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Supply chain-linked sustainability assessment of the US manufacturing: An ecosystem perspective

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ABSTRACT

This paper addresses the ecological resource consumption extents of the US manufacturing industries with a specific focus on renewable and non-renewable resource indicators from the national economic viewpoint. A hierarchical methodology was employed to quantify renewable and non-renewable resource life cycle inventory associated with the nation's manufacturing sectors and to evaluate the ecological sustainability performance. Therefore, first, ecological life cycle inventory of renewable and non-renewable resource consumption of 53 national manufacturing sectors was quantified with the ecologically-based life cycle assessment framework, and then, ecological sustainability performance assessment was performed based on well-known metrics such as loading ratio (LR), renewability ratio (RR) and non-renewable based eco-efficiency (NREE). Results indicated that nonferrous metal and nonmetallic mineral product manufacturing sectors were the drivers of non-renewable resource consumption, which caused these industries, have the least nonrenewable eco-efficiency (NREE) scores, renewability ratios (RRs) and the highest environmental loading ratios (LRs). Ecological life cycle inventory results indicated that nonferrous metal production and processing non-renewable resource consumption shares ranged between 46% and 55% in the entire supply chain network. Additionally, nonmetallic mineral product manufacturing had usage share of various non-renewable resources between 23% and 74% of the supply chains' total usage. Besides, food, tobacco and apparel manufacturing were found to have the highest RRs where the average NREE was found to be 0.4. Furthermore, sensitivity analysis of non-renewable resource indicators to NREE scores indicated that the average sensitivity ratios ranged between 5.1% and 22.4%, where 'Talc and pyrophyllite' was found to have the highest sensitivity.

Keywords: Ecologically-based life cycle assessment (Eco-LCA); Sustainable manufacturing; Non-renewable resource eco-efficiency (NREE); Loading and renewability ratios; Sensitivity analysis; Green supply chains

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1. Introduction

1.1. US manufacturing and the environment

In the US, industrial sectors are responsible for severe environmental burdens due to higher resource consumption, such as water, land, energy footprint including renewable and non-renewable energy resources (Duflou et al., 2012). The Environmental Protection Agency (EPA) reports that industrial sectors are responsible for approximately 20% of total GHG emissions and energy consumption (EPA, 2011). According to the US Energy Information Administration (EIA, 2011), amount of non-renewable energy consumed by the US industrial sectors is about 89% (6% on coal, 44% on natural gas, and 39% on petroleum), while only 11% of renewable energy (such as hydroelectric power, geothermal, solar, wind, and biomass) is consumed. In terms of water withdrawals, about 355,000 million gallons of water are used by US industrial sectors per day and irrigation, and livestock sector accounts for over 45% of total water withdrawals. The three largest sectors that consume water include thermo-electric power, irrigation, and public supply, which account for 90% of the national total, and other remaining sectors, such as industrial, aquaculture, mining, domestic, and livestock use about 10% of total water withdrawals. Land uses, such as forest land, crop land also have significant impact on carbon sequestration in the industrial sector, which account for 17% of global greenhouse gas emission resulted from deforestation, peat soil, and land clearing for agriculture (Pfister et al., 2009).

The aforementioned statistics critically highlight the importance of balancing the renewable and non-renewable resource consumption to reduce the loadings on the ecosystem associated with the US industries. And, since manufacturing industries (276) account for 64% of the US economic sectors (429), it is critical to specifically assess the resource consumption extents of the US manufacturing and benchmark eco-efficiency of resource consumption. In order to prioritize policy initiatives for reducing the environmental impacts in the long run, macro-economic comprehensive approaches are necessary (Egilmez et al., 2013, 2014). Many studies in the literature also address industrial energy efficiency (Bentzen, 2004) and countries' energy consumption (Jin, 2007; Bentzen, 2004) and encourage shifting from use of non-renewable energy to the use of renewable energy such as solar and hydropower, which has been of great interest to industrial sectors (Blesl et al., 2007; Zhang and Wang, 2014), where US industries have to be integrated in such efforts (IRNA, 2014).

1.2. On the importance of supply chain-linked sustainability assessment

Supply chain performance assessment has been of great interest in the literature, which dealt with a systematic way of measuring sustainability performance of supply chain activities or specific sector (Acquaye et al., 2014; Kucukvar and Samadi, in press). Therefore, measuring sustainability performance of direct and indirect supply chain activity using appropriate method is a very useful way to identify areas of improvement (Beamon, 1999), because nearly all sectors require energy consumption from consuming energy by itself or consuming energy from an indirect sector (Sorrell and Dimitropoulos, 2008). The assessment of the sustainability performance of the supply chain has been undertaken from various perspectives from social, economic, and environmental aspect such as the manufacturing sector (Egilmez et al., 2013, 2014; Kucukvar et al., 2015), buildings (Onat et al., 2014a,b); transportation (Egilmez and Park, 2014; Park et al., 2015), and construction sector (Kucukvar et al., 2014a; Kucukvar and Tatari, 2013). Several studies address sustainability assessment of manufacturing systems and processes related to the environmental impacts or ecological resource consumptions by means of life cycle assessment (Finnveden et al., 2009; Lind, 2008; Jiménez-González et al., 2011). Emissions inventories, particularly GHG, energy, and water consumption, and other environmental impacts of manufacturing activities studied extensively, especially in food production systems which include: ready meal (Calderón et al., 2010) fresh and canned food (Lozano et al., 2009), milk (Eide, 2002), bread (Espinoza-Orias et al., 2011), soft drinks (Amienyo et al., 2013), and breakfast cereals and snacks (Jeswani et al., 2015). The aforementioned studies successfully analyzed the certain environmental impact categories in the various levels of food production processes; however supply-chain related indirect impacts were not fully covered due to the use of process-based life cycle assessment methods.

Only input–output (I-O) analysis based studies address the importance of supply chains linked sustainability assessment which includes on-site (direct) and supply chain (indirect) impacts (Egilmez et al., 2013, 2014; Onat et al., 2014a,b). In the literature, the ecological resource consumption assessment-based works that utilize input–output analysis are abundant. However, a focused assessment of US manufacturing, considering the extents to consumption of individual industries and related ecological sustainability performance assessment has not been addressed. In this context, for instance, in a recent study, Egilmez et al. (2013) quantified the environmental impacts of US manufacturing sectors from a supply-chain linked life cycle perspective. In this study, GHG emissions, energy use, water withdrawals, hazardous waste generation, and toxic releases of 53 manufacturing sectors were quantified using the economic input–output based life cycle assessment (EIO-LCA) model from cradle to gate perspective and sustainability performances were evaluated by using linear programming-based eco-efficiency assessment. In another study, Egilmez et al. (2014) utilized a similar approach to compare sustainability performance of 33 US food manufacturing sectors from the life cycle point of view. The researchers considered cropland, forest land, grazing, and fishery impacts as ecological footprint impacts along with the environmental impacts in the study.

Input–output analysis captures the economy-wide financial transactions between the sectors of the national economies that enable researchers to model the environmental impacts associated with the economic activities from macro-economic perspective (Egilmez et al., 2014; Egilmez and Park, 2015). An illustration about the supply chain-linked assessment is provided in Fig. 1. The frozen food manufacturing is being supplied by industries up to the Nth order (according to the NAICS classification, the theoretical dimension is 429 $\times$ 429 industries for the US economy) in terms of materials (M), energy (E) and services (S). Input–output analysis successfully captures these multi-dimensional economic relationships and provides estimation about the associated environmental, social, and economic impacts (Kucukvar and Tatari, 2013; Kucukvar et al., 2014b).