Dossier of Manufacturing and Environmental Sustainability: An Empirical Model

Man Djun Lee, Shahidul Islam

Abstract— **This paper is about model building to evaluate manufacturing sustainability. This study aims to support manufacturing industries by providing with a tool to evaluate the degree of sustainability by measuring their production performance. Literature review, data collection, conceptual model building, mathematical model building and report writing are the main steps involved of this work. Information has collected from scientific publications on sustainable manufacturing, green manufacturing, sustainable life cycle engineering, remanufacturing and edited. This study has successfully generated an empirical model to evaluate the sustainability degree of manufacturing industries' production process. Literature suggest, wastage or underutilized capacity creates gap in productivity and appears as non-value added input to production process. This gap contributes to increase production cost, reduce production performance and ultimately it negatively impacted on economy and environment. In this aspect, developed model is useful for relevant stakeholders to eliminate non-value added inputs for achieving economic and environmental sustainability. The developed model is original as developed from fundamental manufacturing concept. This work will add new information in the manufacturing knowledge domain; in this aspect, this work is novel. This paper will provide guideline for future research in sustainable manufacturing.**

Index Terms— **Manufacturing, Sustainability, Operations Research, Green Manufacturing, Capacity Utilization.**

1. INTRODUCTION

Manufacturing industries plays an important role in global development. However, global scenarios affecting manufacturing industries such as depleting natural resources, increasing world population, global warming, pollution control and ever growing world economy have driven the industry to accommodate sustainability (Peng, 2014). In this regards, many studies on sustainable manufacturing such as environmental friendly manufacturing, green manufacturing, remanufacturing, and sustainable life cycle engineering, have been reported (Anityasari, 2011). However, these studies only provide general discussion on new requirements for sustainable manufacturing (Brennan et al., 2015). These studies lack of corresponding methods or models for their implementation. Therefore, this study is designed to address this issue by building a model for manufacturing industries to evaluate sustainability degree in production.

To achieve the goal of this study, the rest of the paper is organized as follows. In Section 1.1, a brief review is given on why sustainable manufacturing is needed. In Section 1.2, the meaning of sustainability is clarified by literature survey. In Section 2.0, the conceptual model summarized from literature review is presented followed by the mathematical model in Section 2.1. Section 2.2 provides guidelines for relevant stakeholders to measure their production performance and indicators for achieving manufacturing sustainability. The industrial implications of the model are listed in Section 3.0. The discussion and scenario analysis of the model is shown in Section 4.0. The study finalized with conclusions and discussion on potential future research works in Section 5.0.

A. The Meaning and Understanding of Manufacturing Sustainability

Manufacturing sustainability evolved from the concept of sustainable development (Rosen and Kishawy, 2012) and first appeared in the 1980s. It was defined by World Commission on Environment and Development (1987) as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Later in the 2000s, sustainable manufacturing was defined by Mihelcic et al. (2003) as "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment." It was further added with green manufacturing by Allwood et al. (2008) as "developing technologies to transform materials without emission of greenhouse gases, use of non-renewable or toxic materials or generation of waste." Today, the most widely accepted definition is by U.S. Department of Commerce (2010) as "the creation of manufacturing products that use materials and processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound". The meaning is manufacturing process that is design and operate for achieving higher value added product by optimizing inputs in the process with higher productivity, technical efficiency and economic efficiency.

B. The Needs of Sustainability in Manufacturing

Manufacturing industries have significant influence over global development as backbone of economy for most countries in the world. However, manufacturing industries also contribute significantly in creating negative impact on the environment. For example, in year 2006, manufacturing sector in the U.S. was responsible for 36% of carbon dioxide emissions and 71% of all toxic releases within the U.S. industrial sector (Egilmez et al., 2013; Haapala et al., 2013). Additionally, it is also reported that manufacturing industry

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Man Djun Lee, Faculty of Engineering, Universiti Malaysia Sarawak
Shahidul Islam, Faculty of Engineering, Universiti Malaysia Sarawak

produces more than 60% waste annually (Bi, 2011). In this regards, the concept of environmental sustainability has gain significant attention over the years due to the five drivers of sustainability. Table 1 presents the five drivers of sustainability (Bi, 2011; Peng, 2014):

Table 1: Driving Force of Sustainability

Sustainability Driver	**Current Scenario**
Depleting Natural Resources	Natural resources as inputs for manufacturing industries such as oil, coal, and fresh water clean air are depleting. The prices for manufacturing inputs are increasing as the availability is decreasing.
Increasing World Population	As world population increases, more resources will be consumed to satisfy this dynamic demands and contribute to create more wastes.
Growing World Economy	Governments around the world are actively involved in formulating policy for manufacturing industries to add values to the society or social-economic development.
Pollution Control	The society demand products with less negative impact to the environment. Governments are penalizing manufacturing industries that responsible for discharging hazardous waste to the environment.
Global Warming	Manufacturing industries are responsible for discharging greenhouse gases since industrial age. The world is warmer than ever in human history. Some efforts of governments and NGOs are trying to reduce greenhouse gases emissions are such as Kyoto Protocol and promoting the use of green technology.

2. Manufacturing Sustainability Conceptual Model

The conceptual model summarized from literature review is shown in Figure 2 below:

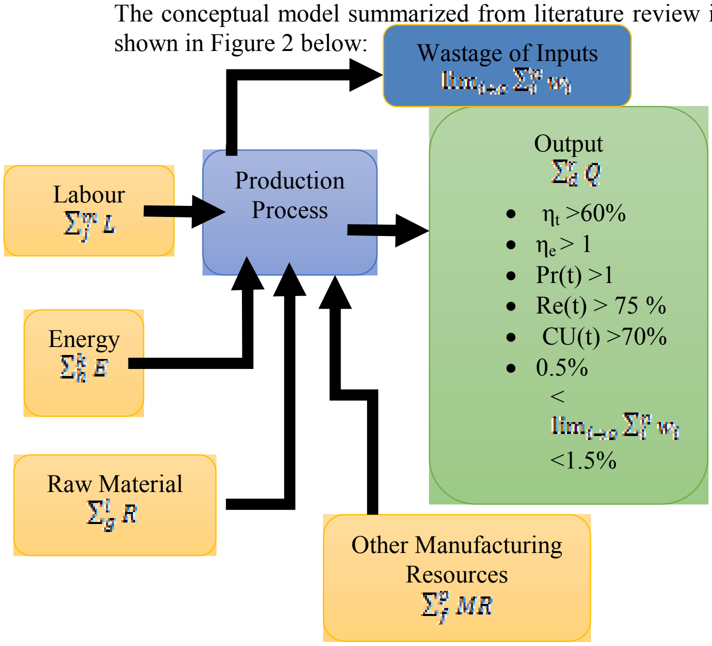

Figure 1: Conceptual Model of Manufacturing Sustainability

Where η_p = Technical Efficiency
η_e = Economic Efficiency
Pr(t) = Manufacturing Productivity
CU(t)= Capacity Utilization
Re(t)= Plant Production Machineries Reliability

The index for evaluating degree of sustainability such shown in Figure 1 will be explained in details in section 2.2. From the conceptual model, wastage is the result of inefficient production process that contributes to reduce outputs. The sources of wastage come from underutilized inputs such as labour, energy, raw materials and other manufacturing resources from production process.

2.1 Mathematical Model

The mathematical expression to represents conceptual model from Figure 2 is shown in Equation (1).

$$\sum_d^r Q = K\,[Input\left(\sum_j^m L \,.\, \sum_h^k E \,.\, \sum_g^l R \,.\, \sum_f^p MR\right) - Wastage\left(\sum W_L \,.\, \sum W_R \,.\, \sum W_E \,.\, \sum W_{MR}\right)] \quad (1)$$

Where
Q = outputs
K= input transformation factors with respect to wastage
L= labour
E= energy
MR = other manufacturing resources
W = wastage with respect to inputs

2.2 Sustainability Evaluation Index

A manufacturing firm must know how it controls sustainability to act sustainably, and this creates the need of sustainability indicators to measure progress for achieving sustainability (Rosen and Kishawy, 2012). In this regards, there are increasing number of researchers engaged in developing indicators to measure environment, social or sustainability. Farrell (1996) introduced one of the earliest frameworks to measure sustainability in three dimensions: economic, ecological and social measures. Likewise, Veleva and Ellenbecker (2001) proposed sustainable model that comprises energy and material use, natural environment, economic, community development and social justice, workers, and products aspects. Similarly, Islam et al. (2015) proposed a set of framework to measure sustainability in three aspects (technical, economic and environmental) and provided milestone to measure sustainability. Table 2 presents a summary of performance models for measuring manufacturing sustainability.

Table 2: Performance Indices for Sustainable Manufacturing

Performance Parameters	**Performance Models**	**Index in Evaluating Degree of Sustainability**	**References**
Technical Efficiency (η_t)	$\eta_t = \frac{Output}{Input}$	$\eta_t > 60\%$	(Chen et al., 2014; Islam et al., 2015)
Economic Efficiency (η_e)	$\eta_e = \frac{Value\ of\ Output}{Production\ Cost}$	$\eta_e > 1$	(Chen et al., 2014; Egilmez et al., 2013; Farrell, 1996; Islam et al., 2015)
Productivity [Pr(t)]	$Pr = \beta \frac{\sum R_Q}{\alpha \sum X_i}$ R_Q = Revenue of outputs; X_i = Cost of all inputs; B = Constant depends on the potentials manufacturing process variables; α = dimensionless coefficient	Pr>1	(Houseman, 2007; Shahidul & Syed Shazali, 2011)
Plant Operating Reliability[Re(t)]	$Re(t) = \int_0^t f(t)dt = 1 - e^{\alpha t}$ α = failure rate of machine; t = failure time	Re> 75%	(Das, Lashkari, & Sengupta, 2007; Islam et al., 2015)
Capacity Utilization [CU(t)]	$CU = \frac{Actual\ Capacity, Q_A}{Potential\ Capacity, Q_P}$	CU>70%	(Cigolini & Grando, 2009; Islam et al., 2015)
Wastage (W)	$\sum W = \sum I - \sum Q$ $\sum I$ = Inputs used in process; $\sum Q$ = Production Output	0.5%<∑W<1.5 %	(Allwood et al., 2008; Bi, 2011; Shahidul et al., 2013)

3. Model Implications in Manufacturing Industry

The main objective of this research is to build conceptual model to understand sustainability and empirical model to evaluate degree of sustainability. Developed models would have practical implications in manufacturing industry and society. The expected implications are:

•The model would be useful for decision makers in formulating operating strategy for optimizing the input usage and reducing wastage of inputs as part of sustainable manufacturing program.

•The model would serve as a holistic approach towards better understanding of manufacturing and environmental sustainability.

•The indicators provided in the models would serve as measuring tools to evaluate degree of manufacturing sustainability.

4. Insight of Manufacturing Sustainability

The findings of this study indicate that higher percentage of wastage has higher degree of negative impacts on economic and environment. The industrial wastage has two options; either is disposes off, or could be recycled to produce products. The classification of industrial wastage is shown in Table 3 (Heilala et al., 2008). Dispose of wastage, indeed, has a negative impact on environment; on the other hand, recycle contributes to increase economic performance of manufacturing. In these aspects, wastage has to be recycled for attaining both economic and environmental sustainability (Jovane et al., 2008).

Table 3: Classification of Industrial Wastes

Type of Waste	**Description**
Input Wastes	Inputs used in production process such as energy, water, raw materials, labour hours being consumed in excess to produce outputs.
Pollutants	Material wastes, discarded scraps or pollutants that being discharged into the environment such as wastewater, air emissions and solid wastes.
Hazardous wastes	By product or hazardous substances that being used during production process or presence in outputs. This waste can cause serious effects on human health or environment.

The waste concept from sustainable manufacturing is different from lean manufacturing. Lean manufacturing focus on minimizing waste to reduce time and cost for achieving only economic sustainability. On the other hand, sustainable manufacturing focus on reducing the negative impact on environment without sacrificing economic performance (Heilala et al., 2008). In this regards, concept of sustainable manufacturing is more superior and more challenging for the industry to implement. In order to achieve sustainability, high level of production performance such as higher level of capacity utilization could contribute to reduce wastage for achieving economic and environmental sustainability.

Sustainability and productivity growth could be stimulated by reducing non-value added inputs and maximizing output (Shahidul & Syed Shazali, 2011). This is due to wastage or underutilized capacity creates productivity gap acts as non-value added input contributes to reduce production performance. This scenario could be justified with other findings; Shahidul et al. (2013) reported that capacity utilization and wastage is negatively associated. They found that low level of machinery maintenance and skills of machine operators could cause failures to achieve higher performance of machinery. This scenario contributes to increase waste such as rejection of products, increases exhaust gases of machineries with unburned fuel. Likewise, Egilmez et al. (2013) found that about 90% of total manufacturing sectors of the US are actually inefficient, and significant improvements in their performance are required to reduce industrial waste. They concluded that manufacturing industries should focus on reducing direct and indirect overall energy consumption to increase their environmental sustainability. Heilala et al. (2008) also reported that underutilized production machinery (idle operating hour in production) uses a lot of energy even though it is not producing any product, and the actual machining only required 14.8% of the total energy. Al-Najjar (1996) stated that maintenance activities are essential in eliminating potential problems at early stage for ensuring good quality and reliability of products and processes as the internal and external failures costs could be 10-15 per cent of turnover.

Conclusion and Recommendations for Future Study

This study has addressed sustainability by building an empirical model for evaluating degree of sustainability of manufacturing performance. Literature indicates wastage of inputs or underutilized capacity creates productivity gap that acts as barrier to growth and achieving sustainability. In this aspect, this study would be useful tool for policy makers, further research for academicians, government agencies and other relevant stakeholders in formulating strategy to reduce wastage for achieving sustainability. Indeed, this is an important piece of research that bring the insight of manufacturing sustainability which is not available in published papers. This work will definitely add new knowledge in the stock of present manufacturing domain. Eventually, the study would be a foundation for further research in manufacturing sustainability including research in plant operations capacity optimization to reveal and reduce its capacity gap.

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