A Methodology Integrating the Three Pillars of Sustainability as a Unified Sustainable Manufacturing Index of Products

by

Feri Afrinaldi

A Dissertation

in

Industrial Engineering

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

DOCTOR OF PHILOSOPHY

Approved

Hong-Chao Zhang, Ph.D.
Chair of Committee

Ismael Regis de Farias Jr., Ph.D.

Masha Rahnama, Ph.D.

Milton Smith, Ph.D.

Annette Hernandez Uddameri, Ph.D.

Mark Sheridan, Ph.D.
Dean of the Graduate School

May, 2015

TABLE OF CONTENTS

ABSTRACT

Currently there are three separate methods that can be used to measure the three pillars of sustainability, environmental life cycle assessment (ELCA) for the environmental aspect, environmental life cycle costing (ELCC) for the economic aspect and social life cycle assessment (SLCA) for the social aspect. Guidelines to conduct ELCA and ELCC can be found in ISO standards, but SLCA is still in early development. It is recommended that ELCC and SLCA methodologies be integrated into ELCA methodology. This research follows this recommendation. Its objective is to develop a methodology to integrate the three pillars of sustainability (environment, economic and social) so that a life cycle based sustainability index of a product can be created. In order to accomplish this objective, the following steps are proposed: (1) eliminate subjectivity from ELCA weighting method and propose a new weighting method (2) use ELCA to estimate the environmental impacts of a product, (3) use ELCC to quantify the economic impacts of a product, (3) quantify the social impact of a product, (4) integrate the social and environmental impacts of a product, and (5) develop the socio-environmental portfolio. In order to quantify the social impacts, value-added in the form of employee compensation transferred to a product over its life cycle is used as a variable to estimate the social impacts of a product. It is expressed as the health benefit triggered by the life cycle of a product. The health benefit is measured in the form of disability-adjusted life years (DALY), a metric used by the World Health Organization (WHO) to conduct health impact assessments. To integrate the environmental and social impacts, the relationship between DALY and global warming potential (GWP) is modeled. To construct the socio-environmental portfolio, a graph that reflects the sustainability index of products, an eco-efficiency approach is utilized. To validate the proposed methodology, the sustainability performance of a new and remanufactured diesel engine is assessed using a case study.

The case study shows that the methodology proposed to eliminate subjectivity from ELCA is simple and can be applied for a generic application. For the environmental impacts of the diesel engines, it is found that abiotic depletion (ADP) (elements and fossil fuels), ozone depletion (ODP), human toxicity (HTP), fresh water aquatic ecotoxicity (FAETP), terrestrial ecotoxicity (TETP), marine aquatic ecotoxicity (MAETP), and acidification (AP) are mainly caused by the material extraction. The use phase of the diesel engines has the largest impact on global warming potential (GWP), photo chemical oxidation potential

(POCP), acidification potential (AP), and eutrophication potential (EP). If the environmental impacts of both engines are compared then by remanufacturing the diesel engine, 35.14%, 17.30%, -0.26%, 59.94%, 49.63%, 53.08%, 12.51%, 49.77%, 1.55%, 2.90%, and 0.03% savings are gained on ADP elements, ADP fossil fuels, GWP, ODP, HTP, FAETP, MAETP, TETP, POCP, AP, and EP, respectively. The 0.26% increase on impact on GWP is caused by the consumption of diesel fuel during the pyrolysis process, a step in remanufacturing process. A very small saving on POCP, AP, and EP is due to the impacts caused by the new components used to replace the old components of the diesel engine that reaches its end-of-life. Pyrolysis process and kerosene burned during the remanufacturing process also have contribution on POCP, AP, and EP.

For the economic impacts, the case study shows that the total costs required over the life cycle of the remanufactured engine is only 2% lower than the costs required over the life cycle of a new diesel engine. For the social impacts, the case study indicates that the health benefit achieved by the socio-economic growth triggered by the life cycle of the diesel engines is higher than the health loss caused by the pollutants produced over the life cycle of the diesel engines. Furthermore, the health benefit triggered by the new diesel engine is higher than the benefit stemming from the life cycle of the remanufactured engine.

The results of the sensitivity analysis show that the socio-economic growth triggered by the life cycle of the diesel engine generates a higher health benefit in a lower income country than in a higher income country. This might be one of the reasons why developing countries put higher priorities on economic development. Finally, it is found that the sustainable manufacturing index (SMI) of the new diesel engine is 1.450 and the index for the remanufactured diesel engine is 1.379. It is clear that the remanufactured diesel engine has a better sustainability performance than the new diesel engine.