Chapter 16
The Reduction of CO_2 Emission into the Supply Network Design: A Review of Current Trends in Mathematical Models

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16.1 Introduction

Greenhouse gas emissions (GHGs) as key contributors to global warming have become a major concern for governmental bodies and the industrial sector in recent years. Upon the signing in 1997 of the Kyoto Protocol (Protocol 2007), whose aim was to reduce six types of greenhouse gases, 187 states (both developed and developing) have developed strict goals to their CO_2 emissions in the near future.

Virtually the entire scientific, political, business, and social community is aware of the significance of this environmental challenge. Many companies also view a "green supply network" (GSN) as a means of maintaining a positive public image, as consumers increasingly value environmentally responsible production.

One of the ways the business sector has found to reduce CO2 emissions is by establishing international standards for measuring environmental impact through emissions inventories. Various tools and guides have been developed to help companies design effective strategies to reduce emissions. One of these tools is the Greenhouse Protocol (GHG Protocol) (WBCSD/WRI 2001), which allows for the measurement of direct and indirect GHG emissions from a corporate standpoint. Another regulatory tool is ISO 14064 (ISO 14064 2006), which is coherent and compatible with the GHG Protocol. In general terms, ISO 14064 identifies the "What" and the GHG Protocol, the "How" and "Why". ISO 14064 is oriented toward audits, while the GHS protocol is oriented toward providing a set of options for reducing GHGs.

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There is another specification with a focus on the product rather than the company known as PAS 2050 (BSI 2008, 2011), which provides a method for assessing gas emission of products and services based on Life Cycle Assessment (LCA).

Companies interested in making environmental improvements to their supply network often use LCA to analyse environmental impacts within their processes (De Benedetto and Klemes 2009). LCA assesses the environmental impact throughout a product's life cycle and includes all stages within the supply network, from raw material extraction and processing, to manufacturing, transport, distribution, consumption, reuse, recycling, and waste treatment. LCA is also used to assess possible investment alternatives related to environmental impact (Freeman et al. 1992) (raw material selection, suppliers and manufacturing processes).

Many publications use LCA for assessing and quantifying environmental impact within a supply network. One case looks for a minimization of environmental impacts in supply network design and traditional economic costs (Mir Saman and Razmi 2011). In their article, the authors propose a fuzzy, multiobjective mathematical model under conditions of uncertainty, which uses LCA to find a balance between positive economic balance and environmental impact.

This present article reviews current trends in reducing GHG emissions in supply networks and mathematical models used. This article organizes publications according to the authors' specific area of focus for reducing CO_2 emissions in the tactical-operational field (production and distribution planning) or the strategic field (technology selection and facilities locations).

This article is structured in the following manner: The article begins with an introduction explaining the importance of integrating decisions related to GHG reduction. The article then reviews the most important contributions in this field, with particular focus on the mathematical models used in network supply design that include environmental characteristics. The final section of the article includes the main conclusions and proposals for future research.

16.2 Importance of Integrating GHG Reduction into Supply Network Design

Environmental factors in supply network design have become a focus of research in recent years. Studies have analysed the implications of different transportation types with regard to CO_2 emissions, as well as of energy-saving technology in both transportation and production. The concept GSN has recently appeared to include the environmental factor in supply network design.

GSN design needs to consider initial investment in environmental protection equipment and techniques; financial needs; and consequences for system functioning. Decisions regarding facility location and capacity must be integrated with decisions regarding environmental investment, given this investment can affect environmental indicators in the operational phase.

16.3 Mathematical Models in GSN Design

Over the last two decades, environmental management has been increasingly integrated into network supply design, due, in part, to pressure on the business sector to protect the environment (Wu and Dunn 1995). This development has been accompanied by an increase in literature on GSN. We analysed the most recent contributions in the field of CO2 emission reduction in supply network design.

In Table 16.1 publications are classified according to the type of network supply design decision. Each publication is classified according to how variables reducing CO_2 emissions are integrated into the mathematical model.

This section of the article will centre on mathematical models that simultaneously optimize economic and environmental impacts in the same network design. A synthesis of the most significant contributions will be presented in order to identify the concepts considered in each article and their associated decision variables. The type of objective function and model used will also be indicated.

The following sections will discuss each of the concepts included in Table 16.1. Each section highlights the most important aspects and techniques used by the authors to reduce GHGs when designing supply networks.

16.3.1 Facility Location and Capacity

Determining number and location of facilities is one of the strategic decisions included in GSN design. One can determine the location of productive plants (Hugo and Pistikopoulos 2005; Letmathe and Letmathe 2005); the size of

Table 16.1 Publications on mathematical models for designing green supply networks

	Mathematical models					
	Location of facilities	Selection of technologies	Carbon market	Production	Transport	Recycling
2004						[10]
2005	[11]	[11]		[11]; [13]	[11]	
2006	[15]			[21]		
2007						
2008						
2009	[2]	[2]			[2]	
2010	[23]; [5]	[23]	[19]	[5]; [19]	[17]; [22]; [5]; [19]	[5]
2011	[1]		[1]	[14]; [1]	[14]; [1]	[14]

Numbers correspond to cited references

productive plants and distribution centres (Chaabane et al. 2010; Abdallah et al. 2011); as well as the location of pick-up and recycling centres (Min et al. 2006). Others studies include facility locations as variables within a multi-objective mathematical model to find a balance between possible environmental damage and economic impact (Wang et al. 2011; Bajarski et al. 2009).

16.3.2 Technology Selection

Despite the consensus on the importance and benefits of adopting sustainable practices along the entire value chain, one of the major challenges continues to be searching for innovative technologies. Thus the importance of generating long-term planning models to determine investment decisions relating to optimal selection, installation, and expansion of processes technologies (Hugo and Pistikopoulos 2005).

Economic impact is often related to environmental impact. When dealing with investment in technology, the balance between total costs and environmental effects is especially important. Choosing the level of environmental protection is one of the variables to decide in designing a GSN, and is related to the investment in processes technology (Wang et al. 2011). A greater investment in technology leads to reduced CO_2 emissions. Investment in environmental protection can imply buying equipment or technology or adopting cleaner processes. The multi-objective model developed by latest cited authors introduces a new decision variable, “environmental protection level”. Technology selection depends on the environmental protection level set in the planning phase. Generally, the greater the investment gets the greater the protection. Another multi-objective model is proposed in which potential plants may be selected using different types of technology (Hugo and Pistikopoulos 2005). Their model is based on LCA principles, and presented as a support tool in sustainable investment planning.

16.3.3 Carbon Market

Article 17 of the Kyoto Protocol sets forth a new concept allowing both countries and companies to optimize CO_2 emissions by establishing an “emissions trading” scheme. Under this scheme, companies can buy or sell CO_2 credits, and in so doing, meet their environmental goals. Regardless of whether the company has set voluntary reduction goals or is subject to GHG emission caps, this scheme is based on assigning a quota of emission credits [1 credit = the right to emit one metric ton of carbon dioxide equivalent to (tCO_2e)], which each company must manage in the most efficient manner possible. At the end of each period, each company’s emissions are verified. If real emissions are greater than the imposed emission quota, the difference may be compensated by purchasing credits on the market. If real emissions are less than the permitted, the company may sell CO_2 credits on the market and earn profits (Chaabane et al. 2010).

The environmental impact can be measured by converting CO_2 tonnage caused by supply network activities into CO_2 credits, according to the CO_2s tCO_2e price in the CO_2 market (Ramudhin et al. 2008). These authors propose a mixed integer linear programming (MILP) model for designing a green supply network integrating decisions related to "carbon trading". The model allows companies to assess different strategies regarding supplier and subcontractor selection, product allocation, productive capacity utilization, and transport configuration in terms of their impact on GHG emissions.

Managing CO_2 emissions through CO_2 credits is an interesting means of attaining environmental goals. In one mathematical model, CO_2 emission credits may be managed by introducing an average expected cost per CO_2 credit into a company's economic objectives (Abdallah et al. 2011). They present an optimization model which seeks to minimize traditional costs and CO_2 emissions by introducing a new concept known as "green procurement", where companies are able to decide how to manage their CO_2 emissions within the CO_2 market. Their MILP model also includes assessing supplier CO_2 emissions in order to design a green supply chain beginning at the point of material procurement.

16.3.4 Production Operations

Production operations contribute to increased greenhouse gases in two main ways: (a) through the energy source used, or (b) by emissions related to the production process, itself. The energy source used for production is the main factor in GHGs (Moomaw 1996), which means that more efficient energy use, cleaner energy sources, and cleaner processes technology can significantly reduce GHGs.

At the strategic level, it is possible to pose the problem in a long-term planning horizon that includes processes technology selection and expansion capacity (Hugo et al. 2006), and develop a systematic focus to identify the synergy among different energy generation systems (Soylu et al. 2006). They propose a multi-period, discrete and continuous MILP model, which includes investment in energy generation systems within production planning.

Some papers analyse the problem of CO_2 emissions caused by company production processes. One present mathematical models that may be used in industry to determine optimal production levels and product mix in the presence of various environmental restrictions and typical production planning limitations (Letmathe and Letmathe 2005; Bojarski et al. 2009).

16.3.5 Transport Operations

The impact of transportation on the environment may be analysed in each supply network phase from transport of raw materials from providers to production plants (Hugo and Pistikopoulos 2005) to transport of finished products to distribution centres, retailers, consumers, and recycling centres.

Others authors propose an optimization model for freight consolidation in which CO_2 emissions are computed for two transport types (highway and railroad). The relation between emissions and type of transport and freight are nonlinear functions, which are later linearized with "piecewise" function (Pan et al. 2010).

One of the main causes of increasing CO_2 emissions is the low utilization of freight trucks (Van de Klundert and Otten 2010). They propose improving freight vehicle capacity use by accepting additional freight through linear programming and heuristics techniques.

Calculation factors for type of transport (Abdallah et al. 2011), travel distance, and mass transported are frequently used in calculate CO_2 emissions.

16.3.6 Recycling, Reuse and Disposal

For waste recycling and treatment, LCA is used to design models for identifying solid and liquid waste, as well as gas emissions due to various production processes (Chaabane et al. 2010). Models also analyse waste inside the supply network by analysing waste flow through the standpoint of accumulated costs (Hicks et al. 2004). Depending on the industrial sector, contributions in the area of industrial waste are found in the automotive (Duval and MacLean 2007), electronic (Ravi 2012), and paper (Counsell and Allwood 2007) industries, among others.

16.4 Conclusions

This article has analysed and classified the most important contributions relating to integration of environmental variables in supply network design. Articles published in the area of GSNs focus on specific issues such as transport; finding cleaner energy; or reducing energy consumption through technological or strategic innovation.

With respect to proposed mathematical models, in five analysed papers their authors use MILP models. Some authors adapt their models to a LCA approach (in four articles), while others authors present multi-objective models (in two analysed papers) or multi-period models in only one analysed paper.

Both facility location and technology selection are determined in the design stage, and allow a company to assess the environmental and economic impact of the supply network. While a greater investment in technology can lead to lower GHG emissions, it is important to find a balance between the economic and environmental impact of every supply network decision.

The CO_2 Market is an interesting alternative for managing CO_2 emissions via CO_2 credits. However, it is must be stressed that trading CO_2 credits does not directly lower GHG emissions.

The areas in which GHGs emissions can be significantly reduced are: production operations, transport, and recycling. In production, GHGs can be lowered through more efficient energy generation; selecting new sources of energy; introducing cleaner processes technology. In transport, emissions can be reduced by consolidating freight and maximizing freight truck utilization. And finally, in waste management and recycling, CO_2 emissions can be lowered by analysing waste flow along the supply network.

In conclusion, carbon emissions reduction in supply networks is a growing concern, requiring greater in-depth research on how to reduce CO_2 emissions in all phases of the supply network. The findings of such research must provide solutions that capitalize on the scientific and technological possibilities that exist to- day, and that can be adapted to corporate and governmental needs and realities.

The final objective of such research is to design a supply network, in which all logistical and industrial activities contribute to CO_2 reduction, preserving the environment, and as a result, obtaining strategic benefits.

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