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Sustainability has been the focus of intense discussions over the past two decades, with topics around the entire product life cycle. In the manufacturing phase, research has been focused solely on environmental impact assessment or environmental impact and cost analysis in its assessment of sustainability. However, few efforts have investigated sustainable production decision making, where engineers are required to concurrently 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. The results from the assessments 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. Sensitivity analysis is conducted to study the robustness of the results. For future research, it is desired that a tool which integrates manufacturing information system information and the sustainable manufacturing assessment approach can be built to assist production engineers in considering sustainability performance when making decisions.

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

by
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APPROVED:

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Hao Zhang, Author

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A_a	Alternative *a*
A_{chip}	Chip area
$A_{workcell}$	Work cell area
a_{ij}	Normalized social impact of metric *i* in alternative *j*
$C_{coolant}$	Coolant cost for each knife
$C_{endmill}$	Endmill cost per cutting end
C_{energy}	Energy cost for each knife
C_{knife}	Production cost for each knife
C_{labor}	Labor cost for each knife
$C_{workcell}$	Cost for processing one knife in the work cell
$C_{material}$	Steel cost
C_{tool}	Tool cost for each knife
CI	Consistency index
CR	Consistency identifier
d_1	Initial diameter of the hole
d_2	Hole diameter after rough cut
d_3	Hole diameter after finish cut
E_{heat}	Heating energy
E_{light}	Lighting energy

LIST OF VARIABLES (Continued)

f	Milling feed
f_{high}	Milling feed of high point in experiment design
f_{low}	Milling feed of low point in experiment design
f_{mid}	Milling feed of middle point in experiment design
I_{k_j}	Impact value for of domain k for alternative j
k	Domain identifier
L_{tool_finish}	Tool life under finish cutting conditions
$L_{tool\_profile}$	Profile machining tool life
L_{tool_rough}	Tool life under rough cutting conditions
m	Number of alternatives
n	Number of metric in a domain
$n_{standard}$	Standard number of knives produced per hour
n_{blanks}	Number of knife blanks per fixture
$n_{machines}$	Number of machines in the work cell
P_{i_idle}	Idle power for process i
P_{i_work}	Work power for process i
P_j	Work cell social performance for alternative j
P_{local}	Local social performance standard
Q_{actual}	Actual production quantity per month

LIST OF VARIABLES (Continued)

$Q_{minimum}$	Minimum production quantity per month
RI	Random index
$r_{coolant}$	Coolant cost rate
$r_{electricity}$	Electricity cost rate
r_{injury}	Injury rate
r_{steel}	Stainless steel cost rate
r_{loss}	Coolant loss rate
$P_{lighting}$	Oregon lighting control requirement
Sus_{j}	Sustainability performance for jth alternative
S_{injury}	Local standard of injury rate
T_{actual}	Actual production time
$T_{chamfering}$	Chamfering time
T_{cutter}	Cutter rapid movement time
T_{cycle}	Work cell cycle time
T_{finish}	Finish machining time
T_{i_idle}	Idle time for process i
T_{i_work}	Work time for process i
$T_{inspection}$	Inspection time
T_{knife}	Average time to process a knife

T_{month}	Effective monthly production time
T_{outer}	Outer profile machining time per fixture
T_{rough}	Rough machining time
T_{setup}	Setup time for each cycle
$T_{standard}$	Standard cycle time
$T_{toolchange}$	Tool change time
$T_{working}$	Operator working hours per month
$t_{thickness}$	Raw material sheet thickness
v	Milling cutting speed
V_{base}	Base volume of the coolant tank
$V_{coolant}$	Coolant volume for processing one knife
V_{high}	Milling cutting speed of high point in experimental design
V_{low}	Milling cutting speed of low point in experimental design
V_{makeup}	Makeup coolant for six months
V_{mid}	Milling speed of middle point in experimental design
W_{base}	Base monthly wage for operators
$W_{standard}$	Standard operator wage in local area
$w_{k,n}$	Weight for n^{th} metric of economic domain
w_k	Weight of domain k impact

LIST OF VARIABLES (Continued)

w_t	Metric weight for alternative ranking
λ_m	Maximum eigenvalue of a matrix
$Ø^-(A_j)$	Negative flow value for alternative j
$Ø^+(A_j)$	Positive flow value for alternative j
$Ø^-(A_j)$	Net flow value for alternative j
$\pi(A_j, A_k)$	Preference index for alternative j over alternative k

Chapter 1. Introduction

This chapter introduces the motivation and background of this research, as well as the objective and structure of this thesis.

1.1 Motivation

The world market has enabled manufacturers to trade globally and even position their factories in other countries where labor cost is low. With a changing environment and increasing concern for the human-ecology system, manufacturers have started to take responsibility for and reducing industrial emissions to the atmosphere (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). The idea of sustainable manufacturing has emerged over the past 40 years (Haapala et al., 2011), which can be defined as producing products in a way that minimizes environmental impacts, takes social responsibility for employees, the community, and consumers throughout a product's life cycle, and achieving economic benefit. Manufacturing environmental emissions originate from the manufacturing floor and, thus, manufacturing engineers need to be more aware of economic, environmental, and social problems as well as tools to address them.

1.2 Background

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. To process products sustainably on a shop floor, engineers are required to make decisions that involve balancing economic, environmental, and social benefits when setting up and improving processing conditions. Prior research on sustainable manufacturing, which is discussed in Chapter 2, focuses on minimizing environmental impact and reducing production costs. The challenge of developing an approach to integrate economic assessment, environmental impact assessment, social impact assessment for the decision making at the production work cell level motivated the research reported herein.

1.3 Research objective and tasks

The objective of this research is to improve manufacturing work cell sustainability performance through multi-criteria decision making. Two tasks have been identified to achieve this objective:

1) Develop a decision making approach which includes defining and quantifying the metrics, identifying and implementing an appropriate weighting method, and identifying and implementing an appropriate ranking method.

2) Demonstrate the approach, which requires identification and characterization of a representative work cell, and application of the integrated sustainability assessment

method.

1.4 Thesis outline

This document is organized into five chapters. Chapter 1 introduces the motivation of this research and background of the problem and the research objective and tasks. Chapter 2 reviews the related literature and limitations of prior research. Chapter 3 proposes an approach for integrating sustainable manufacturing assessment into decision making. In order to demonstrate the use of this approach, a representative machining work cell case is presented in Chapter 4. A study of decision making differences based on varying sustainability objectives is also presented. Chapter 5 summarizes the thesis, draws conclusions based on the work, highlights the contributions of the research, and presents recommendations for future research.

Chapter 2. Literature review

This chapter reviews the tools and models developed in economic assessment, environmental impact assessment, and social impact assessment towards sustainable manufacturing on shop floor, as well as decision making approaches that have been applied on integrating assessments. This review is followed by a discussion of prior research limitations and the potential contribution of the work conducted.

2.1 Sustainability assessment

Sustainability assessment includes economic assessment, environmental impact assessment, and social assessment. In this section, tools, models and prior research on each assessment are reviewed.

2.1.1 Economic assessment

Other than commonly used economic analysis methods (e.g. net present value and cost benefit analysis), life cycle costing (LCC) is often used in sustainability assessment. LCC is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and decommissioning (SAE 1999).

Life cycle costs are summations of all the costs related with the material use, length of equipment life and also annual time increments during the equipment life with considering the time money value (Barringer, 2003). The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives to achieve the lowest long-term cost of ownership. Usually the cost of operation, maintenance, and disposal costs exceed all other first costs many times over. The best balance among cost elements is achieved when the total LCC is minimized (Landers 1996). As with most engineering tools, LCC provides best results when conducting a project that is with a time value (Barringer, 2003). On shop floor, LCC can be utilized to assess the costs of equipment and facility with time value. The LCC process is as follows (Barringer, 2003):

1) Identify the goal and scope of the study including, system characteristics, life time period, etc.
2) Focus on the technical features by way of the economic consequences to look for alternative solutions.
3) Develop the cost details by year considering memory joggers for cost structures.
4) Select the appropriate cost model, simple discrete, simple with some variability for repairs and replacements, complex with random variations, etc. required by project complexity.
5) Acquire detailed information relating to the project that is impacts cost.
6) Integrate the yearly cost profiles.
7) For key issues prepare breakeven charts to simplify the details into time and money.

8) Sort the big cost items into a Pareto distribution.
9) Test alternatives for high cost items.
10) Study uncertainty/risk of errors or /alternatives for high cost items as a sanity check and provide feedback to the LCC studies in iterative fashion.
11) Select the preferred course of action and plan to defend the decisions with graphics.

However, cost assessment usually depends on decision maker’s goal and scope of the decision making problem. LCC does not always fit the problem if time value of certain equipment and facility is not considered.

2.1.2 Environmental impact assessment

Life cycle assessment (LCA), is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (US EPA, 2010). Practitioners and researchers from many domains come together using LCA to calculate indicators of potential environmental impacts that are linked to manufactured products, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise (Rebitzer, 2004). The phases involved in life cycle assessment include goal and scope definition, inventory analysis, impact assessment, and interpretation. In manufacturing shop floor, LCA can be conducted on analyzing environmental impact of production processes, where pollution and emissions directly come from. The framework and the application on manufacturing shop floor are further explained in Chapter 3 and Chapter 4.

Economic Input/Output Life Cycle Assessment (EIO-LCA) is another mathematically defined procedure using economic and environmental data to determine the effect of changing the output of a single sector. The method can be applied to any economy defined by transactions between sectors (Hendrickson, 1998). Inputs and outputs of each sector are identified as requirements and demands from other sectors. One can determine the total external outputs associated with each dollar of economic output by adding external information to the EIO framework. The method uses information about industry transactions - purchases of materials by one industry from other industries, and the information about direct environmental emissions (e.g., CO_2) of industries, to estimate the total emissions throughout the supply chain (GDI, 2012). However, this method is designed to assess sector level problems instead of shop floor problems

Regarding tools and models developed in recent years for assessing manufacturing environmental performance, Dahmus and Gutowski (2004) presented a system-level environmental analysis of machining, including not only the environmental impact of material removal process but also the impact of associated processes, such as material preparation and decreasing fluid preparation. Narita et al. (2006) proposed a predictive method which enables the calculation of environmental burden (equivalent CO_2 emissions) due to the electricity consumption of machine tool components, cutting tool condition, coolant quantity, lubricant oil quantity, and metal chip quantity. Rao (2008) presented a methodology for environmental impact assessment of manufacturing processes using a combinatorial mathematics based decision-making method. Haapala (2008) explored how the use of LCA in the design process can address environmental impacts in terms of energy use, resource consumption, waste production, and human health for manufacturing. Yuan (2009) developed a system-level approach for reducing the environmental impact of manufacturing and sustainability improvement of nano-scale manufacturing. Sheng et al. (1998) presented an approach for incorporating multi-endpoint, environmental effects in manufacturing systems planning, in which unit process models, hazard evaluation, and systems simulation are combined to develop a predictive capability for energy consumption, waste flows, and exposure risks over a planning horizon. Recently CO2PE! Collaborative research developed a methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI). The methodology comprises two approaches, with screening approach, which provides an insight into the unit process and results in a set of approximate LCI data, and in-depth approach, which leads to more accurate LCI data as well as identification of potential for environmental improvements of the manufacturing unit processes (Kellen et al, 2011). Those approaches provide good tools to design and improve manufacturing processes, but they are environmental-based and lack consideration of economic and social factors.

2.1.3 Social impact assessment

The social domain of sustainable manufacturing considers human safety and societal benefit. Manufacturers are responsible for creating a safe and healthy environment considering safety protection, illumination, noise level, and injuries. Meanwhile, they take social responsibilities for the community, such as creating job opportunities, purchasing insurance, providing worker compensation, and executing public policies. It is important to note that research on analyzing the social impacts of manufacturing is limited. Jørgensen et al. (2007) reviewed some approaches in order to highlight methodological differences and general shortcomings. The review reveals a broad variety in how the approaches address the steps of the environmental LCA methodology, particularly in the choice and formulation of indicators. Hutchins and Sutherland (2009) studied the degree to which social impacts have been included in LCA and how social metrics could be incorporated into input-output analysis. Though research on social life cycle approaches and its relationship with LCA was recognized in the 1990s (O'Brien et al., 1996), little work was done for the next decade (Hunkeler, 2005). Dreyer (2006) proposed a framework for social life cycle impact assessment (SLCA) which aims at facilitating companies to conduct business in a socially responsible manner by providing information about the potential social impacts on people caused by the activities over the life cycle of their products. UNEP released guidelines for social life cycle assessment (Benoî & Mazijn, 2009). The guidelines follow the four phases of LCA, goal and scope definition, life cycle inventory, impact assessment, and interpretation. However, the guidelines are general and under development, especially the methodology of quantifying and weighting of social metrics. Meanwhile, the framework is product based and lack of focus on manufacturing shop floor.

In order to properly work with industry, practitioners should use different tools with different social evaluation cases, and should consider local characteristics and the product itself in the assessment (Hauschild et al., 2008). Lee et al. (2010) proposed a set of dimensions for human work to assist industrial sustainability assessment. Based on the effect variation, different aspects are categorized into individual and societal levels. The dimensions identified include compensation, physical and mental safety, demand, variety of tasks and roles, social interaction, growth of skills and knowledge, opportunities for accomplishments and status, value of work, autonomy, and growth and personal development. Lee et al. (2012) further proposed quantifying these metrics by setting up identifiers for the dimensions and establishing the difference between work that is ideal for the society and work the company offers to the workers of the society. In recent years, several researchers have focused on developing social metrics of sustainability, which can be found in Parris and Kates (2003), Labuschagne and

Brent (2006), and Hutchins (2009). However, currently there is no well agreed upon approach that would appropriately assess social impact on the manufacturing shop floor level.

2.2 Multi-criteria decision making

Decision making problems regarding sustainable manufacturing often involve multiple criteria and metrics. Therefore, decision making methods commonly used are multi-criteria decision making methods. In this section, some methods that have been applied for decision support of integrating economic assessment and environmental impact assessment are reviewed.

The Analytical Hierarchy Process (AHP), developed by Thomas Saaty in 1980, is a quantitative comparison method (Saaty, 1980). It can be used in both metric weighting and decision making. When it is used in weighting, the decision maker needs to make pairwise comparisons between metrics and the results are composed into an $n \times n$ matrix which is used to calculate the biggest eigenvalue and the corresponding eigenvector (the weights for each metric) (Saaty, 1980). The merit of AHP is that the pairwise comparison results reflect the decision maker's preferences and the matrix is able to ensure the consistency of decision maker's judgments and generate the weight by matrix transformation. However, since the matrix is only able to ensure the decision maker's consistent judgments it is likely that error happens even the pairwise comparison results are consistent.

The AHP method first decomposes a multi-criteria problem into a hierarchy of sub-problems. Usually, three levels are created (e.g., goal, criteria, and alternatives, as shown in Figure 2.1). The first level is the top goal of decision making; the middle level includes all the criteria involved; and the bottom level consists of the alternatives of the problem.

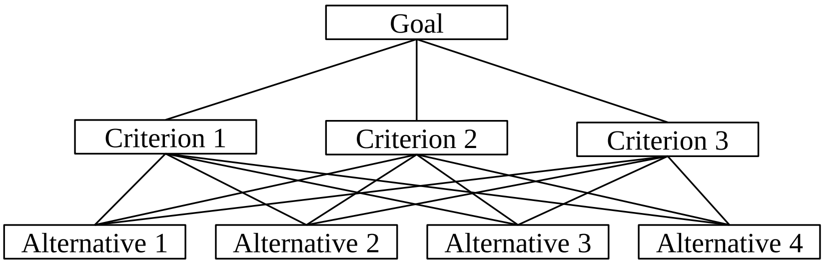

Figure 2.1. Hierarchy of a three-level decision making problem.

A pairwise comparison will then be made to evaluate relative performance of each criterion. The relative performance is determined by the preferences of the decision maker. The relative preference of two alternatives is assigned a number on a scale. A common scale is the Saaty scale shown in Table 2.1.

Table 2.1. Saaty rating scale (Saaty, 1980).

Importance	**Definition**
1	Equal importance or preference
3	Moderate importance or preference of one over another
5	Strong or essential importance or preference
7	Very strong or demonstrated importance or preference
9	Extreme importance or preference
2,4,6,8	When compromise is needed

This method relies on the supposition that humans are more capable of making relative judgments than absolute judgments. The rationality assumption in AHP is more relaxed than in MAUT (Linkov et al., 2005) because AHP is able to deal with decision makers' error judgments. It calculates the inconsistency index as a ratio of the decision maker's inconsistency when making pairwise comparisons and a randomly generated index. This will be further explained in Chapter 3. The inconsistency index is important to assure the decision maker that judgments were consistent and that the final decision is made that reflects his or her will.

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 with the ease of use and low complexity (Pohekar and Ramachandran, 2003). Similar to MAUT methods, outranking methods require a weighting and a performance value for each criterion. It starts from a decision table with weights assigned to each criterion for each alternative. The sum of the weights for each alternative is 1. Then, to give a preference value (Table 2.2) in the decision table, a pairwise comparison is conducted. Pi(A_j, A_k) is the function for the preference value, where A_j signifies the value for alternative j, A_k signifies alternative k, and i signifies criterion i.

Table 2.2. PROMETHEE preference scale (Brans and Vincke, 1985).

P_i (A_j, A_k)	Definition
0	A_j has no preference or indifference to A_k
≈ 0	A_j has weak preference to A_k
≈ 1	A_j has strong preference to A_k
= 1	A_j is strict preference to A_k

After obtaining all the preference values, a preference index $\pi(A_j, A_k)$, which is also between 0 and 1, is then defined considering all the criteria (Eq. 2.1).

$$\pi(A_j, A_k) = w_t * P_i(A_j, A_k) \tag{2.1}$$

Alternatives are then ranked in both positive and negative flows. The value of positive ranking flow signifies how much each alternative is outranking the others. The positive ranking for alternative j is determined by dividing the sum of weighted sums of A_j compared to A_k by m-1; m is the number of alternatives (Eq. 2.2).

$$Ø^{+}(A_j) = \frac{1}{m-1} \sum_{k=1}^{m} \pi\,(A_j, A_k) \tag{2.2}$$

The value of negative ranking flow signifies how much each alternative is outranked by the others. Its negative ranking is determined by dividing the sum of weighted sums for A_k compared to A_j by m-1 (Eq. 2.3). The same principle applies to the negative outranking flow. The smaller $Ø^{-}(A_j)$ is, the better the alternative.

$$Ø^{-}(A_j) = \frac{1}{m-1} \sum_{k=1}^{m} \pi\,(A_j, A_k) \tag{2.3}$$

In the end, a net ranking $Ø(A_j)$, which integrates both positive and negative flow values, will be generated for analysis by the decision maker (Eq. 2.4).

$$Ø(A_j) = Ø^{+}(A_j) – Ø^{-}(A_k) \tag{2.4}$$

The net ranking values determine the order of preferred alternatives. The alternative with the highest net ranking value is the preferred choice among all alternatives.

The methods discussed above are commonly used for multi-criteria decision making. However, in a work cell sustainability problem, the decision maker would measure the most effective metrics that indicate cost, environmental impact, and social impact. Prior research (Clarke-Sather, 2011) utilized AHP to assign weight to metrics, however, even though the weights assigned were subjective, the method is able to reduce decision maker's inconsistent judgments. In this thesis, a weighting method utilizes pairwise comparison and a data analysis technique to assign weights to sustainability metrics. This method not only allows the production engineer to make decisions with respect to the system itself on individual economic and environmental impacts, but also allows the production engineer to assign subjective weights for each sustainability domain weights and social weights.

2.3 Research on integrating sustainability assessment into decision making

Research into integrating sustainable manufacturing assessment to decision making has been performed since as early as late 1980's. Malakooti and Deviprasad (1988) developed an interactive multiple criteria approach and decision support systems (DSS) for metal machining operations. They worked on minimizing machining cost and maximizing production without sacrificing workpiece quality. During the past three decades, researchers have attempted different approaches to integrate environmental assessment into decision making, and many decision-making methods have been applied to assist manufacturing assessment, including AHP (Avram et al., 2010), Markov processes (Milacic et al., 1997), and Pairwise Comparison Analysis (Basu and Sutherland, 1999). Hersh (1999) posited that sustainable decision-making research is required in a number of different areas. These areas include 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. Further understanding should be gained regarding the types of decision makers, organizations, and situations which make approaches from one end of the spectrum more appropriate than those from the other. Research on model classification should include the development of a classification of the different types of problems that occur in sustainable decision making. Romaniw (2010) argued that detailed assessments are still lacking, as stakeholders need detailed impact assessments in their particular phase of life. More detailed assessments give stakeholders information that can be used for better environmental management (EM) and more environmentally benign operations.

Olson (1998) proposed a method utilizing Input-Output Analysis coupled with Markov decision making to assist plant managers in determining and modifying the environmental impacts of their plant. Markov decision making is more preferred in dealing with stochastic environments and it does not fit all manufacturing processes. Basu and Sutherland (1999) integrated multi-objective programming into decision making involving several sets of objective functions in order to optimize a process. Pairwise Comparison Analysis (PCA) was undertaken to assign importance to each objective. This work provides a foundation for assigning weights to criteria of such assessments. Recent work includes that by Shao et al. (2010), who proposed a virtual machining model for sustainability analysis. They modeled sustainable machining in a shop floor environment, and systematically considered available model and data in a virtual environment. A decision guideline system was introduced that analyzes environmental impact data to derive an optimal measure based on the desires of the decision maker that need to be integrated with the simulation system.

Yang et al. (2009) developed a matrix approach to perform technology for sustainability assessment. This approach integrated social concerns into assessment, however, uncertainty of process parameters as well as weighting method is a limitation. Avram et al. (2010) proposed a multi-criteria decision method for economic and environmental assessment of the use phase of machine tool system. AHP was used to structure the decision problem at both process and system level.

From the research described above, it is clear that many of these works focused on an operation in a laboratory environment rather than in an actual manufacturing shop floor. Tools that can assist shop floor engineers improve sustainability performance of production processes are deficient. Furthermore, other issues (e.g. cycle time, metric selection, and weighting) that may be involved in production need to be addressed concurrently. Therefore, even though separate research efforts have been conducted into each sustainability domain, existing frameworks, methods, and tools for integrating sustainability assessment into production shop floor decision making for process setting improvement are lacking. This thesis addresses this deficiency by developing an approach to integrate sustainable manufacturing assessment to decision making in order to assist manufacturing engineers in conducting process planning at the work cell level. This approach is described in Chapter 3, and is demonstrated in Chapter 4 with a knife production work cell application.

Chapter 3. Approach for integrating sustainable manufacturing assessment into decision making

This chapter proposes an approach to integrate sustainability assessment in three domains (economic, environmental, and social) on a work cell, and to apply the assessment results into decision making. The first part of this chapter consists of an overview of the approach developed as a part of his research. The methods for economic, environmental, and social assessment (i.e., cost analysis, LCA, and SLCA) are then described. A methodology is then proposed to integrate the assessment results into a decision making process, and, lastly, utilization of this approach to improve the sustainability performance of a work cell is discussed.

3.1 Overview of the approach

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 to improving processing conditions. In each assessment, certain tools or models are applied. Economic assessment using cost analysis is flexible, and practitioners can select appropriate tools that would fit the situation depending on their goal and scope, as long as costs are well documented. Environmental impact assessment is conducted with life cycle assessment not only because LCA provides a standard framework defined by ISO 14040 to conduct the assessment, but also because it has been widely used by practitioners for decades and is well accepted worldwide. Social assessment follows the framework of social life cycle assessment which has been developed by United Nations Environment Programme (UNEP) and integrates a life cycle thinking of social impact. However, due to the complexity of social impact, there is hardly any well accepted method for social assessment. In this approach, certain social metrics are identified based on SLCA and a measuring method is proposed. 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. PROMETHEE ranking method is used for ranking alternatives which allows decision maker to evaluate the scores of the different alternatives. PROMETHEE is also used because of its simplicity and applicability in various work cell situations. These assessment methods are discussed in section 3.2 and section 3.3.

Figure 3.1 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 input and output flows. The inputs of the work cell include physical flows and information flows. Process conditions include operation settings (e.g., lighting, machining parameters, and working hours). Outputs of the work cell include the processed part, solid and liquid waste, as well as economic, environmental, and social impacts.

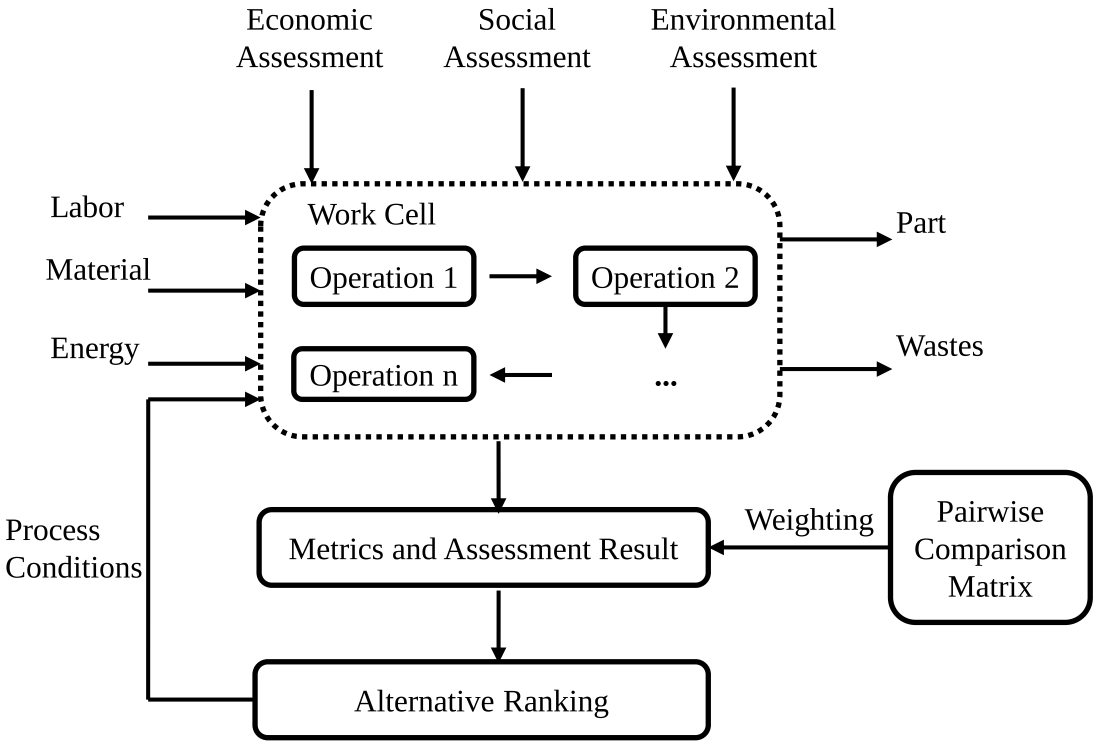

Figure 3.1. Approach for sustainability assessment of a production work cell.

The vertical flows in the figure depict the assessment 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 settings can be identified and chosen as a new working condition.

3.2 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.

3.2.1 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 benefit 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. The result of cost assessment can be a single value. It can also be multiple values in different categories, which gives more detailed information of cost analysis on specific materials. This work uses former approach to assist ranking of alternatives and the latter for contribution analysis.

3.2.2 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). Figure 3.2 shows how each phase is related to other phases in LCA. Practitioners can conduct environmental impact assessment following the framework of LCA. For example, by identifying the quantity of materials and energy use for a functional unit during different processes in the work cell, practitioners can associate the inputs and outputs material and energy use with environmental impact categories. The four steps are described below.

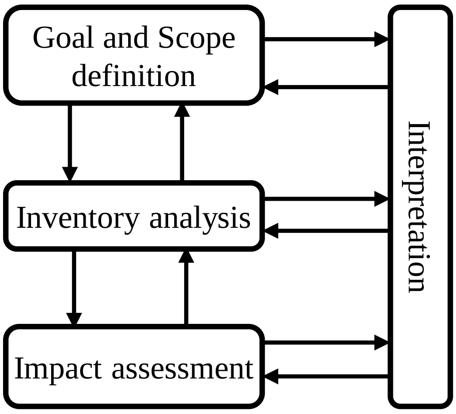

Figure 3.2. Phases of a life cycle assessment (based on ISO 14040, 1997).

Goal and scope definition identifies what is being studied and why, as well as the inputs and outputs that are involved in the work cell, and the functional unit (Currant, 2006). Therefore, practitioners need to identify operations, equipment, boundary, impact categories, and allocation methods. Aside from understanding the work cell, study goals should be described in this phase along with any assumptions and limitations.

Life cycle inventory (LCI) analysis involves creating an inventory of flows within the work cell, including raw material, energy, release to air, and any resources related to the work cell process. Since engineers are analyzing the operation of the work cell, the result of this step is a flow model with input and output data identified in the first phase. Data collection is a critical task in creating a life cycle inventory because data is often unavailable, and practitioners should use other sources with care. In creating a life cycle inventory for a work cell, practitioners should be clear about the inputs of the work cell and outputs of the work cell, as well as materials and energy required to complete the processes, and wastes and emissions to the environment.

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. According to ISO 14040, one must document the environmental relevance of each indicator by describing the link to the end points. End points can be selected by the practitioner, as long as the reasons for including or excluding endpoints are clearly documented (Goedkoop et al., 2008). Currently two indicator systems have been widely used, Eco-indicator 99 and ReCiPe 2008. These methods transform the long list of life cycle inventory results into a limited number of indicator scores (Goedkoop, 2008). These indicator scores express the relative severity of environmental impact categories. The impact categories are addressed at the midpoint level, and at the endpoint level (e.g., ecotoxicity and ozone depletion). Most of the midpoint impact categories are further converted and aggregated into three endpoint categories, i.e., damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA). ReCiPe 2008 method addresses 18 midpoint indicators and three endpoint indicators shown in Table 3.1 (Goedkoop et al., 2008).

Table 3.1. ReCiPe 2008 Environmental impact indicators (Goedkoop et al., 2008).

Midpoint (Impact categories)	**Endpoint (Damage types)**
Climate change	Human health
Ozone depletion	
Marine eutrophication	
Human toxicity	
Photochemical oxidant formation	
Particulate matter formation	
Ionising radiation	
Agricultural land occupation	Ecosystem diversity
Terrestrial ecotoxicity	
Freshwater ecotoxicity	
Marine ecotoxicity	
Urban land occupation	
Natural land transformation	
Terrestrial acidification	
Freshwater eutrophication	
Water depletion	Resource availability
Mineral resource depletion	
Fossil fuel depletion	

Environmental indicators can be applied based on three perspectives, individualist (I), hierarchist (H), and egalitarian (E), which account for variation in social values (Goedkoop et al., 2008). Perspective I is based on short-term interest, impact types that are undisputed, and technological optimism as regards human adaptation. Perspective H is based on the most common policy principles with regards to time-frame and other issues. Perspective E is the most precautionary, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available.

Interpretation evaluates the accuracy of the results from life cycle inventory and life cycle impact assessment. Based on the results, practitioners can conduct contribution analysis, which is to determine the relative process contribuious to the environmental impacts. Since there are uncertainties in the data, practitioners also need to describe how the uncertainties affect final results. Sensitivity analysis can be used to investigate the effect of making a certain changes in the model. For a work cell analysis, interpretation should answer which operation or material contributes most to the environmental impact, the uncertainties of the collected data, and also the process models. In the end, conclusions and recommendations for improvement should be drawn in the interpretation phase.

Instead of linking LCI results and the assessment method manually, LCA software tools, (e.g., GaBi, SimaPro, OpenLCA) have been developed to assist environmental impact assessment. Software tools link with databases that have been developed worldwide. Due to the uncertainties of data collection and weighting, a comparison of two or more results based on different assessment methods can reduce uncertainty for practitioners. Practitioners are able to establish a system model of work cell processes in the software, which will generate aggregated environmental impact values based on the database information and data collected from work cell.

3.2.3 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. As discussed in Chapter 2, SLCA provides a framework for analyzing the social impact of a system. 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 (Beno î and Mazijn, 2009). 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 involved in the product's life cycle, 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 in a higher level, for example the community and society. However, the impact is compared with what is very low so that it can be narrowed to work cell social impacts (e.g., wage, injuries, and workload)

In the life cycle inventory phase, the system is modeled, data is collected, and results are obtained. Once the work cell is modeled, practitioners need to collect data. Data collection for desktop screening can be conducted through literature review and web search. Site-specific data collection may be carried out through a social audit that may involve (Beno î and Mazijn, 2009):

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

In the work cell life cycle inventory, after practitioners have composed the metrics, they need to collect data regarding social impact. However, collecting social impact data is not an easy task because sometimes not all the data can be retrieved from records, and the validation of collected data is an issue. Practitioners should 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 (Benoî and Mazijn, 2009). For each stakeholder type, there are subcategories that can be quantified to evaluate social performance. Considering the focus of this work, several metrics were selected for practitioners (Table 3.2).

Table 3.2. Stakeholder categories and subcategories for work cell social assessment (Benoit and Mazijn, 2009).

Stakeholder categories	**Subcategories**
Worker	Fair salary
	Working hours
	Forced labor
	Equal opportunities/Discrimination
	Health and safety
	Social benefits/Social security
Consumer	Health and safety
	Transparency
	End of life responsibility
Local community	Cultural heritage
	Safe and healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
Society	Contribution to economic development
	Prevention & mitigation of armed conflicts
	Technology development
	Corruption
Value chain actors not including consumers	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

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 is to evaluate the difference between local performance standard (P_{local}) and the performance (P_j) of the work cell. Then social impact measures are normalized into relative values which sum to 1 for all scenarios analyzed. The normalized value (a_{ij}) is calculated using the following equation:

$$a_{ij} = \frac{P_{ij}\text{-}S_{ij}}{\sum_{j=1}^{m} P_j\text{-}S_j} \quad (3.1)$$

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. 3.2):

$$I_{3\_j} = \sum_{i=1}^{n} a_{ij} \quad (3.2)$$

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

3.3 Decision making for work cell sustainability

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

Step 1: Metric definition

Decision makers often address many factors in a decision making problem. Therefore, it is necessary to categorize the metrics and simplify the problem to be analyzed. Here, the metrics are categorized into three levels (Figure 3.3).

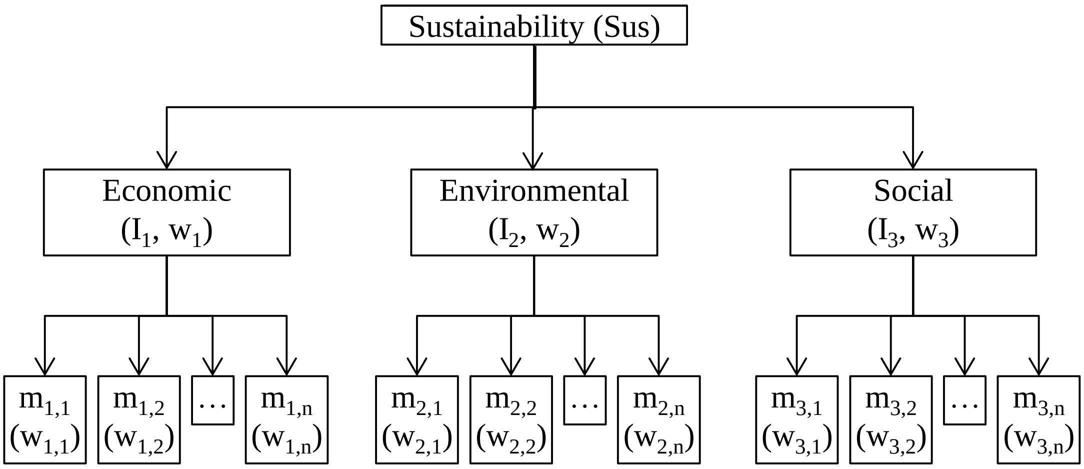

Figure 3.3. Sustainability performance (Sus) as defined by three domains and associated weightings (w_k) and a number of metrics for each domain ($m_{k,n}$) and associated weightings ($w_{k,n}$).

The top level shows the overall decision-making problem, which is to achieve sustainability of the work cell 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, 3=social). The set of n metrics are defined for each domain based on a discussion of all decision makers involved. Normally the metrics should consider decision makers' goals as well as regulations and company policies. In the end of the discussion, a set of metrics should be generated, ready to be assigned weights.

Step 2: Weighting assignment

In order to give a proper weighting, a pairwise comparison of importance between metrics needs to be conducted by the decision maker, who will judge $\frac{n(n-1)}{2}$ times. Pairwise comparison will increase the correctness of judgment in case any error is made.

Table 3.3. The fundamental scale of absolute numbers (Saaty, 2008).

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.

The eigenvector of the matrix A is the weights of all the metrics in the comparison, W= $(w_{1k}, w_{2k} \ldots, w_{nk})^T$, where, k is the domain identifier (Eq. 3.3).

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \quad (3.3)$$

In general the eigenvalue λ_m can be used to determine if A is a consistent matrix, because $\lambda_m = n$ when matrix A is consistent, and $\lambda_m > n$ when the matrix is not consistent. An index (CI) is defined to evaluate the inconsistency as (Eq. 3.4):

$$CI = \frac{\lambda_m - n}{n-1} \quad (3.4)$$

RI is the average value of CI for random matrices using the Saaty scale. Various authors have computed and obtained different RIs depending on the simulation method and the number of generated matrices. Saaty and Uppuluri (1980) simulated the experiment with 500 and 100 runs, respectively, and obtained the RI values with matrix size ranging from 1-15 in Table 3.3.

Table 3.3. 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

The Consistency Identifier (CR) is the ratio of CI and RI (Eq. 3.5), which indicates the acceptability of the judgments made by the decision maker.

$$CR = \frac{CI}{RI} \quad (3.5)$$

When $CR < 0.1$, the consistency of the matrix is acceptable, or 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, 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 weighting (w_k) of the three domains. An integrated weight (w_t), which is the result from domain weight (w_k) and metric weight ($w_{k,n}$) in a certain domain, is calculated using Eq. 3.6.

$$w_t = w_{k,n} * w_k \tag{3.6}$$

Step 3: Alternative ranking

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. 3.7).

$$P(A_a, A_b) = G\,(f(A_a) - f(A_b)) \tag{3.7}$$

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 the criteria (Eq. 3.8).

$$\pi(A_a, A_b) = \sum_{i=1}^{n} [w_t * \ Pi(A_a, A_b)] \tag{3.8}$$

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. 3.9).

$$\varnothing^{+}(A_a) = \frac{1}{m-1} \sum_{b=1}^{m-1} \pi\ (A_a, A_b) \tag{3.9}$$

Similarly, a negative outranking score represents how much alternative A_a is not preferred comparing with all the other of alternatives. The value can be calculated with Eq. 3.10.

$$Ø^{-}(A_a) = \frac{1}{m\text{-}1} \sum_{b=1}^{m-1} \pi\ (A_a, A_b) \qquad (3.10)$$

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

In the end, a net ranking score $Ø(A_a)$ represents the integration of both positive ranking preference and negative ranking preference. The net score Ø(Aa) can be calculated with Eq. 3.11.

$$Ø(A_a) = Ø^{+}(A_a) – Ø^{-}(A_a) \qquad (3.11)$$

The net ranking is the final ranking and recommendation for the decision maker in this problem.

3.4 Utilization of the approach

The approach described can be applied to a manufacturing work cell when its working condition needs improvement, for example, by investigating process settings (e.g., feed and speed) and scheduling (e.g., layout and material planning) variations. Process settings affect sustainability with respect to all three domains. First, process settings impact material consumption rate and energy use. Second, process setting changes may affect production rate. Environmental impact increases partly due to the consequence that more parts are processed in the work cell. In this case, energy and material consumption also causes environmental impact because of the change of production rate. Third, the increase of production rate causes more social impact. Higher workload results in higher worker mental and physical challenges. Injuries may be more frequent with the increase of production rate.

Sustainability performance can also be affected by work cell scheduling. Cellular manufacturing allows engineers to assign jobs to machines so utilization of machines can be maximized in processing different products. Therefore, scheduling variations within the work cell are able to generate different economic, environmental, and social impacts due to fewer machines involved and shorter cycle times in processing. The approach described will assist production engineers in comparing sustainability performance of different scheduling settings.

In this chapter, the sustainable manufacturing assessment approach developed as a part of this research has been described; however, applying this approach to a specific production work cell is a challenging, systematic problem because a change within the work cell may affect the performances of each sustainability domain. In the next chapter, a work cell for machining a part feature is presented to demonstrate the use of this approach.

Chapter 4. Application of the approach

Chapter 3 presented an approach for integrating sustainability assessment into decision making. In this chapter, the approach is applied to a work cell processing stainless steel knives.

4.1 Application background and assumptions

The hypothetical company considered in this study produces stainless steel knives. With the development of the business, its production is expanding year by year. Meanwhile, production cost and waste are of concern for production managers. Therefore, a change of manufacturing conditions is needed on the shop floor. The production managers would like to produce knives sustainably to reduce production cost, environmental impact, and social impact. The shop floor processes are shown in Figure 4.1. First, knife blanks are cut from a stainless steel sheet using a laser. 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 out to retailers.

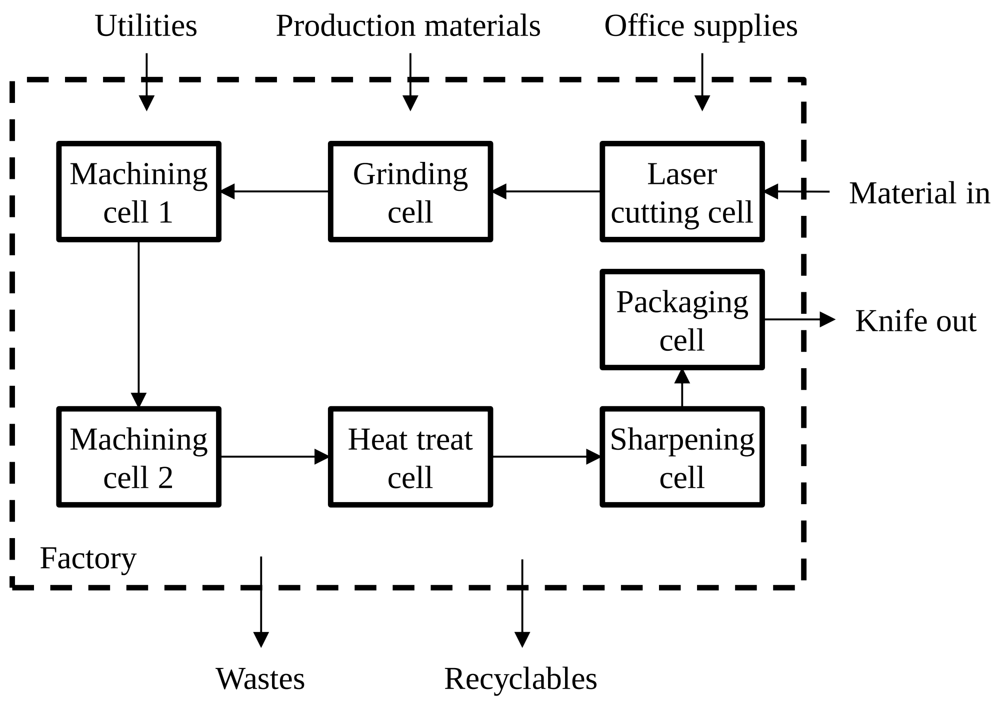

Figure 4.1. Arrangement of work cells in the knife factory.

The change begins with a machining cell 1 that processes portions of the inner and outer profile knife X (Fig 4.2). In order to create a smooth surface and precise dimensions, a work cell (Machining cell 1) is being specifically set up to process the inside surface of the hole. Machining cell 2 processes the reminder of the handle after refixturing, and part of the outer profile. With the new work cell set up, in process inventory will be reduced. The production engineer will undertake a sustainable manufacturing assessment by focusing on machining cell 1 of the lanyard hole for Knife X (Figure 4.2).

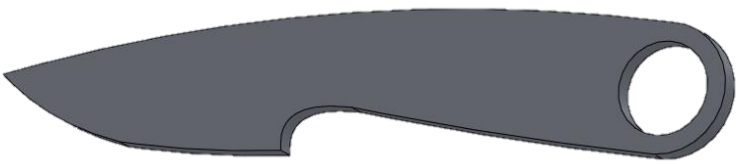

Figure 4.2. Representative Knife X with lanyard hole.

The study begins with the setting of milling parameters (speed and feed), which affect the surface quality, as well as several other sustainability metrics.

4.1.1 Work cell description

The work cell investigated in this study includes two CNC milling centers (M1 and M2), a coordinate measuring machine (CMM), a chamfer mill, and an operator (Figure 4.3).

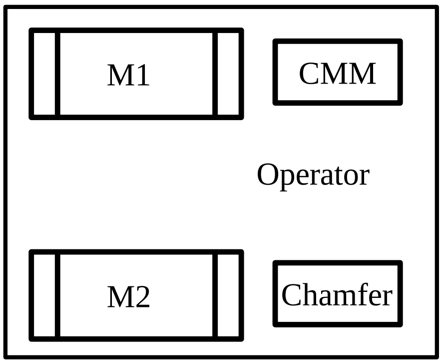

Figure 4.3. Layout of the work cell investigated.

The CNC is operated under a power condition of 208 volts and 40 amps (Haas Automation, 2011). Energy use varies depending on machine utilization. The CMM draws 2.5 kW during operation (Mitutoyo, 2012). In this study, due to the limitation 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_{month}) is 154 hours per month.

The operator starts with 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 knives. Then, the operator initiates the milling sequence. The outer profile is machined at the 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 knives are then chamfered, which takes about one minute. In this case, 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 4.4 shows the process flow for the work cell.

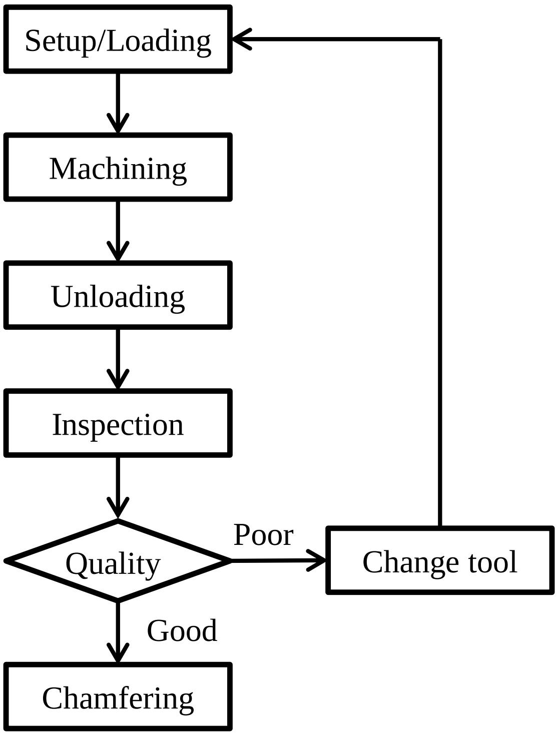

Figure 4.4. Work cell process flow.

4.1.2 Knife characteristics

The blank for Knife X is laser cut from a 0.124 inch (3.15mm) thick sheet of 154CM stainless steel alloy. Surfaces are subsequently processed using peripheral milling with an end mill to achieve a desirable surface finish. For the case of this illustration, the work cell is assumed to receive knives from laser cuting work cell. Milling requires a high performance tool and appropriate cutting feedrate and speed because 154CM is a premium grade stainless steel which offers great corrosion resistance with good toughness and edge quality (Benchmade, 2011). The hardness of this material under normal temperature conditions (0 ℃-40 ℃) is 58.5 HRC (Seamount, 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 (d1) of 0.73 in. (18.5 mm). A two end, four flute, 5/32 in.

(3.97mm). carbide endmill is then used to conduct a two inch outer profile machining operation. A rough machining operation then enlarges the hole to a diameter (d2) of 0.74 in. (18.8 mm). The hole is further enlarged to the final diameter (d3) with a finish machining operation using the same type of tool (Figure 4.5).

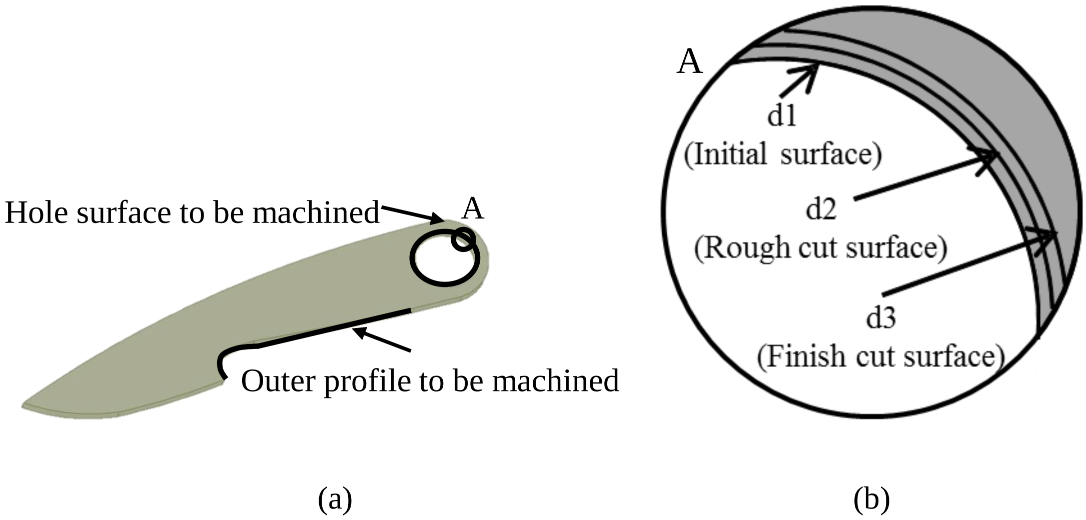

Figure 4.5. Knife X (a) hole surface and outer profile to be machined and (b) respective hole diameters.

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 under different operator’s compensation. To support this study, machining energy data was collected by conducting a set of experiments on a

CNC center. Due to limitations, some data is collected from other sources. Tool life is estimated based on the number of test holes machined with qualified dimension measured from 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.

4.1.3 Machining experiments

Machining experiments were conducted to assist in identifying milling feed and speed settings. Based on handbook (Oberg and Jones, 2008) and manufacturer recommendations (OSG, 2011), potential feed (f) and speed settings (v) were identified. The experiment is similar to published studies that use designed experiments to estimate the parameters of a Taylor Tool Life equation (Sharif et al., 2006, Ginta et al., 2009). A first order surface response design with one center point was selected. Equation 4.1 and 4.2 are the calculations for center point parameters in the design.

$$\log f_{mid} = (\log f_{low} + \log f_{high})/2 \qquad (4.1)$$

$$\log v_{mid} = (\log V_{low} + \log v_{high})/2 \qquad (4.2)$$

After the sustainability assessment, the experiment may go to second order for further optimization in the future. In this study, only the first order is studied to illustration the application of the approach. The second order would repeat the same process of applying the approach. The experiment selected a high feed and a low feed, a high speed and a low speed as four corners of the experiment. The experiment conducted one replication at each corner point, and three replications at the center point to get the measure of experiment error (Table 4.1).

Table 4.1. 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

Machine power use was measured with a power monitoring device (Fluke 43B Power Analyzer) for each setting during machining. Power data is shown in Appendix A (Figures A1-A5). Table 4.2 reports the CNC machining power draw when idle and during cutting for each setting.

Table 4.2. Spindle motor power for the selected cutting setting alternatives.

Alternative	Spindle motor power (kW)	
	Idle	Machining
A1	2.9	5.1
A2	2.9	7.2
A3	2.9	8.4
A4	2.9	5.0
A5	2.9	6.3

Tool life was judged based on the dimension and surface finish of the profile. In Table 4.3, tool life is reported in terms of machining time, total length machined, and number of knives produced. The results show that A1, A2, A4, and A5 provide more than 500 seconds of tool life, and A3 has the shortest tool life. Alternatives A1, A4, A5 can machine over 60 holes.

Table 4.3. Tool life for each alternative.

Settings	Tool life (s)	Total length machined (in.)	Total length machined (mm)	Number of knives produced
A1	554.3	55.5	1409.7	74
A2	897.1	24.0	609.6	32
A3	2.7	0.75	19.1	1
A4	525.4	50.25	1276.4	67
A5	1043.5	54.0	1371.6	72

It was found that A3 results in an unacceptable surface finish. A2 and A4 provide acceptable surface finish but tool life is shorter than A1 and A5. Therefore, based on the test results, A1 and A5 were selected as candidate settings for rough and finish machining settings. Since A5 provides a better surface finish than A1, A5 is preferred for finish machining in an A1-A5 combination. Therefore, three scenarios (Table 4.4) 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 4.4. 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)

Based on the time for each process, and the time requirements for human operations, three Gantt charts were created to illustrate the process and total cycle time for each scenario (Figure 4.6-4.8). Two assumptions are made, the cutter movement time from one hole to the next is 0.033 min. (2 s) and tool change time is 0.083 min. (5 s).

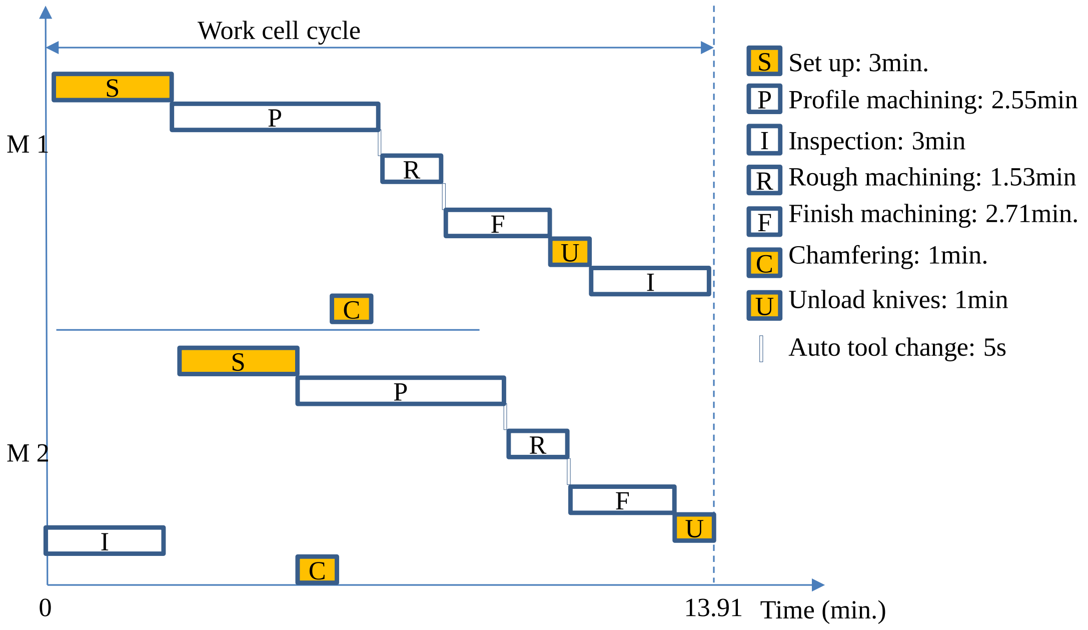

Figure 4.6. Scenario S1 Gantt Chart.

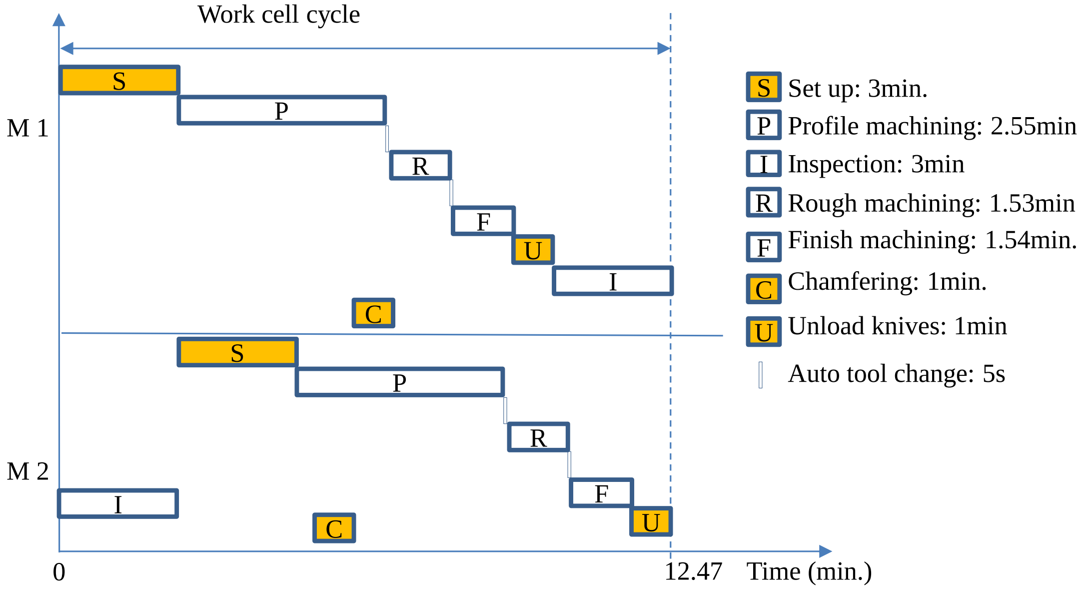

Figure 4.7. Scenario S2 Gantt Chart.

The Gantt chart illustrates parallel operations as they would occur during continuous operation, so during a work cell cycle the operator inspects and chamfers knives from the previous cycle. Taking into account concurrent operations, the work cell cycle is the sum of setup times (including loading and unloading), machining time, and inspection time.

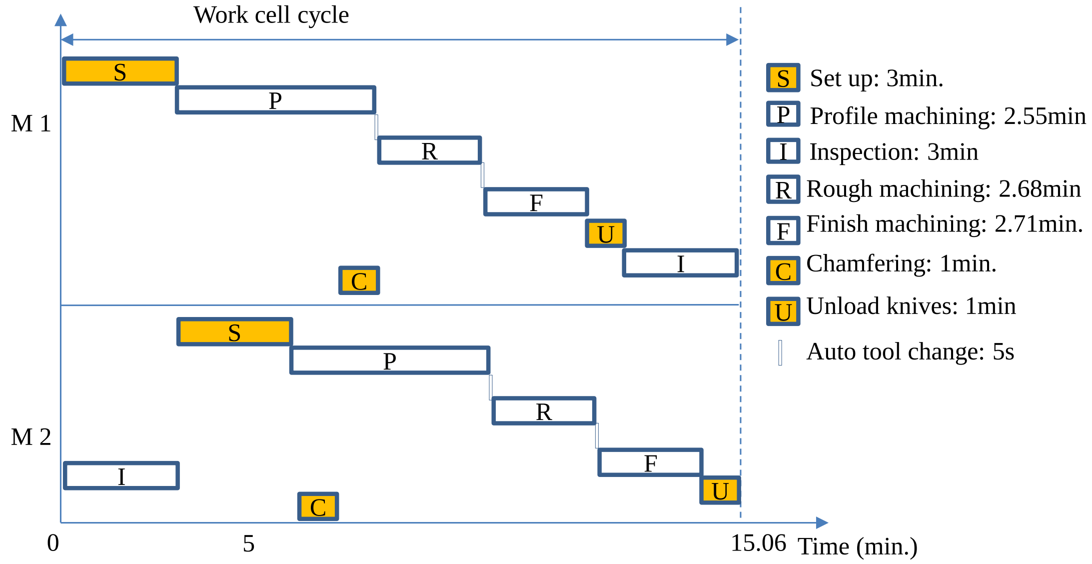

Figure 4.8. Scenario S3 Gantt Chart.

The summarized process time information for Machining Cell 1 is shown in Table 4.5.

Table 4.5 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_{outer})	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	18206	14819

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.

4.2 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 can be integrated into multi-criteria decision making, and sensitivity analysis can be 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 for contributions work cell production. Work cell sustainability performance will be analyzed on the basis of processing one part in Machining Cell 1, which is the functional unit for this study. The system boundary encompasses the work cell system, including utilities (Figure 4.9). Impacts of prior material processing are not accounted for in this study.

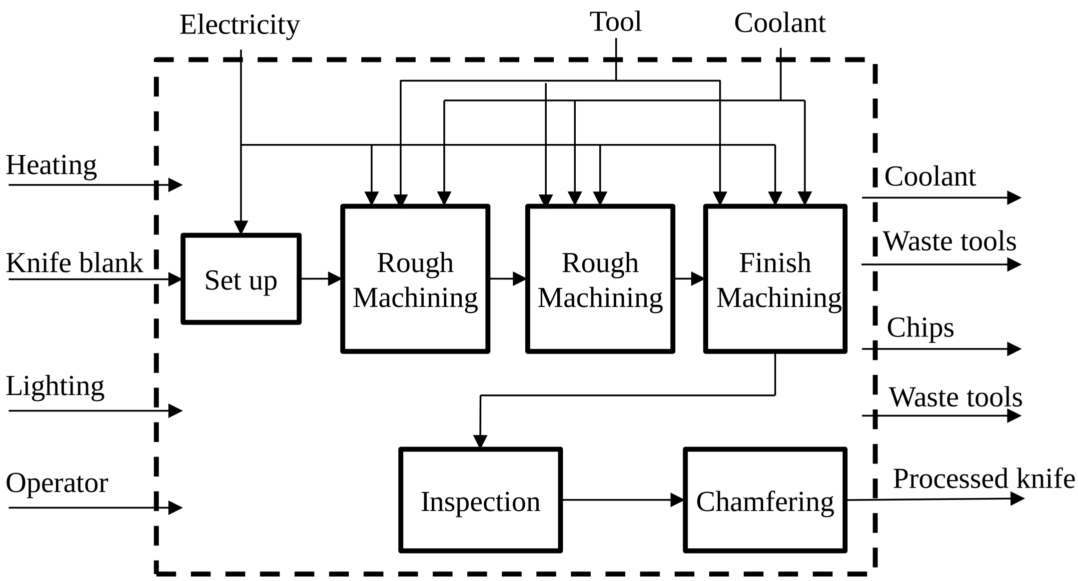

Figure 4.9. Work cell system boundary.

4.2.1 Cost assessment

Production costs for machining the hole include labor cost, stainless steel cost, coolant cost, tool cost, and energy cost. To determine labor cost (C_{labor}), the operator's wage includes two parts – a $4,200 monthly base wage (C_{base} = $4200) including benefits, and a bonus, which is calculated based on the number of knives machined per month. The minimum production quantity ($Q_{minimum}$) is 12,600 knives per month. The operator will get a $0.50 bonus for each knife produced. The labor cost per knife can be calculated as follows (Eq. 4.3):

$$C_{labor} = [C_{base} + (Q_{actual} - Q_{minimum})*0.5]/Q_{actual} \quad (4.3)$$

The labor costs for machining one part for the three scenarios are shown in Table 4.10.

For stainless steel cost, only the volume machined in machining cell 1 accounted for in the cost assessment In this case study, it is assumed that the cost of stainless steel for the knife is allocated to all work cells. Thus stainless steel cost is calculated as follows for Machining Cell 1:

$$C_{material} = V_{steel} * r_{steel} = t_{thickness}*A_{chip}*r_{steel} \quad (4.4)$$

$$A_{chip} = \pi*(d_3^2-d_1^2)/4+l*d_r \quad (4.5)$$

The steel thickness (t) is 0.124in (3.150 mm). Chip area is calculated by considering three machining processes, profile machining, rough machining, and finish machining, where d_r is the radial depth of cut, l is the length of profile cut. The 154CM stainless steel cost rate is assumed based on a market price of $5.47/in.^{3} (ASK, 2012). Therefore the chip volume is 0.0078 in.^{3}, and cost \$0.0429/knife.

Tool cost (C_{tool}) is calculated based on results from machining tests described above. Each endmill is purchased at a price of \$20 ($C_{Endmill}$= \$10). Tool cost of processing one knife can be calculated as follows (Eq. 4.6):

$$C_{Tool} = (T_{Rough} * C_{Endmill} / L_{Tool\_Rough}) + (T_{Finish} * C_{Endmill} / L_{Tool\_Finish}) + (T_{Profile} * C_{Endmill} / L_{Tool\_Profile}) \quad (4.6)$$

The calculated tool life cost results for each scenario are shown in Table 4.6.

Table 4.6. Tool life for each of the three scenarios.

Scenario	**Profile tool life (s)**	**Rough tool life (s)**	**Finish tool life (s)**	**Tool cost per knife ($)**
S1	1043	554	1043	0.798
S2	1043	554	554	0.791
S3	1043	1043	1043	0.806

The CNC machine is equipped with a coolant system to improve machinability. The tank has a 95 gallon capacity (V_{base}). Coolant cost rate is ($r_{coolant}$) \$21.6/gallon (\$81.76/L). Coolant cost ($C_{coolant}$) includes the cost of new coolant and make-up coolant. The coolant loss rate (r_{loss}) is assumed to be 10% of annual coolant use (Gutowski, 2001). Coolant will be changed every 6 months. The coolant for processing one knife is calculated in the following way (Eq. 4.7 and 4.8):

$$V_{coolant} = (V_{base} + V_{makeup})/(6*Q_{actual}) \quad (4.7)$$

where

$$V_{makeup} = V_{base} * r_{loss} /(1- r_{loss}) \quad (4.8)$$

Therefore, the coolant cost is:

$$C_{coolant} = V_{coolant} * r_{coolant} \quad (4.9)$$

The coolant cost results in Table 4.7 show that S3 has the highest cost and S2 has the lowest coolant cost per knife.

Table 4.7. Coolant costs for each of the three scenarios.

Scenario	**Coolant use (gal./knife)**	**Coolant use (L/knife)**
S1	0.0013	0.0049
S2	0.0012	0.0045
S3	0.0014	0.0053

The energy cost (C_{energy}) including equipment energy use, heating and lighting, is calculated knowing energy use and machining time per hole. The industrial electricity cost rate ($r_{electricity}$) is assumed to be 6.73 ¢/kWh (USEIA, 2012). The energy used in each process is calculated based on the process time and consumed power. The way of calculating energy cost of machining one hole is shown as below (Eq. 4.10):

$$C_{energy} = r_{electricity} (P_{i\_idle} * T_{i\_idle} + P_{i\_work} * T_{i\_work}) \quad (4.10)$$

The power for each process, and the total power required are shown in Table 4.8.

Table 4.8. Energy cost for each of the three scenarios.

	S1	**S2**	**S3**
Profile machining power (kW)	6.3	6.3	6.3
Profile machining time (hr)	0.0425	0.0425	0.0425
Rough power (kW)	5.1	5.1	6.3
Rough machining time (hr)	0.00205	0.00205	0.00397
Finish power (kW)	6.3	5.1	6.3
Finish machining time (hr)	0.00402	0.00208	0.00402
CNC idle power (kW)	2.9	2.9	2.9
Idle time (hr)	0.0111	0.0128	0.0111
CMM power (kW)	2.5	2.5	2.5
CMM (hr)	0.1887	0.1692	0.2078
Chamfering power (kW)	1.5	1.5	1.5
Chamfering (hr)	0.00167	0.00167	0.00167
Heating (kJ)	14.94	13.69	16.18
Lighting (kWh)	0.00810	0.00166	0.00196
Total energy cost ($)	0.013	0.012	0.015

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 on average (Bawaneh, 2011). The work cell is 3.2 m (10.5ft.) in length and width.

Table 4.9. Work cell heating energy and lighting energy for each of the three scenarios.

Scenario	**Cycle time (min.)**	**Workcell Area**		**Heat power W/m^2**	**Heating energy (kJ)**	**Lighting (Wh)**
		(m^2)	**(ft.^{2})**			
S1	13.91	10.24	110.22	30.59	14.94	1.81
S2	12.74	10.24	110.22	30.59	13.69	1.66
S3	15.06	10.24	110.22	30.59	16.18	1.96

The heating energy per knife E_{heat} is based on the work cell area ($S_{workcell}$), cycle time (T_{cycle}), heating power intensity (P_{heat}), and number of knives per blank (n_{blank}).

$$E_{heat} = P_{heat} * A_{workcell} / Q_{actual} \quad (4.11)$$

The calculated heating energy results are shown in Table 4.9. To estimate lighting energy use, the Oregon lighting control requirement $P_{lighting}$ of 1.24W/ft.^{2} is used as the lighting density in the workspace (OEESC, 2010). Lighting energy can be calculated with Eq. 4.10, and the results are shown in Table 4.9. The calculated cost results for each scenario are shown in Table 4.10.

$$E_{Lighting} = T_{actual} * P_{lighting} * A_{workcell} / Q_{Actual} \quad (4.12)$$

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. 4.13.

$$C_{workcell} = C_{Labor} + C_{Tool} + C_{Coolant} + C_{Energy} + C_{material} \quad (4.13)$$

Table 4.10. Summary of costs for processing one knife for each scenario.

	Cost ($/knife)		
	S1	**S2**	**S3**
Material	0.0429	0.0429	0.0429
Labor	0.319	0.296	0.341
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

Since these costs are only for machining, upstream costs, including raw material costs, are not included in the analysis. Next, environmental impacts are estimated for the three scenarios by applying the same boundary.

4.2.2 Environmental impact assessment

Environmental impact assessment is conducted within the framework of life cycle assessment (LCA). Impacts 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. Several sources of impact are involved in machining, e.g., CNC energy use, spent tools, coolant, and chips. In order to complete the LCI, some assumptions are made. The first, process and material databases in the LCA software used (SimaPro) do not include 154CM, 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%). Next, the cutting tool is modeled as its individual constituents, i.e., cobalt, tantalum carbide, and tungsten carbide, based on Jaharah (2009) as shown in Table 4.11.

Table 4.11. Endmill material constituents (Jaharah, 2009).

Constituent	Percentage (%)	Subconstituent (%)	Percentage (%)
Cobalt	0.164		
Tungsten Carbide	0.826	Tungsten	0.939
		Carbon	0.061
Tantalum Carbide	0.010	Tantalum	0.938
		Carbon	0.062

Tungsten carbide is further assumed to be composed of tungsten and carbon, and tantalum carbide composed of tantalum and carbon, all of which are available in the LCA material databases used. The mass of each material is shown in Table 4.12 for each alternative. The chips, worn cutter, and used coolant are recycled.

Table 4.12. Endmill material use for each setting (per knife).

Setting	A1		A5	
	Finish	**Rough**	**Finish**	**Rough**
Cobalt ($\times10^{-6}$lb.) [$\times10^{-6}$kg]	8.86 [19.48]	8.74 [19.23]	9.1 [20.02]	8.98 [19.76]
Tungsten ($\times10^{-5}$lb.) [$\times10^{-5}$kg]	4.187 [9.21]	4.13 [9.09]	4.3 [9.46]	4.25 [9.35]
Tantalum ($\times10^{-7}$lb.) [$\times10^{-7}$kg]	5.4 [11.88]	5.33 [11.73]	5.55 [12.21]	5.48 [12.06]
Carbon ($\times10^{-6}$lb.) [$\times10^{-6}$kg]	2.769 [6.09]	2.73 [6.01]	2.85 [6.27]	2.81 [6.18]
Material/knife ($\times10^{-5}$lb.) [$\times10^{-5}$kg]	5.4 [11.88]	5.33 [11.73]	5.55 [12.2]	5.48 [12.06]

In Table B1, each process is assigned a process identifier, which is used in life cycle inventory data of Appendix Tables. The LCA models used are reported in Table 4.13.

Table 4.13. Material and energy types and corresponding LCI process models.

Materials and Energy	**Process model (SimaPro 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

To determine environmental impacts, the ReCiPe Endpoint (H) method with World ReCiPe H/A weighting is selected, because of its categorization of impact. Then, LCI data are imported to LCA software (SimaPro), which generates environmental impact results shown in Table 4.14.

From the impact results, it is clear that six impact indicators have relatively higher scores than the rest, i.e., climate change-human health, human toxicity, particulate matter formation, climate change-ecosystems, metal depletion, and fossil depletion. The results are consistent with the assumption that the change of feed rate and speed affects energy use and tool life.

Table 4.14. Environmental impact of processing one knife in the work cell.

Environmental impact category	**Environmental Impact (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

4.2.3 Social impact assessment

Social assessment follows the UNEP Social LCA framework, which involves goal and scope definition, life cycle inventory, impact assessment, and interpretation (Benoî and Mazijn, 2009). 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 work cell conditions affect workers. The social LCA framework categorizes social impact into eight aspects, i.e., wage, working hours, workload, injuries, community engagement, local employment, and technology development (Benoî and Mazijn, 2009). Work cell operating conditions contribute directly to three social impact categories, i.e., wage, workload, and injuries. 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 4.15). Therefore, it is defined as positive impact, though the normalized values (calculated by Eq. 3.7) are negative. The normalized wage impact is zero if the work cell wage equals to local standard $51,856 per year for machining operators (Oregon Wage Information, 2011).

Table 4.15. 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
Wage ($/mo.)	4540	5150	4034
Annual wage ($/mo.)	54486	61801	48403
Standard wage ($/mo.)	51856	51856	51856
Percentage of difference	0.051	0.192	-0.067
Normalized wage impact	-0.16	-0.62	0.22

Workload is directly related to changes in production rate. In Table 4.16, all the three scenarios outperform the standard workload. The assumption is made that standard work cell cycle time ($T_{Standard}$) is based on 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. 4.12).

$$T_{Standard} = 1/(n_{standard}/n_{machines}*n_{blanks}) \tag{4.14}$$

Where $n_{standard} = 14808$, $n_{machines} = 2$, and $n_{blanks} = 20$

The average injury rate (s_{injury}) at this occupation is assumed to be 4.6 based on a government report (U.S.BLS, 2006). The risk of injury is assumed to increase when production rate increases. The work cell injury rate is calculated in the following way (Eq. 4.15):

$$r_{injury} = S_{injury}*T_{Standard} /T_{cycle} \tag{4.15}$$

The injury social impact results are shown in Table 4.17.

Table 4.16. Workload conditions in the work cell.

	S1	S2	S3
Cycle time (min.)	13.91	12.74	15.06
Standard cycle time (min.)	12.48	12.48	12.48
Percentage difference	-0.12	-0.02	-0.21
Normalized	-0.335	-0.062	-0.603

Community engagement, local employment, and technology development, are not expected to vary with the change of production scenario, because the same work cell, same operators, and same working hours are analyzed. Thus, the normalized values are zero for each scenario for these impact categories.

Table 4.17. Injury conditions for the three work cell scenarios.

	S1	S2	S3
Cycle time (min.)	13.91	12.47	15.06
Standard injury rate (%)	4.6	4.6	4.6
Standard cycle time (min.)	12.48	12.48	12.48
Injury rate (%)	4.13	4.50	3.81
Difference	-0.475	-0.096	-0.790
Normalized	-0.349	-0.070	-0.581

Normalized values determined for each category are next summed to obtain an overall social impact value for each scenario. The social impact results are summarized in Table 4.18.

Table 4.18. Total social impact indicators for the work cell.

Indicators	S1	S2	S3
Wage	-0.16	-0.62	0.22
Workload	-0.335	-0.062	-0.603
Injuries	0.349	-0.070	-0.581

4.2.4. Weight assignment

In this step, each metric is assigned a weight that represents its level of importance to the decision maker. As introduced in Chapter 2, there are many ways to assign weights, but the approach herein utilizes both an objective statistical method and subjective pairwise comparisons. This approach can not only deal with cost and environmental impact weightings, but also social weightings, which are more of subjective. For environmental impact, endpoint impact categories are selected as they represent overall impact domains on environment (Table 4.19).

Table 4.19. Environmental impact endpoint categories.

Categories	S1	S2	S3
Human health	15.93	15.31	16.23
Ecosystem	1.14	1.10	1.16
Resource	17.08	16.40	17.40
Total	34.15	32.81	34.79

For cost metrics and environmental impact metrics, the pairwise comparisons are based on the average value for the three alternatives and are made by evaluating the preference rating against each other metric. Stainless steel cost for each of the scenarios is the same; only metrics with variability were conducted in the decision making. The weight is then given according to the actual metric value in fraction form (Table 4.20).

Table 4.20. Weighting matrix for production cost 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

Once the pairwise comparison results are obtained, a consistent matrix can be made. In this case, the maximum eigenvalue, λ_m, is 4 and the corresponding eigenvector is calculated with Matlab. The eigenvector for the economic domain, W_1 (k =1 means economic domain) is:

W1 = (0.3705 0.0332 0.0390 0.9274).

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 4.21 in fraction form.

Table 4.21. Weighting matrix for environmental impact metrics.

	Human health	**Ecosystem**	**Resource**
Human health	1	14	14/15
Ecosystem	1/14	1	1/15
Resource	15/14	15	1

The maximum eigenvalue λ_m, and the corresponding eigenvector, W_2, are then calculated as:

$\lambda_m = 3$, and

W_2 = (0.6810 0.048 1 0.7306).

Since social metrics are relatively subjective, the weightings need to be based on the decision maker's judgment which is in contrast to economic and environmental weighting. In this case, matrix were first randomly generated ranging from 0 to 9 weighting values. The randomly generated matrix values are shown in Table 4.22.

Table 4.22. Original weighting matrix of social metrics.

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

The largest eigenvalue λ_m of this matrix is 5.3 which is greater than the number of metrics ($\lambda_m > n$). This means the weighting values from 0 to 9 is inconsistent, and so are the decision maker's judgment. However, even though λ_m is greater than three, it may also be accepted as long as the condition CR<0.1 is met. CR is calculated as follows:

$$CR = CI/RI = 1.97 > 0.1$$

Where $CI = (\lambda_m - 3)/(3-1) = 1.1$ and $RI = 0.58$ (From Table 3.2)

Therefore, the decision maker should make another round of judgments to revise the matrix. The final consistent weighting generated is shown in Table 4.23.

Table 4.23. Final weighting matrix of social metrics.

	Wage	**Workload**	**Injuries**
Wage	1	3/8	3/2
Workload	8/3	1	1
Injuries	2/3	2	1

Now, the largest eigenvalue $\lambda_m = 3.217$ and the corresponding eigenvector W_3 becomes (0.450 0.756 0.476), which is also the weighting of three metrics. The domain weightings are also randomly generated by normal distribution with mean of 0.5 for economic domain, $(1-0.1*w_1)$ for environmental domain, and $(1-w_1-w_2)$ for social domain. The result is 0.5 for the economic domain, 0.2 for the environmental domain, and 0.3 for the social domain.

4.2.5 Alternative ranking

After weightings are generated, the weightings are to be used in alternative ranking. First, an alternative value table (Table 4.24) is organized to help the decision maker make pairwise comparison judgments for each metric in each scenario. The weight of each metric $(w_t)_{k,n}$ is the result of weights of two levels,

$$(w_t)_{k,n} = w_{k,n} * w_k \tag{4.16}$$

For example, labor cost weight $(w_t)_{1,1}$ = 0.185 is calculated by multiplying, which is the metric weight within economic domain $(w_{k,n})$ = 0.3705, and the domain weight (w_k) =0.5.

Table 4.24. Alternative value table.

Attributes (per knife)	**S1**	**S2**	**S3**	**Weight**
Labor cost per knife ($)	0.319	0.296	0.341	0.185
Coolant ($)	0.029	0.026	0.031	0.017
Energy ($)	0.034	0.032	0.035	0.020
Tool ($)	0.798	0.791	0.806	0.464
Human health (mPt)	15.93	15.31	16.23	0.136
Ecosystem (mPt)	1.14	1.10	1.16	0.010
Resource (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

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. For example, in the alternative value table under labor cost, the comparison value of S_1 (0.319) and S_2 (0.296) can be assigned as:

Since 0.319– 0.296 >0,

S1>S2,

thus S1 is not preferred

Here, k refers to the domain; i refers to the metric in the given index value domain; j refers to scenario S1; and j' refers to scenario S2.

Preference ranking results for each of the scenarios are shown in Table 4.25, Table 4.26, and Table 4.27.

Table 4.25. S1 preference ranking value.

S1 preference ranking			
Attributes	**S2**	**S3**	**Weight**
Labor cost	0	1	0.185
Coolant cost	0	1	0.017
Energy cost	0	1	0.020
Tool cost	0	1	0.464
Human health	0	1	0.136
Ecosystem	0	1	0.010
Resource	0	1	0.146
Wage	0	1	0.135
Workload	1	0	0.227
Injuries	1	0	0.143
Total	0.370	1.112	1.482

Table 4.26. S2 preference ranking value.

S2 preference ranking			
Attributes	**S1**	**S3**	**Weight**
Labor	1	1	0.185
Coolant	1	1	0.017
Energy	1	1	0.020
Tool	1	1	0.464
Human health	1	1	0.136
Ecosystem	1	1	0.010
Resource	1	1	0.146
Wage	1	1	0.135
Workload	0	0	0.227
Injuries	0	0	0.143
Total	1.112	1.112	2.224

Table 4.27. S3 preference ranking value.

S3 preference ranking			
Attributes	**S1**	**S2**	**Weight**
Labor	0	0	0.292
Coolant	0	0	0.026
Energy	0	0	0.082
Tool	0	0	0.397
Human health	0	0	0.138
Ecosystem	0	0	0.018
Resource	0	0	0.144
Wage	0	0	0.135
Workload	1	1	0.227
Injuries	1	1	0.143
Total	0.370	0.370	0.739

Calculations of positive flow and negative flow of each alterative are shown in Appendix C. The summary of alternative preference rankings for each scenario is shown in Table 4.28.

Table 4.28. 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

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

4.2.6. 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 factor because the company can purchase tools from different sources, and tool wear rate varies even from the same source. Environmental impact assessment can lead to uncertain ties because the LCA practitioner can use different weighting methods for environmental impact categories or make different assumptions in modeling materials and processes. At the domain level, for example, domain weights are uncertain factors since decision makers may have different preferences regarding sustainability impacts.

Table 4.29. Three level full factorial design of sensitivity analysis.

Economic domain weighting	**Environmental domain weighting**	**Social domain weighting**		
		0.1	**0.5**	**0.9**
0.1	0.1	0.1;0.1;0.1	0.1;0.1;0.5	0.1;0.1;0.9
0.1	0.5	0.1;0.5;0.1	0.1;0.5;0.5	0.1;0.5;0.9
0.1	0.9	0.1;0.9;0.1	0.1;0.9;0.5	0.1;0.9;0.9
0.5	0.1	0.5;0.1;0.1	0.5;0.1;0.5	0.5;0.1;0.9
0.5	0.5	0.5;0.5;0.1	0.5;0.5;0.5	0.5;0.5;0.9
0.5	0.9	0.5;0.9;0.1	0.5;0.9;0.5	0.5;0.9;0.9
0.9	0.1	0.9;0.1;0.1	0.9;0.1;0.5	0.9;0.1;0.9
0.9	0.5	0.9;0.5;0.1	0.9;0.5;0.5	0.9;0.5;0.9
0.9	0.9	0.9;0.9;0.1	0.9;0.9;0.5	0.9;0.9;0.9

The sensitivity analysis focuses on studying the effect of domain weighting changes. Each domain is given three levels of weights, low-(0.1), mid-(0.5), and high-(0.9). The three level full factorial design of experiment is shown in Table 4.29. There are 27 combinations of weight combinations in the design. For each weight combination, a net ranking is calculated. The net ranking results are shown in Table 4.30.

4.2.7 Discussion of results

The assessment results show that S2 provided a better performance in economic and environmental impact than S1 and S3 (Table 4.26). In the sensitivity analysis, three weight levels (low, medium, high) were identified for each domain to investigate how rankings are changed with different domain weightings.

Table 4.30. 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

The results in Table 4.30 showed that S2 ranked highest for most of the weight combinations. S3 ranked highest for only two situations, i.e., when economic and environmental weights are assigned as 0.1, while social weight is assigned as either 0.5 or 0.9. This means that, while S3 had a better social performance among the three alternatives, it only ranks first when social domain is given a relatively higher weight than the economic and environmental domains. For companies concerned with production economics 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 cost contributed most (above 60%) to the total production cost of one knife. Six major environmental impacts were found using ReCiPe 2008: climate change human health, human toxicity, particulate matter formation, climate change ecosystems, metal depletion, and fossil depletion. Second, the weights for economic and environmental factors reflect the rate of effectiveness on that domain. Third, in this work cell, the change of social impact is caused by the difference of production rate. Three aspects (wage, workload, and injury) have been addressed as the major impact categories of social impact. Social metrics were quantified by normalizing the difference between local standards and work cell performance. However, total social impact was not calculated because of the limitation of addressed social factors. Instead, subjective weightings are applied. Fourth, sensitivity analysis showed that S2 was preferred to the other two alternatives for a wide range of domain weightings. S3 had the ranking preference when the social impact domain was given a high weighting and economic and environmental domains were given low weights.

In Chapter 5, conclusions will be drawn from the application of this sustainable manufacturing assessment decision making approach reported in Chapter 4. The method developed as a part of this research will be summarized. Moreover, the limitations of this work and opportunities for future research will also be addressed.

Chapter 5. Summary and conclusions

In this chapter, a summary of the work reported is provided. Conclusions, drawn as a result of the work are discussed. Contributions of the work to the body of knowledge are presented. Lastly, limitations of this study and future research are discussed.

5.1 Summary

In this thesis, Chapter 1 introduced the motivation and objective of this research. Chapter 2 reviewed related research conducted on sustainability assessment and integrating assessment results into decision making. An approach for integrating sustainability assessment into decision making is proposed in Chapter 3. In Chapter 4, the approach was applied to a manufacturing work cell producing stainless steel knives. The approach was used to evaluate machining scenarios to assist the production engineer in defining and quantifying the metrics, and making decisions. The ranking results for the machining scenarios were based on a randomly generated weighting of social metrics and domain areas. Contribution analysis was conducted in economic and environmental assessments. Sensitivity analysis was conducted to provide the decision maker an overview of making decisions with uncertain factors.

5.2 Conclusions

In developing the approach, tools and models for assessing sustainability performance were found to be dependent on the shop floor characteristics. Therefore, the approach for integrating sustainability assessment into decision making is developed in a general sense in order to accommodate various manufacturing shop floor situations. Practitioners are suggested to utilize appropriate assessment methods to fit their goal and scope. Similarly, social metrics and assessment methods need to be selected based on practitioners' concerns and regulation requirements. However, in environmental impact assessment, LCA has been so far proved to be an effective tool, which provides relatively reliable results. The pairwise comparison weighting method allows decision makers make both objective and subjective judgments in assigning economic, environmental, and social metrics weights. Nevertheless, the outranking decision making method gives 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 goal and scope definition. In general engineers should bear in mind that sustainability impact quantification is a complex and dynamic problem. Production situations usually have flexibilities, i.e. cycle time, inspection standards. These may affect the result of decision making. In addition, the social assessment method used in this study is to assist integration of three assessments. The application showed that domain weights and social weights are fairly subject to decision maker's preference. Therefore, decision maker should carefully review the weights on each domain and social metrics, since those weights would affect final ranking of alternatives.

5.3 Contributions

Prior research focused on higher level (e.g. Enterprise, product) and laboratory area of manufacturing sustainability assessment. In addition, prior work often address one or two sustainability domains. In this study, three domains (economic, environmental, and social) are concurrently considered in sustainability assessment at the manufacturing work cell. This approach is able to assist shop floor engineers making decisions on improving processing conditions. The approach is proved to be demonstrated to be applicable and straight forward for implementation into actual production scenarios.

This approach utilizes an existing weighting method and multi-criteria decision making method to rank potential processing alternatives. Prior research focused on optimizing machining conditions. Shop floor engineers however often encounter problems that have limited setting alternatives, rather than being amenable to a continuum of solutions. Thus, the approach delivered herein utilized an outranking multi-criteria decision making principle (PROMETHEE) can assist engineers in ranking those processing alternatives and making decisions.

5.4 Research limitations

Limitations of the approach developed as a part of this research are addressed with respect to three aspects: selection of social metrics, validation of sustainability impact, and availability of production data.

First, due to the lack of research on social sustainability, the selection of metrics follows the UNEP social LCA guidelines, which is a recognized framework for conducting social assessment. Seven aspects have been identified by the guidelines, but only three (wage, injury rate and workload) are selected because of their applicability to the work cell system boundary.

Second, the methods for estimating each of the impacts need validation. Economic impact is calculated by summarizing directly related costs. Indirect costs also affect sustainability for example through society burden, taxes, and fines. Environmental impact can be evaluated by different methods with different weights. For each method, relative results can be different. In this study, ReCiPe 2008 was used as the method to assess the environmental impact. However, within ReCiPe 2008, different weighting methods as discussed in Chapter 4 can be utilized to gauge the sensitivity of results to different value, judgments. All these variations contribute to the imprecision of the result.

Third, the case illustrated in this study was based on a generalized production work cell, which required certain assumptions to be made (e.g., knives per blank and number of shifts). In a production environment, sustainability related information may not be collected or be prohibitively difficult to collect. In an actual production work cell, situations can be more complicated with flexible hours and machine breakdown and maintenance, for example. In this study, some production data was gathered from external sources outside the work cell (e.g., heating energy, light energy, and wage data), which may not be representative of actual conditions.

5.5 Opportunities for future research

With current study limitations in mind, future research should focus on the following aspects: social metric selection, group decision making, and production flexibility.

First, other social metrics should be identified, quantified, and their values authenticated. Such a study would focus not only on selecting production related social metrics, but also on metrics that relate to a community, such as safe and healthy living conditions, and respect of indigenous rights. Effort can also be focused on investigating the severity of social impact of the work cell.

Second, although the process level decision making may not require multiple engineers to make a decision, sometimes there can be different opinions on a certain change. Therefore, a decision may be made by a group of engineers, or a team of engineers and business managers. In this scenario, group decision-making methods should be applied in subjective judgments in weight assignment and decision making.

Third, it is expected that this approach can be extended to assist production engineers assessing sustainability and making decisions in the facility level which may consists of several work cells and operation stations.

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Appendix A

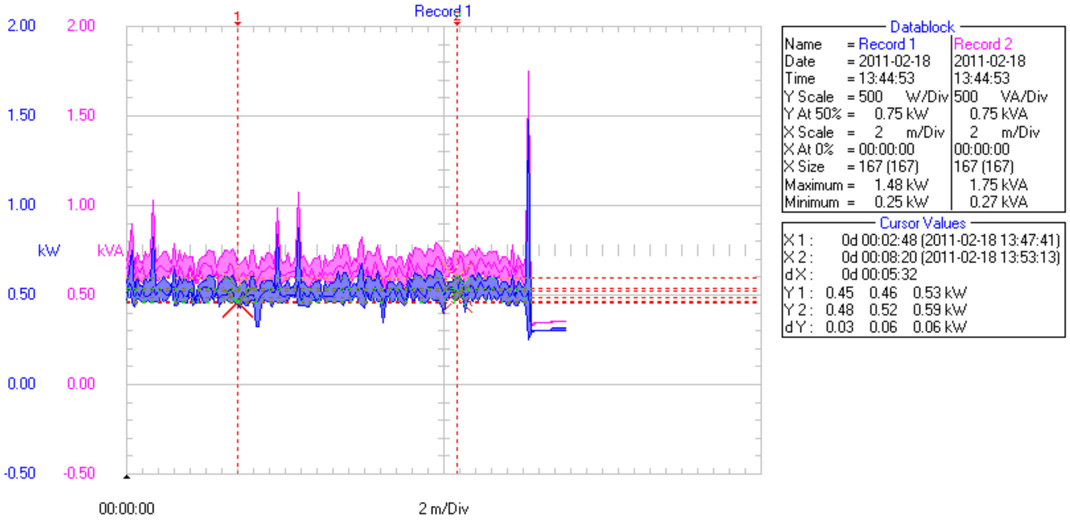

Figure A1. Power chart in A1 setting during machining.

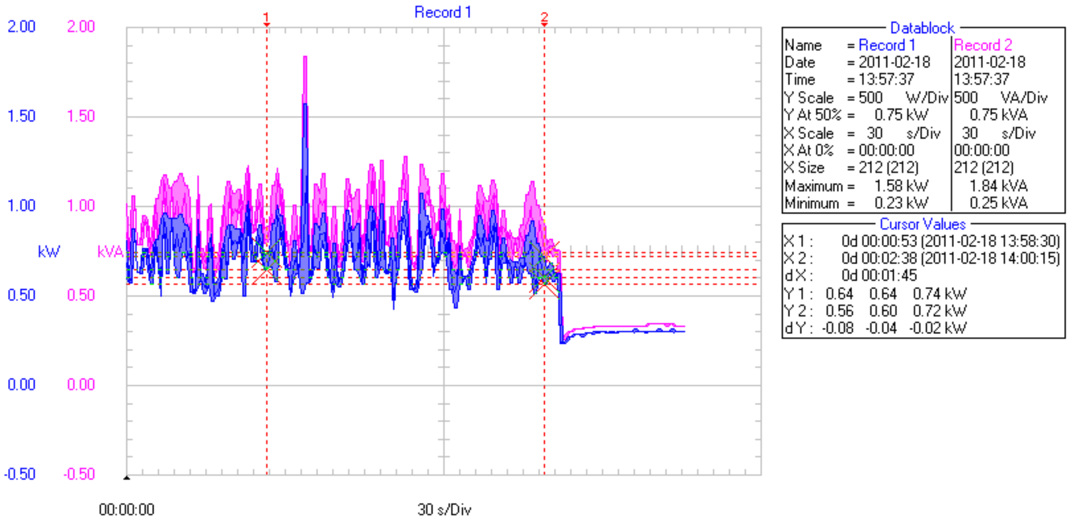

Figure A2. Power chart in A2 setting during machining.

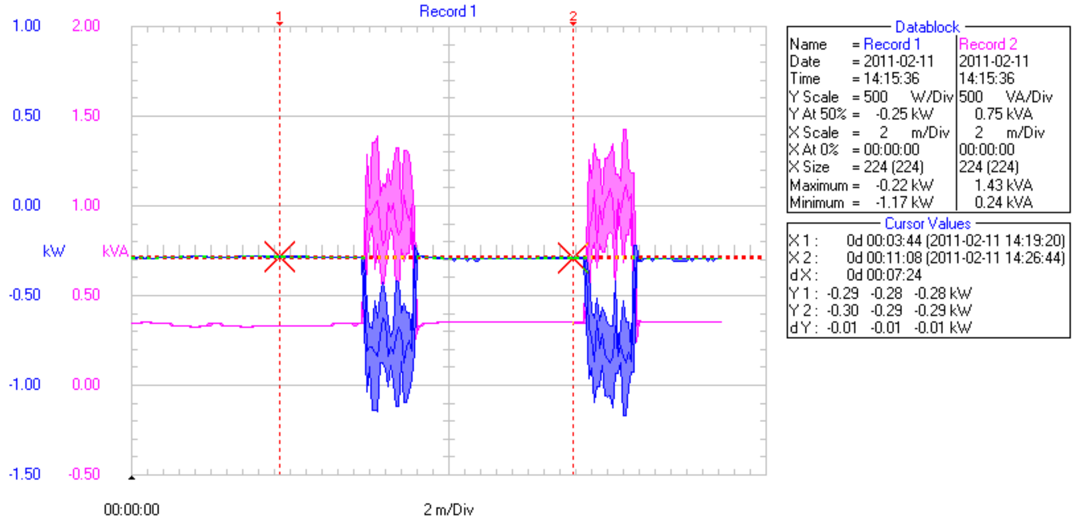

Figure A3. Power chart in A3 setting during machining.

(Note: An error of the device setting caused the conversed value of power showed in blue in the chart. All the values in blue should be positive.)

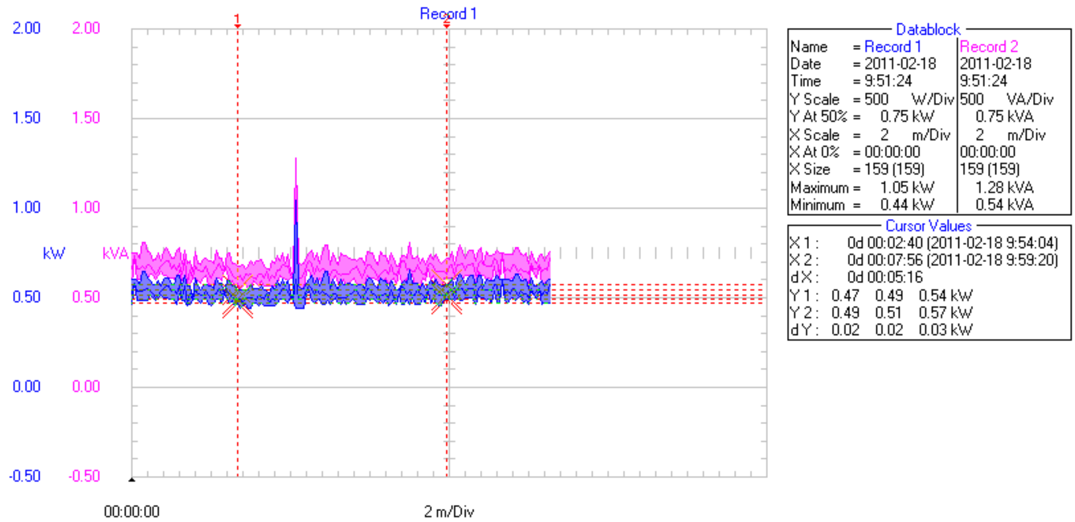

Figure A4. Power chart in A4 setting during machining.

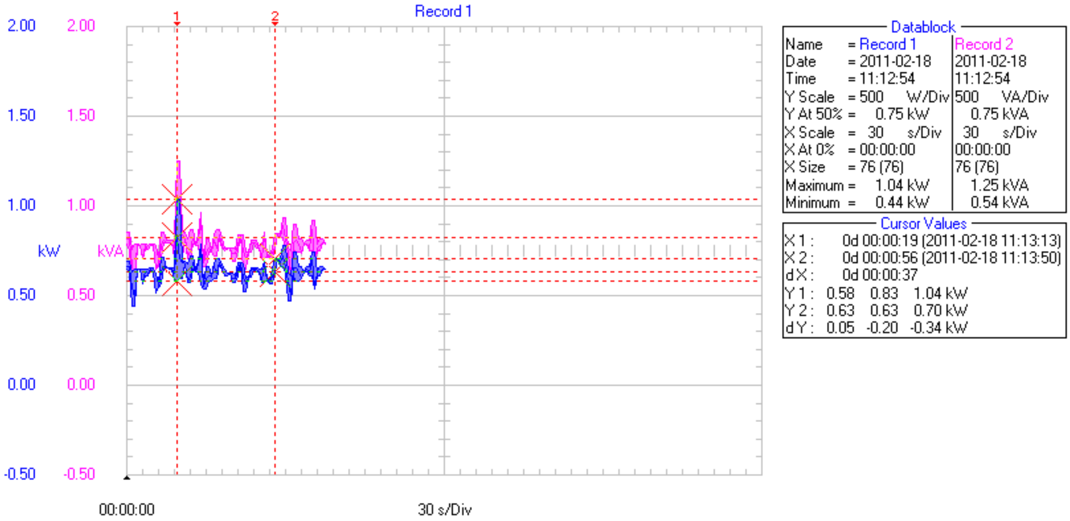

Figure A5. Power chart in A5 setting during machining.

Appendix B

Table B1. Material and energy types and corresponding process models and process identifiers.

Materials/Energy	**Process model (SimaPro LCA software databases)**	**Process identifier**
Electrical energy	Electricity, production mix US/US with US electricity U	a
Knife material	X90CrMoV18(440B)I	b
Cobalt (tool)	Cobalt, at plant / GLO U	c
Tantalum (tool)	Tantalum, powder, capacitor-grade, at regional storage/GLO U	d
Tungsten (tool)	Tungsten I	e
Carbon (tool)	Carbon black I	f
Oil (coolant)	Vegetable oil methyl ester, at esterification plant/FR U	g
Water (coolant)	Tap water, at user/RER with US electricity U	h
Cutter recycling	Recycling non-ferro/RER with US electricity U	i
Coolant disposal	Treatment, sewage, to wastewater treatment, class 5/CH with US electricity U	j
Chip recycling	Recycling steel and iron/RER with US electricity U	k
Heating energy	Heat, natural gas, at industrial furnace low-NOx > 100kW/RER	l

Table B2. Life cycle inventory for Scenario S1.

	Process identifier	**Amount**	**Unit**
Set up	a	0.015	kWh
	b	0.132	lb
Profile Milling	c	1.668E-05	lb
	e	7.888E-05	lb
	d	9.539E-07	lb
	f	5.216E-06	lb
	a	0.023	kWh
	k	0.001	lb
	i	0.0001	lb
Rough Milling	a	0.016	kWh
	c	8.74E-06	lb
	d	5.33E-07	lb
	e	4.13E-05	lb
	f	2.73E-06	lb
	j	7.76E-05	gal
	k	0.000177	lb
	i	5.33E-05	lb
Finish Milling	a	2.69E-02	kWh
	c	9.102E-06	lb
	d	5.551E-07	lb
	e	4.303E-05	lb
	f	2.846E-06	lb
	g	4.416E-05	gal
	h	3.974E-04	gal
	J	1.192E-03	gal
	k	1.799E-04	lb
	i	5.551E-05	lb
Inspection	a	0.027	kWh
Chamfering	a	7.333E-02	kWh
Heating	l	1.49E+01	KJ
Lighting	a	1.81E-03	kWh

Table B3. Life cycle inventory for Scenario S2.

	Process code	**Amount**	**Unit**
Set up	a	0.015	kWh
	b	0.132	lb
Profile Milling	c	1.668E-05	lb
	e	7.888E-05	lb
	d	9.539E-07	lb
	f	5.217E-06	lb
	a	0.023	kWh
	k	0.0006	lb
	i	0.0001	lb
Rough Milling	a	0.016	kWh
	c	8.74E-06	lb
	d	5.33E-07	lb
	e	4.13E-05	lb
	f	2.73E-06	lb
	j	7.64E-05	gal
	k	0.000177	lb
	i	5.33E-05	lb
Finish Milling	a	1.22E-02	kWh
	c	8.85E-06	lb
	d	5.39E-07	lb
	e	4.18E-05	lb
	f	2.76E-06	lb
	g	4.04E-05	gal
	h	3.63E-04	gal
	J	1.09E-03	gal
	k	1.79E-04	lb
	i	5.39E-05	lb
Inspection	a	0.027	kWh
Chamfering	a	1.36E+01	kWh
Heating	l	1.65E-03	KJ
Lighting	a	7.33E-02	kWh

Table B4. Life cycle inventory for Scenario S3.

	Process code	**Amount**	**Unit**
Set up	a	0.015	kWh
	b	0.132	lb
Profile Milling	c	1.668E-05	lb
	e	7.888E-05	lb
	d	9.539E-07	lb
	f	5.216E-06	lb
	a	0.023	kWh
	k	0.0006	lb
	i	0.0001	lb
	a	0.031	kWh
	c	8.98E-06	lb
	d	5.48E-07	lb
	e	4.25E-05	lb
	f	2.81E-06	lb
	j	8.63E-05	gal
	k	0.000177	lb
	i	5.48E-05	lb
Finish Milling	a	2.69E-02	kWh
	c	9.10E-06	lb
	d	5.55E-07	lb
	e	4.30E-05	lb
	f	2.84E-06	lb
	g	4.78E-05	gal
	h	4.30E-04	gal
	J	1.29E-03	gal
	k	1.79E-04	lb
	i	5.55E-05	lb
Inspection	a	0.027	kWh
Chamfering	a	7.33E-02	kWh
Heating	l	1.61E+01	KJ
Lighting	a	1.96E-03	kWh

Appendix C

Preference index is calculated as follows:

$$\pi(S1, S2) = \sum_{i=1}^{13} wt * Pi(S1, S2) = w_{12} + w_{13}$$

$$\pi(S1, S3) = \sum_{i=1}^{13} wt * Pi(S1, S3) = w_1 + w_2 + \ldots + w_{11}$$

$$\pi(S2, S1) = \sum_{i=1}^{13} wt * Pi(S2, S1) = w1 + w_2 + \ldots + w_{11}$$

$$\pi(S2, S3) = \sum_{i=1}^{13} wt * Pi(S2, S3) = w_1 + w_2 + \ldots + w_{11}$$

$$\pi(S3, S1) = \sum_{i=1}^{13} wt * Pi(S3, S1) = w_{12} + w_{13}$$

$$\pi(S3, S2) = \sum_{i=1}^{13} wt * Pi(S3, S2) = w_{12} + w_{13}$$

Positive flow values are shown in the three tables (Table 4.25, Table 4.26, and Table 4.27), which are:

$Ø^{+}(S1) = 1.482$ $Ø^{+}(S2) = 2.224$ $Ø^{+}(S3) = 0.739$

Negative flow values are calculated by:

$$Ø^{-}(S1) = \pi(S2, S1) + \pi(S3, S1) = 1.482$$

$$Ø^{-}(S2) = \pi(S1, S2) + \pi(S3, S2) = 0.739$$

$$Ø^{-}(S3) = \pi(S1, S3) + \pi(S2, S3) = 2.224$$

Net flow values are calculated as follows:

$$Ø(S1) = Ø^{+}(S1) – Ø^{-}(S1) = 0$$

$$Ø(S2) = Ø^{+}(S2) – Ø^{-}(S2) = 1.485$$

$$Ø(S3) = Ø^{+}(S3) – Ø^{-}(S3) = -1.485$$