Journal of Cleaner Production 90 (2015) 220–233

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The role of electric vehicles for supply chain sustainability in the automotive industry

H.-O. Günther [a, *], M. Kannegiesser [b], N. Autenrieb [b]

[a] Dept. of Industrial Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea
[b] Dept. of Production Management, Technical University of Berlin, Steinplatz 2, 10623 Berlin, Germany

ARTICLE INFO

Article history:
Received 25 March 2014
Received in revised form
19 November 2014
Accepted 19 November 2014
Available online 29 November 2014

Keywords:
Sustainable supply chain
Electric vehicles
Automotive industry

ABSTRACT

Electric vehicles are perceived as key technology in the automotive industry to contribute to sustainable development with lower greenhouse gas emissions, less air pollution for citizens and new job opportunities with positive social impact. So far the impact of electrified powertrains on the automotive industry supply chain sustainability and the development of the passenger car fleet have not been investigated in an integrated way. In our study, we focus on the long-term industry supply chain design end-to-end from the raw material exploration down to vehicle sales including the vehicle usage phase as well as reverse supply chain activities. Specifically, we address the long-term dynamics in the industry supply chain together with the fleet and powertrain development towards 2030 from a global perspective with a special focus on Germany and China. Based on industry data and using a sustainable supply chain optimization framework covering economic, environmental and social objectives, the study analyzes where jobs could be created or cut down, how total emissions in the supply chain including the usage phase of passenger cars could be reduced and how supply chain wide costs would develop. In addition, the impact of alternative market and technology scenarios as well as governmental regulations on the mix of powertrains in the vehicle fleet is investigated.

1. Introduction

As stated by Randers (2012) in his report to the Club of Rome greenhouse gas concentration in the atmosphere is expected to continuously grow beyond 2030, which may well trigger self-reinforcing climate change exceeding the 2 °C target by far. The automotive industry and its fossil fuel-based vehicles are seen as a major contributor to the emission of greenhouse gases. A major challenge is to replace fuel-based vehicles by alternative drive concepts like electric and hybrid vehicles. The automotive industry, as one of the largest industries worldwide, thereby has a twofold scope of influence to the emission balance: reducing emissions when *making* vehicles including production, transportation and reverse supply chain activities, and reducing emissions when *using* vehicles with cleaner powertrains.

Recently, enforced by governmental regulations the European automotive industry makes a fresh attempt towards zero emission mobility. The main attempt to reach this goal in the next decades is setting reduced CO_2 emission limits and supporting the introduction of electrified vehicles such as pure electric vehicles or plug-in hybrids powered by energy generated from renewable resources. Various governments introduced incentive programs for the purchase and the use of electric vehicles (no taxes, free lanes and parking in cities, etc.). Moreover, countries like Germany and China released plans to establish local electric vehicle prime markets. The German chancellor announced plans to reach one million electrified vehicles on the road by 2020 (Federal Ministry of Economics and Technology of Germany, 2010), while China intends to obtain this amount already in 2015 (KPMG, 2011) and to reach 5 million electrified vehicles in the fleet and 1 million annual production by 2020 (Reuters, 2010). Today, due to considerable production and specifically high battery costs and minor driving ranges the electric vehicle is still a niche product. However, further technological progress, more advanced batteries, related battery control and switching systems will enhance the range of these vehicles and bring down the costs in the future.

In this paper we address supply chains for conventional and electric vehicles from an industry perspective, i.e. we do not focus

* Corresponding author. Tel.: +82 10 9195 7633.
E-mail addresses: guenther@snu.ac.kr (H.-O. Günther), mkannegiesser@yahoo.com (M. Kannegiesser), niels.autenrieb@alumni.tu-berlin.de (N. Autenrieb).

http://dx.doi.org/10.1016/j.jclepro.2014.11.058
0959-6526/

on individual enterprises or products, but integrate the various company-specific supply chains into one composite supply chain model representing the entire automotive industry. We put particular emphasis on the long-term industry supply chain development end-to-end from the processing of raw materials down to the manufacture and sales of vehicles, as well as reverse supply chain activities, e.g. scrapping and recycling of used parts. Contrary to classical supply chain models, we also include the vehicle usage phase allowing us to compare all impacts of *making* vs. *using* vehicles. We investigate the long-term dynamics in the industry supply chain together with the fleet development towards 2030 from a global perspective with a specific focus on developments in Germany and Europe vs. China.

In our investigation we use mathematical optimization to model the industry supply chain under environmental, social and economic objectives. These three dimensions of the overall development of the industry are based on the so-called “triple bottom line” defined by Elkington (1998). This concept is specifically suited to derive sustainability performance indicators and to set related targets. The employed optimization model is fitted by empirical data from automotive part and final manufacturers as well as public sources. Numerical experiments are conducted for various scenarios in order to predict possible developments of the industry supply chain for electric vehicles. In our investigation, the overall transformation processes of the automotive supply chain within the next 20 years are investigated, evaluating if electric vehicles could be the answer to the sustainable future mobility challenge. Specifically, the following research questions are addressed.

- How could capacities for the manufacture of electric vehicles and related supply chain processes develop long-term and in which regions could these capacities be installed?
- What would be the effects of the required supply chain transformations on the labor market and social sustainability objectives, e.g. minimizing job dismissals?
- Would electric vehicles currently and prospectively be able to compete against internal combustion engines from an economic and an environmental perspective?
- Could total emissions in the make and in the usage phase be reduced towards sustainable levels and what could be the overall impact on costs?
- What would be the potential impact of governmental regulations like the implementation of tax measures or the introduction of national grant programs on the fleet of electric vehicles?

The remainder of this paper is organized as follows. In the next section the relevant literature is briefly reviewed. This is followed in Section 3 by an introduction of the automotive industry supply chain and the types of vehicles considered in our study. The industry model and the related data basis are outlined in Section 4. Results of the numerical experiments are presented in Section 5. Finally, conclusions are drawn and directions of further research are highlighted.

2. Relevant literature

In the last years a plethora of papers focusing on sustainable supply chain management has been published in the academic literature. We do not intend to comprehensively review these contributions but refer to Seuring (2013) who provides a review of more than 300 papers related to sustainable supply chain research published over the last 15 years. Of the reviewed papers 36 focus on quantitative modeling. Seuring classified the different mathematical models into four groups: life-cycle assessment (LCA) based models, equilibrium models, multi-criteria decision making and applications of the analytical hierarchy process. Several papers reviewed are based on LCA type data providing either an assessment of environmental impacts along the supply chain or determining an optimum solution by balancing different objectives within a multi criteria decision making model. Another recent review by Brandenburg et al. (2014) also focuses on quantitative modeling for sustainable supply chain management. The authors evaluate the relevant literature along four dimensions, supply chain management (SCM), sustainability, modeling and research directions, and identify several gaps in the existing literature, e.g. insufficient consideration of the social sustainability dimension and the integration of model-based methods with empirical research. In their review Taticchi et al. (2014) screen 384 papers on decision support tools and performance measurement in the domain of sustainable supply chain management. They conclude that these areas evidently are isolated fields in the emerging literature and that there is a dearth of literature related to the implementation of integrated frameworks. A literature review to clarify the differences between green and sustainable SCM is provided by Ahi and Searcy (2013). Their main conclusion is that green SCM is a subset of sustainable SCM focusing on narrow environmental aspects, while sustainable SCM aims to balance environmental, economic and social aspects.

Also reverse supply chains, which close the loop after the end of product usage and include the reuse and recycling of materials, gained increasing importance in the context of sustainable SCM. Ilgin and Gupta (2010) provide a literature overview of more than 500 papers focusing on environmentally conscious manufacturing and product recovery. They classified the research into product design issues, reverse and closed-loop supply chains, remanufacturing, and disassembly. Tang and Zhou (2012) emphasize the importance to not only adopt the single-company perspective but apply a full industry supply chain view including upstream supply stages and sustainability issues in emerging countries. Another comprehensive literature review on reverse logistics and closed-loop supply chain research is provided by Govindan et al. (2015). They review 382 papers in that area and classify them into four classes: reverse logistics, closed loop supply chain, sustainability, and green supply chain. Further factors such as problem type, consideration of uncertainty, modeling approach, and solution method are applied to characterize the reviewed articles. In addition, future research opportunities are identified. The paper by Stindt and Sahamie (2014) contains a review of research on closed loop supply chain management in the process industry. This paper aims to describe and analyze the main characteristics of closed loop supply chain planning in the process industry in order to determine the evolution and gaps of this research area.

Several authors propose specific frameworks and models in the context of sustainability in the supply chain. Sheu et al. (2005) present an optimization framework which coordinates the logistic operations of the product flow and the respective reverse channel and also shows ways how to assess an equilibrium solution. Quariguasi Frota Neto et al. (2008) developed a multi-objective model for the design and evaluation of logistic networks that balanced economic and environmental impacts. Using the European pulp and paper industry as an example they concluded that the adoption of environmentally preferred solutions is generally bounded by an increase in costs. In their research Hugo and Pistikopoulos (2005) address the environmentally conscious supply chain design problem based on LCA data. More recently, Chaabane et al. (2012) presented a mixed integer linear optimization model and, based on an example from the aluminum industry, demonstrated that for a long-term environmental sustainability the numerous legislative carbon regulations have to be harmonized. Moreover, Chaabane et al. (2011) developed a multi-