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Recommended Citation
Sundarakani, Balan; Goh, Mark; de Souza, Robert; and Shun, Cai: Measuring carbon footprints across the supply chain 2008, 555-562.
https://ro.uow.edu.au/dubaipapers/205

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MEASURING CARBON FOOTPRINTS ACROSS THE SUPPLY CHAIN

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ABSTRACT
Understanding the importance of green supply chain in modern business environment, this research examines the heat flux and carbon wastages across the supply chain. The study has identified some of the heat and carbon influencing drivers as follows: (i) Mode of Transport, (ii) Inventory Policy, (iii) Network Structure, (iv) Trade Policy, (v) Consumer Density, (vi) Traffic Congestion, and (viii) Technology in Use. The research proposes a mathematical model to measure the carbon footprint across the supply chain by using Lagrangian Transport Method. For ease of visualization, “Heat Links” are developed and these links are normalized by a three-tier color coded temperature state. In short, the heat links are represented in three different forms as green (acceptable carbon emissions), amber (borderline carbon emissions) and red (non-green/ unacceptable carbon emissions) across supply chain network. Through our initial analysis, the research offers some operational and tactical strategies to mitigate the carbon emissions across the supply chain. The research is useful to policy makers as it can offer suggestions to areas pertaining to environmental economic tradeoffs.

Keywords: Carbon Footprint, Heat Link, Lagrangian Transport Model

INTRODUCTION
In modern supply chain networks there is a paradigm shift in the way they operate and look for enhancing the organizations productivity. Historically the global supply chain management concepts were focused on managing the upstream functionalities. Now the programs are moving from compliance to value creation. It’s a stage where everybody presence in the supply chain and logistics are conscious about the carbon free supply chain. The concept of green supply chain covers every stage in manufacturing from the first to the last stage of life cycle. According to Srivastara (2007) the Green Supply Chain Management (GrSCM) has been defined as an integrated environment thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and end-of-life management of the product after its useful life. Green supply chain definition has ranged from green purchasing to integrated green closed loop supply chain. Hervani et al. (2005) says that GrSCM is a composition of green purchasing, green manufacturing, green distribution/marketing and reverse
logistics. We adapt this definition by incorporating green forward & reverse logistics, green consumption and green recycling and express this as;

$$\text{Green Supply Chain} = \left\{ \begin{align*} & \text{Green Supply + Green Forward and Reverse Logistics +} \\
& \text{Green Manufacturing + Green Packaging and Distribution +} \\
& \text{Green Consumption + Green Recycling} \end{align*} \right\}$$ (1)

It is generally perceived that GrSCM promotes efficiency and synergy among business partners and their lead corporations, and helps to enhance environmental performance, minimize waste and achieve cost savings. This synergy is expected to enhance the corporate image, competitive advantage, quality of the product and marketing exposure. On the other hand, the use of more environmentally sustainable products, production processes, management practices are often faced challenges within an organization because of the external pressure applied by customers to achieve the requirements of reduced cost, higher quality and faster delivery. There should be a trade off among the cost, quality, carbon emissions, service and international trade.

**MOTIVATION FOR RESEARCH**

Many progressive companies such as Canon, General Motor, and Sony, are realizing the importance of corporate social responsibility and are now focusing on the environmental burden of their logistics processes. GrSCM, begins with recognizing some of the contemporary environmental dimensions such as carbon emissions, demand on energy and other natural resources. To achieve this objective of GrSCM requires high level and detailed planning and steering of complete logistics chains on an end-to-end basis. Some of the current foci of environmentally acceptable and friendly supply chain objectives involve carbon control of assets and infrastructure, energy efficient usage of transporters, waste reduction through process optimization, and sustainable recycling. This is in addition to the traditional supply chain aims of cost reduction, inventory minimization, and network optimization. Indeed, controlling for carbon and measuring the complete carbon footprint across a supply chain is a challenge for organizations today. For instance, IBM has attempted to provide carbon heat map to illustrate the various degrees of carbon impact on a typical supply chain operations. However, there is a need to quantify and rigorously analyze the impact of the heat (carbon) yielding “devices” within a supply chain. GrSCM has been given prime importance among researchers, business practitioners, corporate managers, supply chain designers. Literature in green GrSCM are growing in terms of number of publications per year from the past decades. Articles like Lamming and Hampson (1996), Beamen (1999), EPA (2000), Udel (2006), Hoffman, (2007), Parry et al. (2007) discuss the importance of green supply chain and its necessity. Zhang et al. (1997) and Srivastara (2007) reviewed extensively about green manufacturing and green supply chain in their articles respectively. They prove that there are numerous qualitative, interview and case study based papers existing in the literature that report GrSCM and their necessity for an organisation. There are very few articles that discuss quantitative model based green supply and manufacturing (Sheu et al.(2005), Simpson et al. (2007), Zhu and Zarkis (2007), Srivastara (2007) and Zhu et al. (2008)). Whereas carbon footprint measurement across the supply chain in a modern business environment has not been reported until now. This is
vital for modern business environment to understand its footprint, and therefore this research initiates the essence of a model based carbon footprint analysis and paid a roadmap on this. Discrimination

**RESEARCH METHODOLOGY**
Given this motivation, this paper seeks to map both the non-green and environmentally friendly supply chains and illustrate how the green supply chain framework and practice can affect the architecture of an existing supply chain. We employ the use of both industry survey to better appreciate the evolution of a green supply chain and an empirical approach to triangulate our results. For the purpose of this paper, we shall seek to determine and examine the various “heat” transfer devices within the context of a supply chain. Specifically, we seek to measure the “heat link” across entities, stages and processes of the supply chain to highlight the intensity and downstream effects (if any) of carbon emissions across the entire supply chain network. In doing so, we can then understand the heat flux and carbon wastage at each node of the supply chain and from be able to calculate the total heat (and hence carbon) transferred from one stage of the supply chain to another. Through this approach, we can then decide what and where the areas of sensible heat flux and acceptable carbon emissions are. For this analysis, we consider a closed loop end to end supply chain having reconfigured entities as shown in Figure 1.

![Figure 1. Re-configured closed loop supply chain](image)

In a supply chain, the carbon emission exists from processing raw materials to dispatching finished goods. At supplier side, processing of ore/raw material and preparing the semi-finished parts emits hydrocarbons, oxides of sulfur (SOx) and wastages in the form of gaseous and acidic compounds. At this stage, proper use of technologies and latest equipments could reduce the carbon footprint considerably. In logistics, the levels and type of carbon emissions depend upon: the mode of transportation and the distance travelled. Diesel engine vehicles such as heavy trucks emit gaseous components of carbon monoxide (CO), oxides of nitrogen (NOx), Particulate Matter (PM) and volatile organic compounds (VOC) (Hui et al. (2007). At this stage, the total logistics emissions are calculated from emissions by various mode of transportation, total sea/air port link emissions and total warehouse emissions. Total carbon emissions of the manufacturing stage can be measured from direct and indirect emissions of different
manufacturing stages. Finally total carbon emissions at distribution and consumers side depend upon the type of package used, trade policy, consumer density, and the level of reuse. In general, the heat flux influencing drivers of a supply chain controls the emission from upstream to downstream in a supply chain. As the product enters in each node of the supply chain its heat flux gets increased due to various processes. This increase in intensity is depending upon the performance of the product and process drivers of supply chain as shown in Figure 2. Controlling this flux and carbon emission requires to monitor the entire supply chain and redesign this based on the approach.

\[ f(x,z) = -\int_0^{\frac{x}{u}} \frac{U(z-d)}{u * k x^2} e^{-\frac{U(z-d)}{u * k}} dx \]  

\text{(2)}

\text{FIGURE 2 DRIVING FORCES OF GREEN SUPPLY CHAIN}
Where,

- $x$ is distance from the stations in m
- $U$ is mean integrated wind speed in m/s
- $z$ is measurement height in m
- $u$ is friction velocity
- $d$ is zero plan displacement in m
- $k$ is von Karman constant

We use lagrangian transport model to calculate the emissions because it has been used wide range of applications in water quality models, submarine outfalls, sediment erosion, oil dispersion and other pollution measures (Taylor (1989) & Lee (2000)). Nevertheless, application of this model in carbon footprint measurement has been reported and we feel it’s an appropriate method of measurement because it takes both active and passive tracer in carbon footprint into account.

The lagrangian model expressed by Lee (2000) is of the form:

$$\frac{dc_i}{dt} = E_i + R(c_i) - \frac{v_i E_i}{h} - \Lambda c_i$$

(3)

Where,

- $E_i$ is the emission rate of source in kg/s
- $R(c)$ is the rate of change of source
- $v$ is dry deposition velocity in m/s
- $\Lambda$ is coefficient of wet deposition displacement in s$^{-1}$

We have chosen to apply this model to our study as we felt these allows for sufficient explanation of species growth in open space and better match with carbon emission growth variable in open space domain. Therefore, the modified model is of the form:

$$\frac{dc}{dt} = E + R(c) - \frac{v E}{z} - \Lambda c$$

(4)

Where,

- $E$ is the emission rate in kg/s
- $R(c)$ is the rate of change of footprint
- $v$ is dry deposition velocity in m/s
- $\Lambda$ is coefficient of carbon deposition in s$^{-1}$

The factor “emission rate” is calculated from the total heat emission of all sources. Total heat emissions consist of heat energy liberated due to carbon dioxide, methane, hydrofluorocarbons, nitrogen dioxide, perfluorocarbons, sulfur hexafluoride. Each node and linkage emits these carbon gases at different intensity (Figure 3). Total heat flux induced in a particular node is expressed as:

$$\text{Total heat flux (q)} = \{\text{CO}_2 + \text{CH}_4 + \text{HFC}_s + \text{N}_2\text{O} + \text{PFC}_s + \text{SF}_6\}$$

(5)

The total carbon footprints across a supply chain can be measured by using the equations 2, 4 and equation 5. The model can be verified by applying in a supply chain network.
Visualization of Carbon Footprint in a Network

The carbon footprint amount can be visualized from the network diagram with three different color codes (green, amber and red). Color code green depicts acceptable carbon emissions, amber warns for borderline carbon emission and red shows unacceptable carbon emissions. Herewith we show an example of APAC network having three-color codes (Figure 4).

In the upstream part of the supply chain, the environmental impacts are moderate (bound with ore processing and or cleaning). In stage 2, both manufacturing and transportation processes consume energies such as oil, acids, amino-carbons, and electricity, and thus generate significant carbon emissions. At this stage of reverse auto supply chain, the moving returned products back to the distribution centers or manufacturers reduces the waste and is environmental friendly in general though the transportation of used cars back to the manufacturer generates more carbon emissions. At the downstream side of the supply chain, the amount of carbon emissions is less when compared to the whole supply chain network. Moreover they are strictly controlled by environmental regulatory pressures and emission standards.
STRATEGIES TO MITIGATE THE CARBON EMISSIONS
From the initial analysis, the research offers the following operational and tactical strategies to mitigate the carbon emissions across the supply chain:

- Having innovation at design level
- Proper supplier selection drastically reduces the emission
- Having green supply and purchasing policies
- Keeping environmental regulations on transshipment
- Acceptable carbon regulation at manufacturing level
- Leveraging green innovation at logistics services
- Reducing inventory and increasing visibility at distribution level
- Having green packaging and distribution strategies
- Having reduce, reuse, recycle policy at consumption stage and by
- Creating awareness among consumers against carbon

CONCLUSIONS
Corporate social responsibility brought a new structure in the way that company operates and plans their supply chain structure. Modern supply chain objectives have changed from cost reduction, network optimization, profit maximization to carbon emissions reduction, service level improvements, risk mitigation and value creation. This requires a strategic framework for international organizations to work across the supply chain in a more pragmatic way. This paper is an early attempt in mitigating the carbon emissions across the supply chain. The initial framework, model development, analysis and strategies help managers to redesigning the network. This research can be extended in a global scale taking the cost of carbon emissions into account. It can also be extended considering the various organizational pressures in the model at each stage of the supply chain.

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