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AN OVERVIEW OF SUSTAINABILITY INDICATORS AND METRICS FOR DISCRETE PART MANUFACTURING

Duck Bong Kim, Swee Leong
Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899, U.S.A

Chin-Sheng Chen
Florida International University
Miami, Florida 33199, U.S.A

ABSTRACT

Sustainable manufacturing has become an emerging environmental, economic, societal, and technological challenge to the industry, the academia, and the government entities. Numerous research and development (R&D) efforts have been launched, and many global and domestic efforts have been initiated toward a long-term sustainable world. This paper provides an overview of R&D efforts in the measurement of manufacturing sustainability, based on an intensive literature search. It focuses on sustainability metrics that apply to unit machining processes for discrete part manufacturing. The authors present results from assessing the scope of indicators that exist for sustainability measurement in general, with a quick visit to the taxonomy of manufacturing activities and different classifications of existing SM metrics by unit machining processes. Most metrics at the unit machining level were developed to measure environmental impacts with respect to energy, materials, water, wastes, and air emissions, while a relatively smaller effort was developed to gauge societal or economic impacts. We report on an analysis of energy metrics available for various unit machining processes at the sub-device and sub-unit process level.

INTRODUCTION

The US Department of Commerce [1] defines sustainable manufacturing as the “creation of manufactured products that use processes which minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.” The subject of sustainability has attracted world-wide attention for decades as it closely relates to major global concerns of depleting natural resources, climate changes, and long-term corporate strategies of competitiveness and survival. The concept of sustainable manufacturing is still in its development stage; and the transformation from the traditional manufacturing operations concept to the one of sustainable manufacturing still requires a considerable amount of R&D efforts. Many researchers have been active in pursuing a wide range of sustainable manufacturing (SM) topics including methodologies for SM classification and measurement [2, 3], as well as specific SM indicators and metrics [4-13].

Manufacturing operations typically aim to minimize direct manufacturing costs such as material, labor, and energy [14]. For example, lean manufacturing has been promoted as an operation strategy to reduce wastes, thus resulting in more effective and efficient use of resources [15]. While environmental impact may not be as widely understood and addressed as economic concerns, environmental-friendly manufacturing (also known as environmental-conscious manufacturing) has been increasingly promoted to lower the consumption of resources (i.e., energy, material, and water), consequently addressing environmental impacts of manufacturing [15]. Green manufacturing similarly promotes the practice of environmentally-benign manufacturing based on the 3R (reduce, reuse, and recycle) concept [16]. Sustainable manufacturing recently expanded the 3R concept into 6R, adding recover, redesign, and remanufacture, to cover the product life-cycle [16].

Sustainable manufacturing is a new paradigm of which the goal is to attain a long-term global competitive edge by considering the environmental, societal, and economic factors in each product life-cycle stage. In the past two decades, researchers have worked on indicators and metrics in support for sustainability assessment, performance measurement, and strategic operations decisions. A few SM research efforts have adopted a holistic view at the global, national, sector, corporate, and product levels. Far less attention has been directed at manufacturing sustainability at the unit process level, which is a critical building block for the definition of manufacturing sustainability at the higher levels. Though products and components are usually designed to be different from one another, their processes however should be similar and could be defined with a significantly smaller set of common unit processes such as sawing, drilling, milling, turning, and grinding when it comes to machined parts. This paper focuses on an overview of sustainability indicators and metrics available for unit manufacturing processes, aiming at mapping out SM voids for further research. The long-term goal of our work is to build a scientific foundation for developing a SM methodology and infrastructure for discrete product manufacturing.

The next section presents a review of sustainability indicators at the global, country, sector, corporate, product, and unit process levels, followed by a quick visit to the taxonomy of manufacturing processes. The process taxonomy and indicators hierarchy are used to organize indicators and metrics developed for unit machining operations. This paper also presents an analysis of existing energy metrics at the sub-unit process level by three operation modes of setup, standby, and machining.

SUSTAINABILITY INDICATORS

In the past two decades, many sustainability indicators and metrics have been defined for different purposes and domains of application, as reported in [16-23]. Jayal et al. [16] presented a holistic view for achieving manufacturing sustainability at the product, process and system levels. Feng et al. [20, 21] conducted an overview of indicators and metrics related to sustainable manufacturing, and categorized those measures into a hierarchy of global, country, sector, corporation, facility, process, and product levels, in accordance with the Organization for Economic Cooperation and Development (OECD) toolkit efforts. Lu et al. [24] took a product and process view and conducted a survey of SM indicators and metrics for manufacturing processes. A similar work can also be found in Sarkar et al. [13]. We briefly describe each of the above hierarchical levels and select a major effort from each level to enumerate available sustainability indicators from each perspective.

Global level

At the global level, we chose to review in more detail, the Indicators of Sustainable Development (ISD) developed by the United Nations Committee on Sustainable Development (UN-CSD) [4] and the Core Environmental Indicators (CEI) developed by the OECD [5]. The UN-CSD effort focused on a sustainability indicator framework consisting of 38 sub-indicators and 15 main themes based on the classification of social, environment, economic, and institutional indicators. OECD-CEI includes 50 indicators, which covers a range of environmental concerns such as toxic contamination and acidification in OECD countries. The framework consists of a Press-State-Response model along with the corresponding environmental issues. The Press-State-Response model consists of indicators for environmental pressures, conditions, and societal responses. The environmental issues capture major environmental concerns and challenges in OECD countries.

Country level

At the country or regional level, we chose to the Environmental Pressure Indicators for European Union (EPI-EU) [6], the Environmental sustainability index (ESI) [7], and the Environmental performance index (EPI) [8]. EPI-EU is the first result of the Environmental Pressure Indices project, which consists of 60 indicators reflecting the negative pressure of human activities on the environment in ten policy fields. On the other hand, the ESI was designed to measure the rigorous and data-driven environmental performance for countries. Its final version (i.e., 2005 ESI) was developed to measure the overall environmental sustainability and showed the ranking of the sustainability for 146 countries [7] based on 21 indicators with 76 variables. Based on the ESI, the EPI was developed to assess the impact of policy which results in reduction of negative environmental issues on human health and promoting ecosystem vitality. The 2012 EPI is a result of the seventh iteration of the environmental measurement project, ranking 132 countries on 22 performance indicators in ten policy categories [8].

Sector level

Singh et al. [17] presented an overview of sustainability assessment methodologies and categorized sustainability efforts into market/economy-based indices, eco-system-based indices, and composite-sustainability-performance indices for different industries, which could be further broken down to individual industry sectors such as automotive, aerospace, chemical, oil and gas, and consumer products.

Corporate level

At the corporate level, we reviewed the Global Report Initiative (GRI) [9] and the Dow Jones Sustainability Indexes (DJSI) [10]. The GRI effort [9] made use of a hierarchical framework according to social, economic, and environmental aspects, which identified more than 100 indicators defined in support for sustainability. The DJSI was designed to track the sustainability performance of companies that lead in the field. In the DJSI family, there are also related indices including the DJSI World, DJSI World Enlarged, DJSI Europe, DJSI North America, DJSI Asia Pacific, and DJSI Korea. The corporate sustainability assessment is based upon economic, environment, and social dimensions with 12 criteria.

Product level

At the product level, there exists the National Institute of Standards & Technology (NIST) Sustainable Manufacturing Indicator Repository (SMIR) [13]. The NIST effort on SMIR [13] aims to integrate and extend the thirteen popular sustainability indicator sets [21], resulting in a repository of indicator sets and indices and a SM measurement infrastructure at the product and process levels. The Ford's PSI [11], included in SMIR, consider all three environmental, economic, and societal aspects with emphasis on life-cycle assessment (LCA) and life cycle cost (LCC) analysis from the early stage of vehicle development. It complies with ISO 14040, the international life cycle assessment standard. OECD's toolkit [12] focuses on 18 of its most important and commonly applicable quantitative indicators of environmental performance assessment.

There are other research efforts from academia. Avram et al. [25] proposed a unified methodology for assessing the use phase of machine tool systems based on economic, technological, and ecological criteria. A set of criteria and their hierarchical relationship were proposed at both the system and process levels. Azkarate et al. [26] presented an assessment method for sustainable machine tools design. The sustainability of machine tools was assessed based on economic, environmental, and social factors. The technical aspect of sustainability assessment was not detailed however. Lu et al. [24] presented a framework of product and process metrics for sustainable manufacturing and identified 12 clusters of product related metrics for applications throughout the life cycle stages.

Unit process level

At the unit process level, Kellens et al. [2] presented a methodology for systematic analysis and improvement of unit discrete manufacturing processes and proposed four metrics to measure machining time, power consumption, consumables, and emissions for unit machining processes. The methodology was applied to a case study of two unit machining processes. Metrics were developed to measure machining time, handling time, load/unload time, cleaning time, energy consumption, material loss, and fluid waste, among others [3]. In the framework of product and process metrics for sustainable manufacturing, Lu et al. [24] presented six sets of process-related indicators/metrics for assessment of environmental impact, energy consumption, operator safety, personal health, waste management and operating costs, respectively. A presentation of efforts reviewed at each of the above levels is used to identify SM indicators and to build Tables 1a and 1b.

Classification of sustainability indicators

Table 1a organizes sustainability indicators by categories, themes, and subthemes. The numeric values in the table indicate the number of indicators per sub-theme. This table quantifies the number of indicators from various sources at each hierarchical level. The resulting data suggests the priorities addressed by each indicator set.

Table 1b lists individual indicators in the seven sub-themes deemed relevant to unit manufacturing processes. They are related to resource consumption, waste, emissions, operating costs, and employee health among others. The indicators under these sub-themes are uniquely important indicators at the unit process level. The indicators identified in Table 1b will be used to define the scope of Tables 2, 4, and 5.

Table 1a. SUSTAINABILITY INDICATORS CLASSIFICATION.

Category	Theme	Sub-Theme	Global [4]	Country [8]	Corporate [9]	Product [13]	Unit process [24]
Environmental	Emission	Air emission	0	8	0	1	0
		Climate change	1	6	3	0	1
		Ozone layer depletion	0	6	1	0	0
		Solid wastes	2	11	2	1	0
		Water effluent	0	1	2	0	0
		Wastes for unit process	0	1	0	0	7
	Resource	Land	6	5	0	1	0
		Water	0	13	4	1	1
		Energy	5	4	9	1	5
		Material	4	0	2	1	0
	Ecosystem	Biodiversity	2	5	5	1	0
		Habitat	1	0	0	1	0
Economic	Product	Product	1	0	2	2	0
	Process	Process	0	0	0	1	6
	Investment	Investment	1	0	7	1	0
Societal	Employee	Health & safety	0	0	6	2	8
		Development	0	0	4	0	0
		Satisfaction	0	0	5	1	0
	Customer	Health & safety	0	0	2	0	0
		Customer rights	0	0	7	2	0
	Community	Health & safety	13	0	2	1	0
		Justice	4	0	11	0	0
		Development	30	0	10	0	0
Technological advancement			0	0	0	7	0
Performance management			0	0	0	4	0

Table 1b. INDICATORS FOR SUSTAINABLE MANUFACTURING.

Category	Theme	Sub-Theme	Indicators	Global [4]	Country [8]	Corporate [9]	Production [13]	Unit process [24]
Environmental	Emission	Air emission	Air emission				×	
			NOx emissions		×			
			NMVOC emissions		×			
			SO_2 emissions		×			
			Particles emissions		×			
			Car gas/diesel consumption		×			
			Energy consumption		×			
			Emission of radioactive material		×			
			Index of heavy metal emission to air		×			
		Waste for unit process	Noise		×			×
			Mass of disposed consumables					×
			Consumables reuse ratio					×
			Mass of mist generation					×
			Mass of disposed chips and scraps					×
			Mass of restricted disposals					×
			Ratio of recycled chips and scraps					×
	Resource	Water	Nutrient used		×			
			Ground water abstraction		×			
			Pesticide used		×			
			Nitrogen used		×			
			Water treated		×			
			Organic matter emissions		×			
			Eutrophication		×			
			Fishing pressure		×			
			Development along shore		×			
			Discharges of heavy metals		×			
			Oil pollution at coast/sea		×			
			Discharges of halogenated organic compounds		×			
			Water Consumption		×	×	×	×
			Total water withdrawal by source			×		
			Water sources affected by withdrawal of water			×		
			Water recycled and reused			×		
		Energy	Energy use per capita		×			
			Electricity from fossil		×			
			Energy consumption	×	×	×	×	×
			Energy use-renewable based	×				×
			Energy use intensity	×				
			Passenger-freight transport	×				
			Energy intensity of transport	×				
			Indirect energy consumption			×		×
			Energy saved			×		
			Energy-efficient based product			×		
			Reduction of energy			×		
			Share of private car transport		×			
			Ratio of use of renewable energy					×
			Consumption for transportation					×
			Environmental impact			×		
			Transport of product & service			×		
			Noncompliance with laws			×		
			Impact of transporting products			×		
		Material	Material usage			×	×	
			Recycled materials			×		
			Material intensity	×				
			Fertilizer use efficiency	×				
			Use of agricultural pesticides	×				
			Ozone depletion substance usage	×				
Societal	Employee	Health & safety	Occupational health			×	×	
			Occupational safety			×	×	
			Workforce in joint management			×		
			Fatalities			×		
			Risk-control program			×		
			Health and safety topics			×		
			Exposure to toxic chemicals					×
			Exposure to high energy					×
			Injury rate					×
			Chemical contamination					×
			Mist/dust level					×
			Noise level inside factory					×
			Physical load index					×
			Health-related absenteeism rate					×
Economic	Process	Process	Operating cost				×	
			Labor cost					×
			Cost for use of energy					×
			Cost of consumables					×
			Maintenance cost					×
			Cost of by-product treatment					×
			Indirect labor cost					×

MANUFACTURING/PRODUCTION PROCESSES

The manufacturing process for a product design is usually defined in a process plan, which consists of a network of unit manufacturing processes. However, the manufacturing process plan needs to be expanded into a process flow chart to support a production order [27]. In addition to unit manufacturing processes as specified in the manufacturing process plan, the process flow chart needs to specify additional production activities of transportation, inspection, and storage. From the process point of view, a storage (materials handling) activity uses resources and consumes energy. Similarly, a transportation activity also uses resources, consumes energy, and creates emissions. Likewise, inspection and testing activities may also consume energy and generate wastes. This paper views unit manufacturing processes as a subclass of production activities.

Unit production process

A production plan is a network of unit production processes, consisting of unit manufacturing, transportation, inspection, and storage activities. Each unit production process adds value to the finished goods from the customer's point of view. It usually requires a machine, consumes energy and relies on an operation sheet to specify a unique procedure for the worker to perform at a work center. In addition to machine, a work center is typically equipped with tool crib and work bench. The operation sheet details the procedure in a step-by-step manner for setting up material, tools, and/or machine. It could also detail setup, inspection, and teardown steps. The worker usually needs training and acquires a certificate to perform the task.

Manufacturing/production process classification

From a production planning perspective, Figure 1 classifies the range of unit manufacturing and production activities into four categories: manufacturing, inspection/testing, transportation, and storage. The unit transportation process may be further classified by the methods and equipment used for transportation such as lift truck transport, manual transport, and robot transport. Similarly, unit inspection/testing processes can be sub-classified into visual inspection, manual inspection, and test with equipment. For unit storage processes, there are warehouse storage in enclosed open space, heated space, cooled space and environmentally controlled space. Unit manufacturing processes are multifaceted and could include forming/shaping, micro-electronics fabrication and manufacturing, joining, metal casting, surface treatment, and machining. This paper focuses on unit *machining* processes, as sustainability indicators are reported most often for these processes. Machining is a material removal process that removes excess raw material from the work in process, using various cutting tools and machines.

Most efforts on sustainability assessment have focused on traditional machining operations [2, 3, 28-50] especially on drilling, milling, turning, and grinding. This paper organizes indicators and metrics by these unit processes.

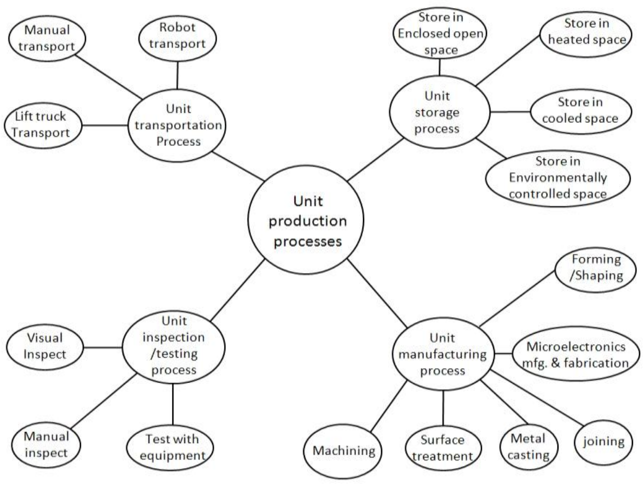

Figure 1. UNIT PRODUCTION PROCESSES.

SM METRICS AT UNIT PROCESS LEVEL

SM metrics developed for unit manufacturing processes are summarized in Tables 2, 4, and 5. Table 2 organizes environmental-related metrics by environmental indicators and unit process types. Tables 4 and 5 are sustainability metrics for economic and societal indicators, respectively. Table 3 is an analysis of the energy metrics by energy consuming elements in different production modes as defined in Kellens et al. [3].

Environmental indicators and metrics

Environmental metrics developed for unit manufacturing processes are reported in [3, 28-50]. The most common environmental indicators are energy, material, solid waste, coolant, lubricant oil, cutting tool, and air emission. Many metrics were developed for machining operations in general, though some were for a particular unit process type. Table 2 labels each metric with a unique ID. For example, "GE1" denotes the first energy metric for the general machining application. Similarly, ME1 means the first energy metric defined for the milling process, while TE1 is the first energy metric for the turning process.

Table 2. ENVIRONMENTAL METRICS FOR UNIT MACHINING PROCESSES.

Category		Environmental						
Theme		Resources					Emissions	
Sub-theme		Energy	Material			Water	Waste	Air emission
Indicator		Consumption	Usage	Lubricant oil	Cutting tool	Coolant	Substance	
Machining	General machining	GE1, 2006 [28] , 2009 [29] , 2008 [30] GE2, 2011 [31] , 2007 [32] GE3, 1997 [33] GE4, 1995 [35] GE5, 2011 [38] GE6, 2009 [41] GE7, 2006 [44] , 2007 [45] , 2009 [46] GE8, 2007 [48]	GM1, 2011 [31] , 2007 [32] GM2, 1997 [33] GM3, 1995 [35] GM4, 2009 [46]	GL1, 2006 [28] , 2009 [29] , 2008 [30] GL2, 2011 [31] , 2007 [32]	GCT1, 2006 [28] , 2009 [29] , 2008 [30] GCT2, 2011 [31] , 2007 [32] GCT3, 2007 [48]	GC1, 2006 [28] , 2009 [29] , 2008 [30] GC2, 1997 [33]	GWS1, 2006 [28] , 2009 [29] , 2008 [30] GWS2, 2011 [31] , 2007 [32] GWS3, 1995 [35]	GAE1, 2011 [31] , 2007 [32] GAE2, 2011 [38]
	Turning	TE1, 1999 [34] TE2, 2010 [39] TE3, 2011 [43] TE4, 2008 [47]			TCT1, 2010 [39] TCT2, 2009 [42]	TC1, 2009 [42]	TS1, 1999 [34]	TAE1, 2008 [47] TAE2, 2009 [50]
	Drilling	DE1, 2011 [3] DE2, 1999 [34]	DM1, 2011 [3]				DS1, 2011 [3] DS2, 1999 [34]	
	Grinding	GRE1, 2010 [37]		GRL1, 2010 [37]				
	Milling	ME1, 1999 [34] ME2, 2010 [36] ME3, 2003 [40] ME4, 2011 [43] ME5, 2011 [49]					MS1, 1999 [34]	MAE1, 2009 [50]

The authors assert that material consumption is an important environmental concern, and cutting tools are viewed as consumables, which have been studied throughout their lifecycle. Various cutting conditions including speed, feed, and depth of cut are evaluated, in parallel with energy consumption, material usage, and surface finishes. During a typical machining operation, coolants are often applied to the cutting point by a pump. Though lubricants are routinely used for most machining operations, a recent study of minimum quantity lubrication (MQL) [16] was directed to addressing the environmental burden issue. As an alternative to the use of consumable coolants, the concept of “clean” cryogenic machining was introduced to eliminate environmental hazards introduced by cooling fluids. Typical solid waste appears in the form of chips, scraps, and defects. Air emission is another environmental burden, as it could contribute to global climate changes. Feng et al. [21] made use of the energy and carbon emission models developed by Ameta et al. [50].

Table 3 is an analysis of energy consumption accounted for by an individual energy metric, according to the three operation modes of a unit machining process as defined in Kellens et al. [2, 3]. They are idle, standby, and machining modes. The energy consumed in the idle mode can be further decomposed into energy consumption by spindle, coolant, pump, axis, computer, and setup. The energy in the standby mode is consumed by loading, unloading, cleaning, tool change, axis, and spindle. All metrics account for energy consumed in the machining mode, but seldom for those in the standby mode.

The energy metrics reported in [28-35, 37, 40] account for energy consumption in the machining mode only. In contrast, the energy metrics reported in [38, 39, 41, 43-47, 49] estimate energy consumption in all three modes. The metric proposed by Gustowski, et al. [44-46] accounts for energy consumption in both idle and machining modes. In the case study of drilling operation reported in Kellens et al. [3], the metric considers energy consumed by the coolant, spindle and axis in the idle mode; loading, unloading and cleaning in the standby mode; and drilling in the machining mode.

Economic indicators and metrics

Table 4 summarizes the economic metrics for unit machining processes, as reported in [24, 51]. They all focus on process-oriented operating costs. Lu et al. [24] presented simple cost metrics for direct labor, energy use, consumables, maintenance, by-product treatment, and indirect labor, respectively. Pušavec et al. [51] developed a cost model summing up machining cost, tooling cost, energy cost, coolant (CLF) cost, and cleaning cost.

Societal indicators and metrics

Table 5 summarizes societal indicators and metrics by unit machining processes. The metrics for societal indicators are focused on employee’s health and safety, including exposure to toxic chemicals, chemical contamination, and high energy, injury, noise, mist/dust, physical load, health-related absenteeism, and ergonomics. Azkarate et al. [26] proposed societal metrics with a focus on user-friendliness and ergonomics. Jawahir et al. [52] considered occupational safety and health as societal indicators, of which both were extended by Lu et al. [24], who presented a range of simple metrics for worker’s safety and personal health as referenced in the table. Worker safety-related metrics include exposure to toxic chemicals or high energy and industrial injury. Metrics under personal health are chemical contaminations in the work environment, mist/dust, noise level, physical load, health-related absenteeism, and ergonomics. All these metrics were developed for general unit machining operations.

Table 3. ENERGY METRICS FOR UNIT MACHINING PROCESSES.

Machining	Metrics	Idle mode						Stand-by mode						Machining mode
		Spindle	Coolant	Hydraulic pump	Axis	Computer	Setup	Loading	Unloading	Cleaning	Tool change	Spindle	Axis	
General	GE1[28-30]													×
	GE2[31,32]													×
	GE3[33]													×
	GE4[35]													×
	GE5[38]						×				×			×
	GE6[41]	×	×		×									×
	GE7[44-46]	×	×	×		×								×
	GE8[48]						×							×
Turning	TE1[34]													×
	TE2[39]						×				×			×
	TE3[43]		×	×		×								×
	TE4[47]		×	×		×								×
Drill	DE1[3]	×	×		×			×	×	×				×
	DE2[34]													×
Grinding	GE1[37]													×
Milling	ME1[34]													×
	ME2[36]						×					×	×	×
	ME3[40]													×
	ME4[43]		×	×		×								×
	ME5[49]						×					×	×	×

Table 4. ECONOMIC METRICS FOR UNIT MACHINING PROCESSES.

Category	Economic					
Theme	Process					
Sub-theme	Process (operating cost)					
Indicator	Labor	Energy	Consumable	Maintenance	By-product treatment	Indirect labor cost
General Machining	GL2, 2010 [24]	GE1, 2010 [24]	GC1, 2010 [24]	GM2, 2010 [24]	GB1, 2010 [24]	GI1, 2010 [24]
Turning	TP, 2010 [51]					

Table 5. SOCIETAL METRICS FOR UNIT MACHINIG PROCESSES.

Category	Societal								
Theme	Employee								
Sub-theme	Health & safety								
Indicator	Exposure to toxic chemicals	Exposure to high energy	Injury rate	Chemical contamination	Mist/dust level	Noise level	Physical load index	Health-related absenteeism rate	Ergonomics
General Machining	GET1, 2010 [24]	GEH1, 2010 [24]	GI1, 2010 [24]	GC1, 2010 [24]	GM1, 2010 [24]	GN1, 1977 [33] GN2, 2010 [24]	GP1, 2010 [24]	GH1, 2010 [24]	GE1, 2011 [26]

CONCLUDING REMARKS

Most R&D efforts on sustainable manufacturing have focused on developing framework and measurement techniques for sustainability assessment, prediction, or optimization at the global, country, corporation, and product levels. More attention is being directed to process and unit process levels. Though there is a vast range of unit manufacturing and production processes, most reports have focused on a few traditional machining operations. Less attention has been directed at non-traditional machining, non-material removal, product assembly, materials handling, inspection/test, and storage processes. Seven environmental indicators are most popularly studied for machining processes. They are energy, material, solid waste, coolant, lubricant, cutting tool, and air emission. Economic metrics tend to be limited to operating costs. At the unit process level, many environmental indicators could be converted into a cost value in a straight forward manner. The conversion becomes non-trivial when multiple products, parallel processes and alternative resources considered.

Toward sustainable manufacturing, materials and manufacturing processes of all kinds must be fully characterized for their sustainability. As there exist a vast array of manufacturing and production processes using a great diversity of resources, a possibly effective approach to characterizing a sufficient number of production activities could lie on a careful analysis of them at the sub-unit process and sub-device levels. Machines and equipment are devices which all consume resources and generate pollutants. Sub devices such as pumps, motors, drives, and computers are components commonly used to build these machine and equipment devices. The sub-device set could be smaller than the one for machines and equipment. Thus it may be logical to focus on developing sustainability metrics for each device element that consumes resources and contributes to emissions. This view could also be applicable to improvement and optimization of processes sustainability, beyond their assessment. Similarly, a typical unit manufacturing process could be broken down systematically to sub-unit activities in three operations modes. Thus, process sustainability effort could focus on modeling the sustainability (energy consumption, resource usage, and emissions) of sub-unit processing activities in each of the three operation modes. This research effort could significantly contribute to building a scientific foundation for addressing sustainable manufacturing issues at multiple levels.

DISCLAIMER

Certain company names or commercial products may have been identified in this paper. Such identification was used only for illustration purposes. This use does not imply approval nor endorsement by NIST. Furthermore, it does not imply that such company names and products are necessarily the best for the purpose.

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