provide the operator with a standard wage. It is calculated based on the standard number of knives produced per hour (Eq. 23):

$$t_{standard} = n_{machines} * n_{blanks} / n_{standard} \tag{23}$$

where $n_{standard}$ is standard number of knives produced per hour (14,808); $n_{machines}$ is number of machines in the work cell (2); and n_{blanks} is number of knife blanks per fixture (1).

(Table 10 near here)

The average injury rate (S_{injury}) at this occupation is assumed to be 4.6 (defined as the number of injuries experienced annually per 10000 full-time workers) based on U.S. government data (USBLS, 2007). The number of injuries is assumed to decrease when cycle time increases, due to less frequent worker-machine interaction. The work cell injury rate (r_{injury}) is calculated in the following way (Eq. 24):

$$r_{injury} = S_{injury} * t_{standard} / t_{cycle} \tag{24}$$

The social impact results for the injury metric are shown in Table 11.

(Table 11 near here)

Normalized values determined for each category are summed to obtain an overall social impact value for each scenario. The social impact results are summarized in Table 12.

(Table 12 near here)

3.2.4. Weight assignment

In this step, each metric is assigned a weight that represents its level of importance to the decision maker. There are many ways to assign weights, but the approach herein utilizes both an objective statistical method and subjective pairwise comparisons. This approach not only deals with cost and environmental impact weights, but also social weights, which are more subjective. For environmental impact, endpoint impacts (ReCiPe 2008) are selected, as they represent overall impact domains on environment (Table 13), and are normalized using an industry standard weighting method (Goedkoop et al., 2009).

(Table 13 near here)

For the cost metrics and environmental impact metrics, the pairwise comparisons are based on the average values of these metrics for the three alternatives and are made by evaluating each preference rating against each other metric. Only metrics with variability between the scenarios were considered in the decision-making process. The weight is given according to the actual metric value in fraction form.

Once the pairwise comparison results are obtained, a consistent matrix can be made. In this case, the maximum eigenvalue, λ_1, is 4. The corresponding eigenvector calculated for the economic domain (k =1), is: $W_1 = (0.3705, 0.0332, 0.0390, 0.9274)^T$.

Similar to cost weight assignment, weights for environmental impact metrics are assigned based on the actual value of each metric. The metric comparison results are shown in Table 14 and 15 in fraction form.

(Tables 14 and 15 are near here)

The maximum eigenvalue and the corresponding eigenvector are then calculated as $\lambda_2 = 3$ and $W_2 = (0.6810, 0.0480, 1.000, 0.7306)^T$, respectively.

Since social metrics are relatively subjective, the weights need to be based on the decision maker's own judgment, which is in contrast to economic and environmental weighting. In this case, a pairwise comparison matrix (M_3) is first randomly generated such that metric preference ratings range from 0 to 9 (Table 16).

(Table 16 near here)

For this situation, the largest eigenvalue is $\lambda_3 =3.217$ and the corresponding eigenvector becomes $W_3 = (0.450, 0.756, 0.476)^T$, which defines the weight of three social metrics. The domain weights are randomly generated from a normal distribution with mean of 0.5. Resulting weights are 0.5 for the economic domain, 0.2 for the environmental domain, and 0.3 for the social domain.

3.2.5 Alternative ranking

After weights are generated, they may be used to rank the alternative scenarios. First, an alternative value table (Table 17) is organized to assist the decision maker in making pairwise comparison judgments for each metric in each scenario. The weight of each metric $(w_t)_{k,n}$ considers the weights at two levels (Eq. 25),

$$(w_t)_{k,n} = w_{k,n} * w_k \quad (25)$$

where $w_{k,n}$ is the weight of metric *n* in domain *k* and w_k is the preference weighting for domain *k*.

For example, labor cost weight $(w_t)_{1,1}$ = 0.185 is calculated by multiplying its respective weighting value for economic domain ($w_{k,n}$ = 0.3705) with the domain preference weight specified by the decision maker (w_k = 0.5).

(Table 17 near here)

A preference function is then selected to help the decision maker to make judgments. In this case, the normal preference function is used since this helps simplify the judgment. The summary of alternative preference rankings for each scenario is shown in Table 18.

(Table 18 near here)

From the table above, the ranking from most to least preferable for the three alternatives is S2, S1, and S3. As mentioned above, the ranking is based on the initial weights of 0.5, 0.2, and 0.3 for the economic, environmental, and social domains, respectively. Since these weights were chosen arbitrarily, sensitivity analysis is conducted to assess the robustness of the ranking result.

3.2.6. Sensitivity analysis

In this case, uncertain factors exist at the domain level and at the metric level. At the metric level, for example, tool cost can be an uncertain because the company may purchase tools from different sources and tool wear rate varies even from the same source. Similarly, environmental impact assessment has uncertainties because the LCA practitioner can make different LCI assumptions in modeling materials and processes and apply different LCIA weighting methods. At the domain level, weights are uncertain factors since various decision makers may have different preferences regarding sustainability impacts. In this study, the sensitivity analysis focuses on examining the effect of domain weight on ranking results. Each domain is given three levels of weights, low (0.1), medium (0.5), and high (0.9). Thus, there are 27 weighting combinations in the experimental design for the sensitivity analysis. For each weight combination, a net ranking is calculated using the method described above. Results of the analysis are presented in the next section.

(Table 19 near here)

3.2.7 Results

The assessment results (Table 19) show that S2 provides a better performance in economic and environmental impact than S1 and S3, while S3 ranked highest only when economic and environmental weights are 0.1 and the social weight is 0.5 or 0.9. Thus, while S3 has a better social performance among the three alternatives, it only ranks first when the social domain is given a much higher weight than the economic and environmental domains. For companies concerned with costs and environmental impacts, S2 is the preferred choice to either S1 or S3.

Several findings were revealed through the application of the approach developed as a part of this research. First, tool (endmill) cost contributed the most (above 60%) to the total production cost of one knife. Next, six major environmental impacts were found using the ReCiPe 2008 method (climate change human health, human toxicity, particulate matter formation, climate change ecosystems, metal depletion, and fossil depletion), which were mainly associated with material and energy used in machining processes Third, the weights for economic and environmental factors reflect the level of impact on that domain.

Next, the three social aspects (wage, workload, and injury) addressed as the major impact categories of social impact vary with production rate, whereas other social metrics (e.g., community involvement) may not be closely tied to production rate. Social metrics were quantified by normalizing the difference between local standards and work cell performance, thus, an overall social impact value was not calculated. Instead, subjective weights are applied. Finally, sensitivity analysis showed that S2 is preferred to the other two alternatives for a wide range of domain weights, while S3 is preferred when the social impact domain is given a high weight and the economic and environmental domains are given low weights.

4. Summary and conclusions

In developing an approach for sustainability assessment of a manufacturing work cell, supporting models were found to be dependent on the shop floor characteristics. Therefore, a general approach for integrating sustainability assessment into decision making is developed to accommodate various manufacturing shop floor situations. Practitioners are able to utilize appropriate assessment methods to fit the goal and scope of their study. Similarly, individual metrics and assessment methods need to be selected based on company concerns and regulatory requirements. For environmental impact assessment, LCA has proven to be an effective tool and provides relatively repeatable and reliable results. Social impact assessment is much more subjective, and requires future standardization to improve repeatability, as well as capturing higher-level metrics. Pairwise comparison allows decision makers to make both objective and subjective judgments in assigning economic, environmental, and social metrics weights, while outranking decision-making methods provide a comprehensive way for shop floor engineers to rank alternatives and make a decision.

In applying the approach, appropriate metrics are selected for a knife production cell based on the defined goal and scope. In general, engineers should bear in mind that sustainability impact quantification is a complex and dynamic problem. Production situations usually have flexibilities, e.g., cycle time and inspection standards. These may affect decision making results. The assessment methods demonstrated can assist in the integration of economic, environmental, and social assessment results. The application of the approach also showed that domain weights and social weights are subject to a decision maker’s preference. Therefore, decision makers should carefully review the weights on each domain and each metric, and explore the concomitant sensitivity of ranking results.

Prior research focused on higher level (e.g., enterprise and product) sustainability performance and conducted laboratory-based sustainable manufacturing assessment. In addition, prior work has often addressed one or two sustainability domains, rather than more comprehensive assessments. In this study, three sustainability domains (economic, environmental, and social) are concurrently considered at the manufacturing work cell level. This approach is able to assist shop floor engineers in making decisions for improving processing conditions. The approach is demonstrated to be applicable and straightforward for implementation based on actual production scenarios.

The approach presented utilizes an existing weighting method (AHP) and multi-criteria decision-making method (PROMETHEE) to rank potential production alternatives. Prior research has focused on optimizing machining conditions (e.g., through response surface methodology), however, shop floor engineers often encounter problems that have limited setting alternatives, rather than being amenable to a continuum of solutions. Thus, the approach presented utilizes an outranking multi-criteria decision-making principle (PROMETHEE) that can assist engineers in ranking discrete processing alternatives.

Limitations of the approach developed as a part of this research are with respect to three aspects: selection and evaluation of social metrics, availability of production data, and the ability to validate sustainability impacts. It is expected that this approach can be extended to assist production engineers assessing sustainability and making decisions at the facility level, which most often consists of multiple work cells and operation stations.

References

Alonso, J.-A., Lamata, M.T., 2006. Consistency in the Analytic Hierarchy Process: a New Approach. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems 14, 445–459.

Asiedu, Y., Gu, P., 1998. Product life cycle cost analysis: State of the art review. International Journal of Production Research 36, 883–908.

Avram, O., Stroud, I., Xirouchakis, P., 2010. A Multi-Criteria Decision Method for Sustainability Assessment of the Use Phase of Machine Tool Systems. The International Journal of Advanced Manufacturing Technology 53, 811–828.

Barrett, S., 1994. Strategic environmental policy and international trade. Journal of Public Economics 54, 325–338.

Basu, S., Sutherland, J.W., 1999. Multi-objective Decision Making in Environmentally Conscious Manufacturing. Presented at the 6th CIRP International Seminar on Life Cycle Engineering, pp. 323–331.

Bawaneh, K., 2011. Industrial facility nonprocess energy life cycle information.

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The Guidelines for Social Life Cycle Assessment of Products: Just in Time! The International Journal of Life Cycle Assessment 15, 156–163.

Böhm, H., Krämer, C., Senner, V., 2008. Subjective Evaluation of Sport Equipment - Deriving Preference Values from Pairwise Comparison Matrices (P162), in: The Engineering of Sport 7. Springer Paris, pp. 127–133.

Brans, J.P., Vincke, P., 1985. A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Management Science 31, 647–656.

Curran, M.A., 2006. Life Cycle Assessment: Principles and Practice (No. EPA/600/R-06/060). EPA/600/R-06/060, U.S. Environmental Protection Agency, Cincinnati, OH.

Dalquist, S., Gutowski, T., 2004. Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting, in: Proceedings of ASME 2004 International Mechanical Engineering Congress and Exposition (IMECE2004). Presented at the ASME 2004 International Mechanical Engineering Congress and Exposition (IMECE2004), ASME, Anaheim, CA, pp. 631–641.

Dreyer, L.C., Hauschild, M.Z., Schierbeck, J., 2006. A Framework for Social Life Cycle Impact Assessment. International Journal of Life Cycle Assessment 11, 88–97.

Gediga, J., Beddies, H., Florin, H., Loser, R., Schuckert, M., Haldenwanger, H.G., Schneider, W., 1998. Process Modeling in the Life Cycle Design - Environmental Modeling of Joining Technologies within the Automotive Industry -, in: Proceedings of Total Life Cycle Conference & Exposition. SAE International, Graz, Austria, pp. 2081–2084.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A.D., Struijs, J., Zelm, R., 2009. ReCiPe 2008 (No. First Edition, Report I: Characterisation). PRé Consultants, The Netherlands.

Gutowski, T., Dahmus, J., Thiriez, A., 2006. Electrical Energy Requirements for Manufacturing Processes, in: 13th CIRP International Conference on Life Cycle Engineering. CIRP International, Leuven, Belgium.

Haapala, K., Khadke, K., Sutherland, J., 2004. Predicting Manufacturing Waste and Energy for Sustainable

Product Development via WE-Fab Software, in: Global Conference on Sustainable Product Development and Life Cycle. Presented at the Life Cycle Engineering, Berlin, Germany, pp. 243–250.

Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D.A., Jawahir, I.S., Clarens, A.F., Rickli, J.L., 2013. A Review of Engineering Research in Sustainable Manufacturing. J. Manuf. Sci. Eng. 135, 041013–1 – 041013–16.

Helu, M., Behmann, B., Meier, H., Dornfeld, D., Lanza, G., Schulze, V., 2012. Impact of green machining strategies on achieved surface quality. CIRP Annals - Manufacturing Technology 61, 55–58.

Hersh, M.A., 1999. Sustainable decision making: the role of decision support systems. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews 29, 395 –408.

Hutchins, M.J., Robinson, S.L., Dornfeld, D., 2013. Understanding life cycle social impacts in manufacturing: A processed-based approach. Journal of Manufacturing Systems 32, 536–542.

Hutchins, M.J., Sutherland, J.W., 2008. An Exploration of Measures of Social Sustainability and their Application to Supply Chain Decisions. Journal of Cleaner Production 16, 1688–1698.

ISO, 2006. ISO 14040:2006, Environmental Management - Life Cycle Assessment - Principles and Framework. International Organization for Standardization.

Jaharah, A.G., Hassan, C.C., Muhamad, N., 2009. Machined surface of AISI H13 tools steels when end milling using P10 tin coated carbide tools. European Journal of Scientific Research 26, 247–254.

Jegatheesan, V., Liow, J.L., Shu, L., Kim, S.H., Visvanathan, C., 2009. The need for global coordination in sustainable development. Journal of Cleaner Production 17, 637–643.

Jeswiet, J., Nava, P., 2009. Applying CES to Assembly and Comparing Carbon Footprints. International Journal of Sustainable Engineering 2, 232–240.

Jørgensen, A., Finkbeiner, M., Jørgensen, M.S., Hauschild, M.Z., 2010. Defining the baseline in social life cycle assessment. Int J Life Cycle Assess 15, 376–384.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M., Duflou, J., 2012a. Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life Cycle Inventory (uplci) CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing), Part 2: Case Studies. The International Journal of Life Cycle Assessment 17, 242–251.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z., Duflou, J.R., 2012b. Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life-Cycle Inventory (uplci)—CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing), Part 1: Methodology Description. The International Journal of Life Cycle Assessment 17, 69–78.

Klöpffer, W., Curran, Mary Ann, Frankl, P., Heijungs, R., Köhler, A., Olsen, S.I., 2007. Nanotechnology and Life Cycle Assessment: A Systems Approach to Nanotechnology and the Environment: Synthesis of Results Obtained at a Workshop in Washington, D.C., 2-3 October 2006. Woodrow Wilson International Center for Scholars, Washington, D.C.

Kong, D., Choi, S., Dornfeld, D., 2013. Software Support for Environmentally Benign Mold Making Process and Operations, in: Nee, A.Y.C., Song, B., Ong, S.-K. (Eds.), Re-engineering Manufacturing for Sustainability. Springer Singapore, pp. 279–284.

Lee, W.-T., Haapala, K.R., Funk, K.H., 2010. Defining the Dimensions of Human Work for Industrial Sustainability Assessment, in: Proc. 17th CIRP International Conference on Life Cycle Engineering (LCE2010). Presented at the CIRP International Conference on Life Cycle Engineering, Hefei, China, pp. 384–389.

Malakooti, B., Deviprasad, J., 1987. A Decision Support System for Computer-Aided Process Planning. Computers in Industry 9, 127–132.

Masanet, E.R., Horvath, A., 2004. A Decision-Support Tool for the Take-Back of Plastics from End-of-Life Electronics, in: 2004 IEEE International Symposium on Electronics and the Environment. Presented at the 2004 IEEE International Symposium on Electronics and the Environment, IEEE, pp. 51– 56.

Milacic, D., Gowaikar, H., Olson, W.W., Sutherland, J.W., 1997. A Proposed LCA Model of Environmental Effects With Markovian Decision Making (No. 971174). SAE International, Warrendale, PA.

Munoz, A.A., Sheng, P., 1995. An Analytical Approach for Determining the Environmental Impact of Machining Processes. Journal of Materials Processing Technology 53, 736–758.

O’Brien, M., Clift, R., Doig, A., 1997. Social and Environmental Life Cycle Assessment. Department of Sociology/Centre for Environmental Strategy, University of Surrey, UK.

Oregon, ICC, 2010. 2010 Oregon Energy Efficiency Specialty Code. International Code Council, Country Club Hills, IL.

Pusavec, F., Kramar, D., Krajnik, P., Kopac, J., 2010. Transitioning to sustainable production – part II: evaluation of sustainable machining technologies. Journal of Cleaner Production 18, 1211–1221.

Rajemi, M.F., Mativenga, P.T., Aramcharoen, A., 2010. Sustainable Machining: Selection of Optimum Turning Conditions Based on Minimum Energy Considerations. Journal of Cleaner Production 18, 1059–1065.

Romaniw, Y.A., 2010. An Activity Based Method for Sustainable Manufacturing Modeling and Assessments in SysML. Georgia Institute of Technology.

Rusinko, C.A., 2007. Green Manufacturing: An Evaluation of Environmentally Sustainable Manufacturing Practices and Their Impact on Competitive Outcomes. IEEE Transactions on Engineering Management 54, 445 –454.

Saaty, T.L., 1980. The analytic hierarchy process: planning, priority setting, resource allocation. McGraw-Hill International Book Co.

Silliman, J.D., 1992. Cutting and Grinding Fluids: Selection and Application. SME.

Stevenson, D., Nelson, J., Marche, P., Riddell, T., Turner, B., 2011. 2011 Oregon Wage Information (No. RSPUB 101 (0711)). Oregon Employment Department, Workforce and Economic Research, Salem, OR.

Thurston, L., 1927. A law of comparative judgment. Psychological Review 34, 273–286.

USBLS, 2007. Workplace Injuries and Illness in 2006 (News No. USDL 07-1562). United States Department of Labor, Bureau of Labor Statistics, Washington, D.C., USA.

Zhang, H., Haapala, K.R., 2012. Integrating Sustainability Assessment into Manufacturing Decision Making, in: Dornfeld, D.A., Linke, B.S. (Eds.), Leveraging Technology for a Sustainable World. Springer Berlin Heidelberg, pp. 551–556.

Tables

Table 1. The fundamental scale of absolute numbers (Saaty, 1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	Experience and judgment strongly favor one activity over another
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
X.1-X.9	If the activities are very close	The size of the small numbers would not be too noticeable, yet they can still indicate the relative importance.

Table 2. Selected Saaty Random Index (RI) values (Saaty, 1980)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Table 3. Process times for Machining Cell 1.

Processes Times	**Process time per cycle, ten knives (min.)**		
	S1	S2	S3
Setup (t_{setup})	3.00	3.00	3.00
Outer profile machining ($t_{profile}$)	2.55	2.55	2.55
Rough machining (t_{rough})	1.23	1.23	2.38
Cutter move time (t_{cutter})	0.33	0.33	0.33
Tool change ($t_{toolchange}$)	0.83	0.83	0.83
Finish machining (t_{finish})	2.41	1.25	2.41
Inspection ($t_{inspection}$)	3.00	3.00	3.00
Chamfering ($t_{chamfering}$)	1.00	1.00	1.00
Work cell cycle (t_{cycle})	13.91	12.74	15.06
Process one knife (t_{knife})	0.52	0.51	0.57
Knives per month (Q_{actual})	16325.00	18206.00	14819.00

Table 4. Selected settings for milling the knife profile.

Alternatives		**Feed rate (μin.)**	**Feed rate (μm)**	**Cutting Speed (in./min.)**	**Cutting Speed (m/min.)**
A1	High/Low	2000	51.0	1158	29.5
A2	Low/High	191	4.9	3240	82.3
A3	High/High	2000	51.0	3240	82.3
A4	Low/Low	191	4.9	1158	29.4
A5	Mid	618	1.6	1937	49.2

Table 5. Three machining scenarios to be investigated.

Scenario	**Rough Machining**		**Finish Machining**	
	Feed rate $x10^{-3}$ in. (mm)	Speed in./min. (m/min.)	Feed rate $x10^{-3}$ in. (mm)	Speed in./min. (m/min.)
S1	2.0 (0.051)	1158 (29.4)	0.618 (0.0016)	1937 (49.2)
S2	2.0 (0.051)	1158 (29.4)	2.0 (0.051)	1158 (29.4)
S3	0.618 (0.0016)	1940 (49.2)	0.618 (0.016)	1937 (49.2)

Table 6. Summary of costs for processing one knife for each scenario.

	Cost ($/knife)		
	S1	S2	S3
Material	0.0429	0.0429	0.0429
Labor	0.3190	0.2960	0.3410
Coolant	0.0286	0.0262	0.0309
Energy	0.0336	0.0317	0.0354
Tool	0.789	0.791	0.806
Total	1.213	1.188	1.256

Table 7. Material and energy types and corresponding LCI process models.

Materials and Energy	Process Model (SimaPro 7.3.3 LCA Software Databases)
Electrical energy	Electricity, production mix US/US with US electricity U
Knife material	X90CrMoV18(440B)I
Cobalt (tool)	Cobalt, at plant/GLO U
Tantalum (tool)	Tantalum, powder, capacitor-grade, at regional storage/GLO U
Tungsten (tool)	Tungsten I
Carbon (tool)	Carbon black I
Oil (coolant)	Vegetable oil methyl ester, at esterification plant/FR U
Water (coolant)	Tap water, at user/RER with US electricity U
Tool recycling	Recycling non-ferro/RER with US electricity U
Coolant disposal	Treatment, sewage, to wastewater treatment, class 5/CH with US electricity U
Chip recycling	Recycling steel and iron/RER with US electricity U
Heating energy	Heat, natural gas, at industrial furnace low-NOx > 100kW/RER

Table 8. Environmental impact of processing one knife in the work cell (SimaPro 7.3.3).

Environmental Impact Category	Environmental Impact (ReCiPe mPt)		
	S1	S2	S3
Climate change, human health	12.0	11.6	12.3
Ozone depletion ($\times 10^{-3}$)	0. 25	0.23	0.26
Human toxicity	0.49	0.47	0.50
Photochemical oxidant formation ($\times 10^{-3}$)	0.99	0. 96	1.00
Particulate matter formation	3.37	3.23	3.44
Ionising radiation ($\times 10^{-1}$)	0.19	0.18	0.20
Climate change, ecosystems	1.07	1.03	1.09
Terrestrial acidification ($\times 10^{-2}$)	0.47	0.45	0.47
Freshwater eutrophication	0	0	0
Terrestrial ecotoxicity ($\times 10^{-2}$)	0.15	0.15	0.15
Freshwater ecotoxicity ($\times 10^{-5}$)	4.76	4.37	4.94
Marine ecotoxicity ($\times 10^{-7}$)	1.21	1.15	1.24
Agricultural land occupation ($\times 10^{-2}$)	0.97	0.89	0.10
Urban land occupation ($\times 10^{-1}$)	0.49	0.48	0.49
Natural land transformation ($\times 10^{-2}$)	0.69	0.63	0.71
Metal depletion	0.25	0.25	0.27
Fossil depletion	13.08	12.62	13.31
Total	39.19	37.5	40.47

Table 9. Wage conditions for the three work cell scenarios.

	Scenario		
	S1	S2	S3
Knives per month	13281	14500	12267
Base wage ($/mo.)	4200	4200	4200
Bonus ($/mo.)	340	950	-166
Total wage ($/mo.)	4540	5150	4034
Annual wage ($/yr.)	54486	61801	48403
Standard wage ($/yr.)	51856	51856	51856
Wage variation (%)	5.1	19.2	-6.7
Normalized wage impact	-0.16	-0.62	0.22

Table 10. Workload conditions in the work cell for the three scenarios.

	S1	S2	S3
Cycle time (min.)	13.91	12.74	15.06
Standard cycle time (min.)	12.48	12.48	12.48
Cycle time variation (%)	-11.45	-2.08	-20.67
Normalized	-0.335	-0.062	-0.603

Table 11. Injury conditions for the three work cell scenarios.

	S1	S2	S3
Cycle time (min.)	13.910	12.470	15.060
Standard injury rate (1/10000)	4.600	4.600	4.600
Standard cycle time (min.)	12.480	12.480	12.480
Injury rate (1/10000)	4.125	4.504	3.810
Injury rate difference	-0.475	-0.096	-0.790
Normalized	-0.349	-0.070	-0.581

Table 12. Social impact indicators for the three work cell scenarios.

Indicators	S1	S2	S3
Wage	-0.160	-0.620	0.220
Workload	-0.335	-0.062	-0.603
Injuries	-0.349	-0.070	-0.581

Table 13. Environmental impact endpoint indicator values (ReCiPe 2008 method).

Endpoint Indicators	Impact (mPt)		
	S1	S2	S3
Human Health	15.93	15.31	16.23
Ecosystem Diversity	1.14	1.10	1.16
Resource Availability	17.08	16.40	17.40
Total	34.15	32.81	34.79

Table 14. Weighting matrix for production economic metrics.

	Labor	Coolant	Energy	Tool
Labor	1	78/7	19/2	2/5
Coolant	7/78	1	75/88	1/28
Energy	2/19	88/75	1	4/95
Tool	5/2	28	95/4	1

Table 15. Weighting matrix for environmental impact metrics.

	Human Health	Ecosystem Diversity	Resource Availability
Human Health	1	14	14/15
Ecosystem Diversity	1/14	1	1/15
Resource Availability	15/14	15	1

Table 16. Weighting matrix for social metrics.

	Wage	Workload	Injuries
Wage	1	7/2	1
Workload	5/4	1	1
Injuries	7	1	1

Table 17. Alternative value table.

Attributes (per knife)	S1	S2	S3	Weight
Labor Cost ($)	0.319	0.296	0.341	0.185
Coolant Cost ($)	0.029	0.026	0.031	0.017
Energy Cost ($)	0.034	0.032	0.035	0.020
Tool Cost ($)	0.798	0.791	0.806	0.464
Human Health (mPt)	15.93	15.31	16.23	0.136
Ecosystem Diversity (mPt)	1.14	1.10	1.16	0.010
Resource Availability (mPt)	17.077	16.40	33.48	0.146
Wage	-0.164	-0.620	0.215	0.135
Workload	-0.335	-0.062	-0.603	0.227
Injuries	-0.349	-0.070	-0.581	0.143

Table 18. Net ranking of alternatives.

Scenario	Positive ($Ø^+$)	Negative ($Ø^-$)	Net (Ø)
S1	1.482	1.482	0.000
S2	2.224	0.739	1.485
S3	0.739	2.224	-1.485

Table 19. Sensitivity analysis results.

Weights			**Net ranking**		
Economic	**Environmental**	**Social**	S1	S2	S3
0.1	**0.1**	**0.1**	0.000	0.410	-0.410
0.1	**0.1**	**0.5**	0.000	-0.216	0.216
0.1	**0.1**	**0.9**	0.000	-0.841	0.841
0.1	**0.5**	**0.1**	0.000	1.578	-1.578
0.1	**0.5**	**0.5**	0.000	0.953	-0.953
0.1	**0.5**	**0.9**	0.000	0.327	-0.327
0.1	**0.9**	**0.1**	0.000	2.746	-2.746
0.1	**0.9**	**0.5**	0.000	2.121	-2.121
0.1	**0.9**	**0.9**	0.000	1.495	-1.495
0.5	**0.1**	**0.1**	0.000	1.506	-1.506
0.5	**0.1**	**0.5**	0.000	0.880	-0.880
0.5	**0.1**	**0.9**	0.000	0.255	-0.255
0.5	**0.5**	**0.1**	0.000	2.674	-2.674
0.5	**0.5**	**0.5**	0.000	2.049	-2.049
0.5	**0.5**	**0.9**	0.000	1.423	-1.423
0.5	**0.9**	**0.1**	0.000	3.842	-3.842
0.5	**0.9**	**0.5**	0.000	3.217	-3.217
0.5	**0.9**	**0.9**	0.000	2.591	-2.591
0.9	**0.1**	**0.1**	0.000	2.602	-2.602
0.9	**0.1**	**0.5**	0.000	1.976	-1.976
0.9	**0.1**	**0.9**	0.000	2.591	-2.591
0.9	**0.5**	**0.1**	0.000	1.351	-1.351
0.9	**0.5**	**0.5**	0.000	3.145	-3.145
0.9	**0.5**	**0.9**	0.000	2.519	-2.519
0.9	**0.9**	**0.1**	0.000	4.939	-4.939
0.9	**0.9**	**0.5**	0.000	4.313	-4.313
0.9	**0.9**	**0.9**	0.000	3.688	-3.688

Figure captions

Figure 1. Approach for sustainability assessment of a production work cell.

Figure2. Sustainability performance (Sus) as defined by three domains and associated weights (w_k), a number of metrics for each domain ($m_{k,n}$), and associated weights ($w_{k,n}$).

Figure 3. Knife X (a) areas to be machined and (b) respective hole diameters.

Figure 4. Machining Cell 1 process flow.

Figure 5. Work cell system boundary.