
System dynamics-based modelling and analysis of greening the construction industry supply chain

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Abstract: Increasing concern on global warming and corporate social responsibility have made environmental issues an area of importance to address for governments and businesses across the world. Among the Middle East countries, the United Arab Emirates (UAE) tops the list in terms of per capita energy spending and per capita carbon footprints. The construction industry is the major contributor to environmental pollution due to its size and nature of activity. The rapid growth of construction sector has a significant environmental impact with increase in carbon footprints. This paper analyses the environmental implications of the rapidly growing construction industry in UAE using system dynamics approach. Quantitative modelling of the construction industry supply chain helps to measure the dynamic interaction between its various factors under multiple realistic scenarios. The potential carbon savings and the impact of each factor are calculated using scenario development analysis. The paper has addressed in detail the various drivers and inhibitors of carbon emission in the construction industry supply chain and ways to evaluate the carbon savings. The paper provides an analytical decision framework to assess emissions of all stages applicable to the construction industry supply chain.

Keywords: construction industry supply chain; system dynamics; carbon emission, United Arab Emirates; UAE.

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1 Introduction

Environment pollution and climate change has turned out to be one of the main challenge for mankind and the natural environment in the 21st century. Carbon emission released into the atmosphere in increasingly growing volumes is recognised to be responsible for this change. The world is presently facing a climate catastrophe due to the build-up of greenhouse gases. Global warming, increasing temperatures and sea levels, severe temperature events and the death of various species threaten the planet. Carbon footprint quantification, analysis and reduction are key to preventing this, by identifying the drivers and inhibitors and finding ways to mitigate emissions, with the ultimate goal of achieving carbon neutral trading. Construction sector has the greatest potential to reduce carbon emissions across the world as currently around 30% of global carbon emissions and 40% of global resource consumption is a result of building construction activity. Also with the economy growing rapidly and increased demand on the real estate industry, the construction industry maintains its growth all over the world. Raising concern on global warming and increasing corporate social responsibility (CSR) have made environmental issues an area of importance to address, for governments and businesses across the world.

1.1 Construction industry in the UAE and green initiatives

In United Arab Emirates (UAE), construction is the major contributor to environmental pollution due to its size and nature of activity. The total construction projects in UAE have an estimated worth of \$958bn as of 2010 and is expected to grow by 9.6% annually between 2010 and 2014 (Shah and Bullock, 2010). Among the Middle East countries, the UAE tops the list in terms of per capita energy spending and per capita carbon footprints (WWF – Living Planet Report, 2008). There is increasing pressure on UAE by world

environmental bodies and governments to cut down the carbon emissions and per capita energy spending.

According to the estimate made by the report on UAE Construction Industry Outlook (2012), UAE accounted for nearly 20.3% of total construction industry in the GCC having outpaced Saudi Arabia in 2008 and becoming the region's largest construction market. Although with slower growth during the global financial depression in 2009, the UAE construction industry still managed to record strong growth and contributed approx 8% to the country's GDP during 2009 (Figure 1). UAE Construction Industry Outlook (2012) also predicts that the UAE construction industry is expected to grow at a CAGR of around 20% during 2010–2013 due to economic development being refreshed which will definitely be a major force to speed up construction activity and infrastructure development in the UAE. Furthermore, the country has drawn investments from all over the world and will put the majority of investment on the development of fundamental infrastructure for tourism and hospitality, education and healthcare industry, etc. Accordingly, "the UAE will continue to develop several projects in tourism, housing, industrial and commercial facilities, education and healthcare amenities, transportation, communications, utilities, ports and airports" (UAE Construction Industry Outlook, 2012) as the mission and efforts of the UAE government has been to continue to diversify its economy from oil-based to other industries.

Figure 1 Construction industry growth rate in UAE (see online version for colours)



Source: Research and Market (2010)

Green supply chain (GSC) is still at its infancy stage in UAE where the construction industry is well established. In 2008, with the start of the economic recession, companies focused on survival and maximising the profits and have forgotten their environmental responsibility. Since 2008, UAE has started number of initiatives to reduce their environmental footprints due to growing international pressure from the world bodies and environmental groups. Abu Dhabi urban planning council in 2010 has introduced the 'pearl rating system' which is a framework for sustainable design and construction. It is now a mandatory requirement to consider and document sustainability aspects of new buildings. Dubai Electricity and Water Authority (DEWA, 2011) have introduced green building regulations which will be complemented by the Dubai municipality codes that

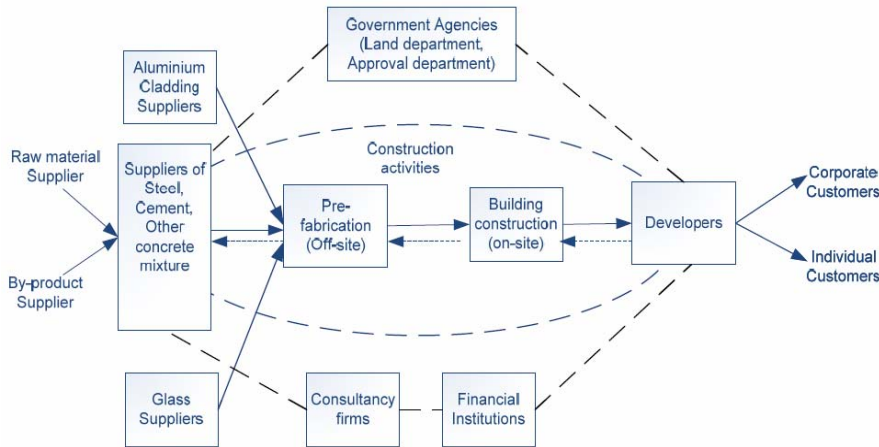
cover issues of site selection, materials used in construction, indoor environmental quality as well as waste management. The World Energy Forum, 2012 and World Future Energy Summit, 2013 were hosted by UAE in a bid to create awareness and promote sustainable living in the UAE. The initiatives have enabled organisations to adopt GSCM in their corporate strategy due to number of reasons.

It is estimated that 13%–18% of the total carbon emission (TCE) of a building is during its construction phase spanning over two to five years. In this GSC paper, we have developed a comprehensive framework to model and measure the carbon footprint across the supply chain network of the construction sector in the UAE. The re-defined supply chain network will focus on minimising the raw material, product and process wastages thereby minimising carbon emissions and help the construction industry players to reduce their carbon footprint.

1.2 Construction industry supply chain in UAE

Schematic representation of the construction supply chain is shown in Figure 2. The schematic representation shows the important activities that have an impact on the carbon emission in the construction industry. Carbon emission is accounted by the supply chain extending from the extraction of raw materials through the transportation of raw materials to the site and onsite construction activities. The schematic representation also shows how government policies and control on the leading property developers could restrain the carbon emission resulting from construction activities in UAE. The schema also represents the impact of developer activities on corporate social responsibility and application of innovative technologies that facilitates in the reduction of carbon emission.

Figure 2 Schematic representation of construction industry supply chain (see online version for colours)



2 Literature review

2.1 Review on models used in GSC

Qualitative studies in the topic of GSC are growing in terms of number of publications per year from the past decades. Articles by Lamming and Hampson (1996), Beamon (1999), EPA Report (2000), Udel (2006), Hoffman (2007) and Parry et al. (2007) have discussed the importance of GSC and its necessity. Zhu and Sarkis (2007) and Srivastava (2007) have extensively reviewed green manufacturing and GSC practices. However quantitative modelling using system dynamics have been used to model only the climate economy issues (Yohe and Wallace, 1996; Dowlatabadi, 1995) and energy economy issues (Beaver, 1993; De Vries and Janssen, 1996). Schuepp et al. (1990) and Hsieh et al. (2000) have also used quantitative models to measure industry level emissions. Similarly, Taylor (1989) and Lee et al. (2000) give a wide range of application of quantitative modelling related to pollution such as water quality, submarine outfalls, sediment erosion, oil dispersion and other pollution measures. These researches have shown that quantitative modelling can help us measure the pollution and emissions that are generated through different activities. Carbon footprint represents carbon emission that take place due to different activities. However, application of quantitative models in carbon footprint measurement has not been reported. As carbon footprint measurement is critical to assess the impact of supply chain practices on the environment, there is no specific model to evaluation and assess carbon footprint created by the construction industry supply chain. There is a knowledge gap that exists regarding a framework to evaluate the carbon footprint across the construction industry supply chain. Levin (1997) pointed out that construction industries often impact our environment significantly and irreversibly.

2.2 Review on GSC

Increasingly organisations have realised that environmental management is an important strategic issue to comply with mounting environmental regulations, to address the environmental concerns of their customers, and to enhance their competitiveness (Bacallan, 2000; Zhu et al., 2008). In supply chain management, one of the most important corporate strategies related to environmental improvement is the adoption of GSC.

The GSC has emerged as a strategy for many leading companies, including Dell, HP, IBM, Motorola, Sony, etc. (Zhu et al., 2006). "Much of the opportunity to address CO₂ emissions rests on the supply chain, compelling companies to look for new approaches to managing carbon effectively – from sourcing and production, to distribution and product after life" [Butner et al., (2008), p.1]. The increasing interests on GSC have also drawn research interests from various regions around the world. In Europe, a study surveyed 186 medium and large Spanish companies and identified two dimensions of pressures, namely, governmental and non-governmental pressures to explain the implementation of environmental practices in logistics (Gonzalez-Benito and Gonzalez-Benito, 2006). Another study which investigated UK supermarket retailers and its suppliers over a four-year period, suggested that firms invest in environmental supply-chain innovation because suppliers with poor environmental practices can expose the customer firm to high levels of environmental risk (Hall, 2006). In Canada, using four-year's panel data

across the oil and gas, mining, and forestry industries, researchers reported that both resource-based and institutional factors influence corporate sustainable development (Bansal, 2005).

The GSC has also received strong research interests from researchers in Asia. Researchers found that greening the different phases of the supply chain leads to an integrated GSC, which ultimately leads to competitiveness and economic performance (Rao and Holt, 2005). Most recently, a survey study in China, with data collected from four typical manufacturing industrial sectors, suggested that different manufacturing industry types display different levels of GSC management implementation and outcomes (Zhu and Sarkis, 2007). The GSC strategy has become one of the most important initiatives for many organisations to achieve competitive advantages (Rao and Holt, 2005) and corporate sustainable development (Bansal, 2005). Much of the literature assumed that the GSC strategy adoption is only driven by rationalistic and deterministic orientation guided by economic and political goals (Dubai Chamber of Commerce and Industry, 2008). However, because supply chain management involves the cooperation and interaction among multiple stakeholders (Banerjee et al., 2003), the decision to adopt the GSC strategy may have more to do with the institutional environment in which a firm is situated. Since this initiative could be influenced by the need for legitimacy, as well as social and economic fitness in a wider social structure, this study draws upon institutional theory to identify and examine key institutional determinants of GSC strategy adoption. It has been argued that organisations within an organisational field may conform to these rules and requirements, not necessarily for reasons of efficiency, but rather for increasing their legitimacy, resources, and survival capabilities (DiMaggio and Powell, 1983) investigating the GSC strategy adoption from an institutional theory lens would contribute to the current understanding of the key drivers for GSC strategy adoption.

Review on modelling in green/carbon emissions reveals that there are very few articles existing in the literature; for example, Sheu et al. (2005), Simpson et al. (2007), Zhu and Sarkis (2007, 2008) and Sundarakani et al. (2010). However these models discussed the quantification of the carbon emission based on green supply and manufacturing, and distribution point of view and not industry focused either or cannot be applied in construction industries in general.

2.3 Review on system dynamics models in supply chain

Originally, Forrester (1961) developed industrial dynamics, which he later extended and called system dynamics. In fact, Forrester has already developed a model for a simple supply chain which has four links, namely retailer, wholesaler, distributor, and factory. He examined how these links react to deviations between actual and target inventories. He found that common sense strategies may amplify fluctuations in the demand by final customers up the supply chain. Much later, Lee et al. (1997a, 1997b) identified this amplification as one of the bullwhip effects; also see Disney and Towill (2003). A recent case study is provided by Higuchi and Troutt (2004), who used SD to model the supply chain for the Japanese pet-toy called Tamagotchi. Spengler and Schröter (2003) also used SD to study the spare parts in a closed-loop supply chain at Agfa-Gevaerts. Ashayeri and Keij (1998) modelled the distribution chain of the European distribution arm of the US Company Abbott Laboratories (EDISCO).

Moreover, reviews of SD simulation of SCM are also not limited. To mention a few, Angerhofer and Angelidis (2000), presented an overview of recent research work in the

area of SD modelling in supply chain. De Souza and Chaoyang (2000) observed that delays in material flow and information flow have different effects on the dynamics. Eliminating them would improve the performance and service level. Swaminathan et al. (1998) described a supply chain modelling framework and discussed a reusable base of domain-specific primitives that enables rapid development of customised decision support tools. Lai et al. (2003) used a computer simulation system to explore the interactions making system dynamics modelling approach. Agarwal and Shankar (2002) discussed a modelling integration and responsiveness on supply chain performance using system dynamics approach. Sahay et al. (1996) developed an SD model for long term fertiliser demand, production and imports in India and also carried out a detailed sensitivity test to examine the robustness of the model.

Higuchi and Troutt (2004) discussed scenario-based dynamic simulations to study the short product life cycle case exemplified by a 'Tamagotchi' case. Lai et al. (2003) developed a system dynamics model for the just-in-time environment. Their integrated framework of JIT and Kanban model provides a new paradigm to analyse the logistics policies of a company and understand the customers, competitors and suppliers interaction that shape the company's performance over time. Shotaro and Daniel (2000) developed a system dynamics model that could contribute to improving the knowledge of the complex logistics behaviour of an integrated food chain. Oscar and Adolfo (2003) presented a classification of managerial spaces where multiple trading partners share critical information using e-collaboration tools and assess the possible local and global impact on the supply chain performance. Adolfo and Carol (2004) carried out a simulation study to extend current methods for real options strategies in the management of strategy commodity-type parts. Bernhard and Angerhofer (2000) developed a system dynamic model in supply chain management focusing the Forrester's supply chain. With this extensive literature review across the depth and width we have identified the research gaps and set the goals to further investigate our research question, which is "How to model the construction industry green supply chain systematically?" An initial form of the work was presented and published in the 8th Euroma Conference (Sundarakani et al., 2011). This paper is an extension of the model and analysis across width, depth and sensitivity analysis to draw some managerial implications that could be useful for construction industries both in UAE and worldwide.

3 Objective of the research

GSC concept has emerged and drawn public attention in the past few years especially with the increased natural disaster and global warming phenomena. Most of the research on the topic of 'green' employs qualitative research such as interviews and case study-based approaches which are largely interpretive in nature. These researches are more prescriptive and do not give any indication of the quantifiable benefits that would accrue from green practices. These researches help governments and business entities to understand the actual environmental impact of their green initiatives but do not provide quantifications of benefits and carbon savings resulting from these green practices.

The main objective of this research is to develop a system dynamics model for the construction industry supply chain that could be used to evaluate different GSC practices. In order to achieve this objective, the proposed research work aims to address the following main challenges:

- to explore the possible factors that contribute to the carbon emissions across the various stages of the construction industry SC
- to develop a system dynamics model to evaluate the carbon footprint for the construction industry SC
- to perform sensitivity analysis against multiple scenarios to understand the policy implications of factors pertaining to the construction industry in the UAE.

This research will create an analytical decision framework to assess emissions from across all stages and processes of the SC in the construction industry and would help to fill the knowledge gap that exists regarding carbon footprint assessment in the construction industry. The framework has the potential to be used by managers, construction organisations and or developers to reduce carbon emissions and draw further insights.

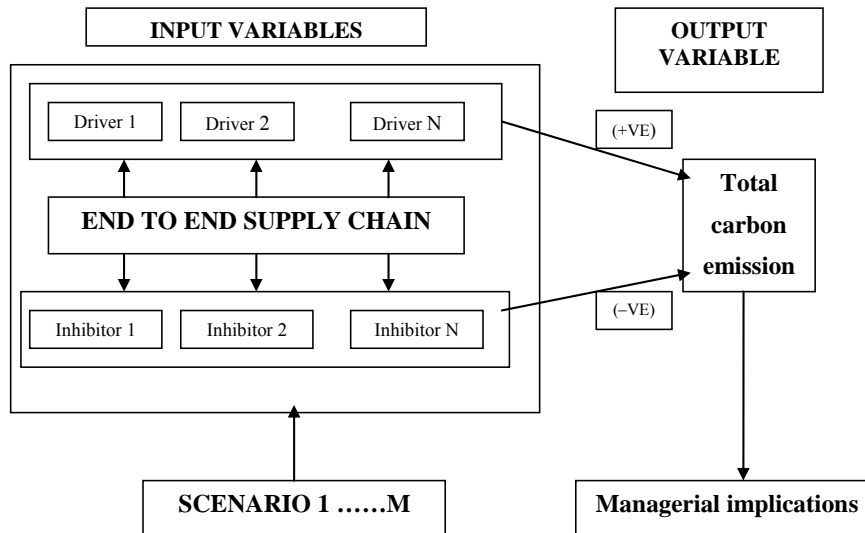
4 Research methodology

Designing a proactive construction supply chain plays a crucial role for implementing the GSC in the construction industry. The construction industry is different from other manufacturing sectors in the way they produce and distribute the goods to the various downstream entities. The end-to-end supply chain of the construction industry could be visualised as having two important phases of emission;

- a procurement phase involving emission from transportation of raw materials to site, raw material selection and its embodied emission, recycling of construction waste, etc.
- b construction phase involving mainly onsite activities.

These two phases consist of activities that would produce carbon emission and mostly would depend on the way the activities are carried out. These are the ‘drivers’ that positively impact the TCE of the construction industry.

However, there are certain factors like environmental regulations, societal pressures, best practices, etc., would act as ‘inhibitors’ and negatively impact on the TCE. The sum total of carbon emission related to these factors would provide the carbon footprint measure of the supply chain. The above relationship is modelled as shown in Figure 3. Different strategies for reducing carbon emission could be tested by creating scenarios of managerial decisions that would impact the factors (drivers and inhibitors) of the model and thus impact the total TCE. Similarly the model could also help identify which factors need to be affected to meet a stated TCE objective.

Figure 3 System dynamics-based representation of the TCEs

The proposed problem can be addressed by:

- identifying the ‘drivers’ and ‘inhibitors’ (and the variables behind each) that contribute to the carbon emissions across the various stages of the construction supply chain network through analysis of existing literature, databases and focused group surveys
- use system dynamic modelling techniques to develop a model to measure and represent the carbon footprint of the UAE’s construction industry supply chain
- analysis of the carbon footprint model to identify the specific challenges and issues involved in the construction industry supply chain network where green initiatives could be applied
- propose strategic and tactical advices to construction industry to proactively design their GSC.

5 Model development

A complete system dynamics modelling of construction supply chain requires the study of large number of variables using different levels of system parameters. A design incorporating all the parameters is practically impossible; hence we have included those parameters which have significant impact on achieving sustainability in the construction supply chain. At first the study looks at the various drivers and inhibitors of carbon emission in the construction supply chain. However the interactions of drivers with other drivers and inhibitors are complex and dynamic in nature. In order to understand the

cause and effect, and mediating relationship a system dynamics approach is used to model the construction supply chain

5.1 Identifying the drivers and inhibitors in the construction industry supply chain

A primary research based on focussed groups was conducted to identify the major drivers and inhibitors of carbon emission. This research was well supported by a secondary research using analysis of existing literature and databases.

5.1.1 Drivers of carbon emission

- Embodied emission of raw materials (aluminium, glass, steel, cement) – The energy used in the extraction and processing of a material is described as its embodied energy, distinguished from the energy used at other stages in the life cycle. Once an element or building has been defined, the whole life of the materials and products can be included in the energy value – the energy used to extract, transport and process raw materials and to convert them into manufactured products and components. Embodied emission factor for each raw material will provide a total estimate of embodied emission from the raw materials.
- Emission from to and fro transportation of raw materials – To bring the building materials for a project a company needs sourcing and purchasing capability from all over the world to satisfactorily meet the requirements of building construction demands. Emission resulting from the combustion of fuel (petrol, diesel, and gas) for transportation of raw materials to the construction site and transportation of waste to landfill would come under this category. Transportation levels are taken into account for the formation of supplies. As emission is affected by the transportation distance, based on the availability of the raw material either imported or sourced locally estimates of average transport distance has been factored in. For example, ready-mix concrete has a smaller average transport distance than steel. Carbon footprint estimates for fuel is calculated as KgCO₂ per litre of diesel.
- Emission from onsite activities – Emission from onsite activities include emission resulting from fuel combustion of onsite vehicles, onsite machinery and onsite usage of electricity. This portion includes the energy expenditure of typical construction equipment operating on site such as excavators, boom trucks, rollers, and pavers. The carbon footprint estimates use KgCO₂ per litre of diesel fuel consumed.

5.1.2 Inhibitors of carbon emission

- Government rules and regulations – Stringent rules and regulations from government on green design, green procurement, waste management, and energy management will reduce the carbon emission in the new construction buildings. However this rule should be enforced as mandatory rather than guidelines.
- Pressure from international environment groups – Pressure from international environmental groups on UAE is enforcing them to take immediate measures to cut down on the carbon emission. This will positively impact the government rules on GSC.

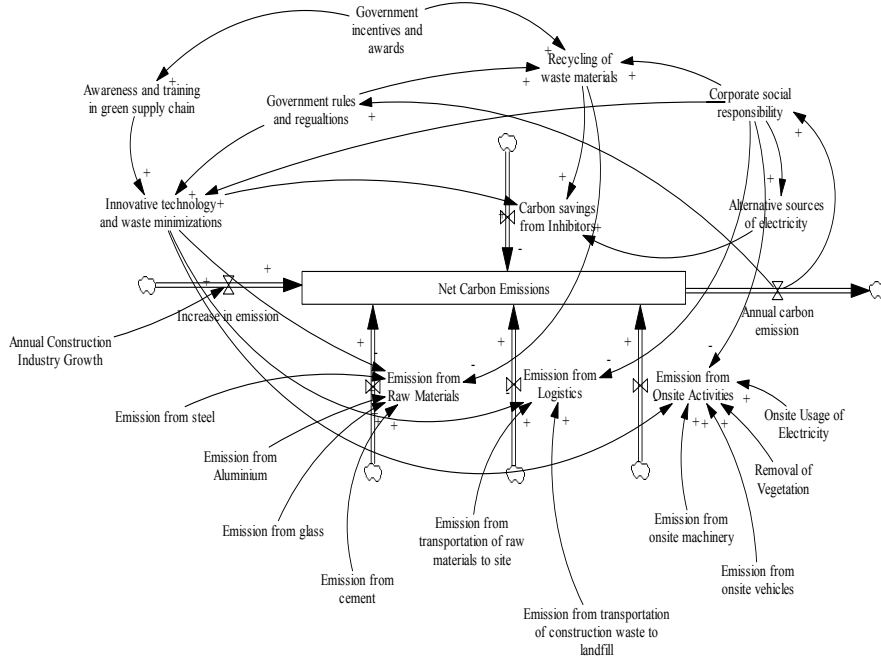
- CSR – Most of the companies in UAE are not showing CSR on reducing carbon emissions, however there are many foreign companies in UAE having CSR included as part of their vision and dedicated to cutting down emissions.
- Government incentives and best practices award – This will act as a motivation for organisation to reduce carbon emissions and also getting awards and recognition that can be used as a marketing tool for companies. This will have a positive impact in reducing carbon emission.
- Waste minimisation and recycling of waste – Waste minimisation can be achieved in the construction industry by better design, good project management and planning. Similarly recycling of waste materials results in less embodied emission of raw materials and hence reduce emissions.
- Alternate source of electricity – Alternate source of electricity like solar energy considering the climatic conditions of UAE is a good option to reduce emission from electricity.
- Counter measures – Improving the natural environment by creating man-made green areas like gardens and green belt around projects, landscaping and tree plantation activities will improve the natural environment and help to reduce the carbon emission and will impact positively and benefit the construction industry.

Identified factors for the model is provided in Table 1.

Table 1 Factors identified for the model

<i>Factors</i>	<i>Units</i>	<i>Classification</i>
Emission from steel	KgCO2/tonne	Driver
Emission from aluminium	KgCO2/tonne	Driver
Emission from glass	KgCO2/tonne	Driver
Emission from cement	KgCO2/tonne	Driver
Emission from transportation of raw materials to the site	KgCO2/l	Driver
Emission from transportation of construction waste to landfill	KgCO2/l	Driver
Emission from onsite machinery	KgCO2/l	Driver
Emission from onsite transportation of vehicles	KgCO2/l	Driver
Net emission from the removal of vegetation (biomass)	KgCO2/tonne	Driver
Emission from onsite usage of electricity	KgCO2/kWh	Driver
Government rules and regulations	KgCO2	Inhibitor
Corporate social responsibility	KgCO2	Inhibitor
Recycling of waste materials	KgCO2	Inhibitor
Awareness and training	KgCO2	Inhibitor
Innovative technologies and waste minimisation	KgCO2	Inhibitor
Alternative source of electricity	KgCO2	Inhibitor
Government incentives and best practices award	KgCO2	Inhibitor

Figure 4 System dynamics model of GSC



5.2 Stock and flow representation of green construction supply chain

Stock and flow model (Figure 4) is developed using system dynamics to measure the impact of each variable in the model. The effect of each variable can be studied in combination or can be studied separately by controlling the other variables depending on the situation and managerial implications of each variable can be drawn. The initial state of each variable is represented by the factor in the model. Each factor is defined by its corresponding weightage and per unit carbon emission. Measuring the carbon emission across all the variables (drivers and inhibitors) can be represented by the following equation (1).

$$TCE_s(t) \int \int \omega_{ij} \times d(E_i^I - I_j^I) / dt + TCE_s(0) \tag{1}$$

where the initial state of the system is,

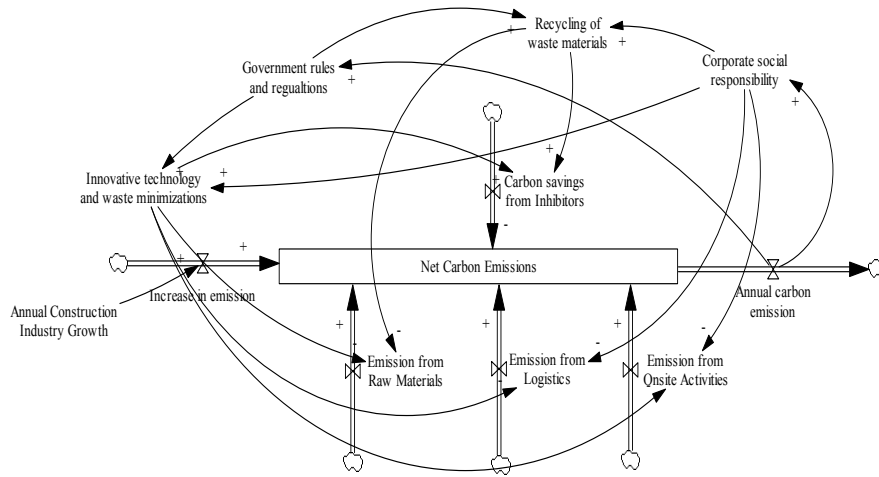
$$TCE_s(0) = E_s(0) - I_s(0) \tag{2}$$

- $TCE_s(t)$ is the total/net carbon emission of the system
- E_i^I is the amount of embodied emission from all drivers (I)
- I_j^J is the control on emission due to inhibitors (J)
- ω_{ij} is the weightage determining the quantum of drivers and inhibitors present in realistic consideration.

6 Sensitivity analysis

The sensitivity analysis is used to determine how sensitive a model is to changes in the value of the parameters of the model and to changes in the model structure. Here sensitivity analysis is performed for TCE in which factors affecting TCE are changed either individually or in combination to see the changes in the dynamic behaviour and to identify the impact of each factor. A complete investigation of the model behaviour requires large number of interactions with various factors; such detailed study is beyond the scope of the paper. So we limit the analysis to factors which we believe have significant impact on sustainability for the supply chain. A simplified model is used to perform the sensitivity analysis is given in Figure 5.

Figure 5 Simplified system dynamics model



The feedback loops from Figure 5 is provided in Table 2.

Table 2 consists of five feedback loops (C1–C5) involving CSR and five feedback loops (G1–G5) involving government rules and regulations. In C1 the annual increase in carbon emission leads to increase in corporate responsibilities which in turn increase the recycling of waste materials and hence reducing the emission from raw materials. This feedback is continued over time till the desired level of annual emission is achieved. Same scenario for feedback loops for C2–C5. In G1–G3 the annual increase in emission

leads to increase in government rules and regulations which in turn lead to innovative technology and waste minimisation and hence reducing emissions from raw materials, logistics and onsite activities. In G4–G5 government rules and regulations leads to direct carbon savings from inhibitors.

Table 2 Feedback loops

<i>Feedback loops</i>	<i>Structure</i>
C1	Annual carbon emission → Corporate social responsibility → Recycling of waste materials → Emission from raw materials → Annual Carbon Emission
C2	Annual carbon emission → Corporate social responsibility → Emission from logistics → Annual carbon emission
C3	Annual carbon emission → Corporate social responsibility → Emission from onsite activities → Annual carbon emission
C4	Annual carbon emission → Corporate social responsibility → Recycling of waste materials → Carbon savings from inhibitors → Annual carbon emission
C5	Annual carbon emission → Corporate social responsibility → Innovative technology and waste minimisation → Carbon savings from inhibitors → Annual carbon emission
G1	Annual carbon emission → Government rules and regulation → Innovative technology and waste minimisation → Emission from raw materials → Annual carbon emission
G2	Annual carbon emission → Government rules and regulation → Innovative technology and waste minimisation → Emission from Logistics → Annual carbon emission
G3	Annual carbon emission → Government rules and regulation → Innovative technology and waste minimisation → Emission from Onsite activities → Annual carbon emission
G4	Annual carbon emission → Government rules and regulation → Recycling of waste materials → Carbon savings from inhibitors → Annual carbon emission
G5	Annual carbon emission → Government rules and regulation → Innovative technology and → Carbon savings from inhibitors → Annual carbon emission

Three set of sensitivity analysis is conducted. In the first set of simulations government regulations is increased to 10% annually from 0% by keeping CSR constant. In the second set CSR is increased to 10% annual from 0% by keeping government rules and regulations constant. In the third set both CSR and government rules and regulations are increased to 10 annually %. The analysis is carried out by assuming both factors as zero at initial time $t = 0$ (base year 2011) and all other variables constant. The analysis is carried out for three years; as the authors believe both CSR and government rules and regulation cannot be increased infinitely and will achieve saturation at three years. The input data used for the analysis is provided in Table 3.

Table 3 Input parameters

<i>Input parameters</i>	<i>Values</i>	<i>Source</i>
Base year for analysis	2011	-
Per capita carbon emission for 2011	25 Metric tonne	World Bank Country Report of UAE (2008)
Per capita carbon emission contribution of construction sector	10 Metric tonne	UNEP (2009)
Per capita carbon emission contribution of construction activities(excluding emission related building life cycle)	2 Metric tonne	BIS (2010)
UAE construction industry growth	12.5% (approx.) annually	Alphen Capital (2012)
Per capita carbon emission from raw materials	1.4 Metric tonne	BIS (2010)
Per capita carbon emission from transportation	0.3 Metric tonne	BIS (2010)
Per capita carbon emission from onsite activities	0.3 Metric tonne	BIS (2010)

Four scenarios are considered for the simulations. Scenarios 1–3 are more ideal scenarios in which the variables varies at fixed rate and all other variables are assumed to be constant while ignoring random, transitory fluctuations. However scenario 4 is a more practical and realistic, in which the variables, government regulations and CSR varies depending on the market demand and industry growth.

The simulations reveal the following attributes associated with the variables of the system,

- Scenario 1: An annual increase of 10% in the government rules and regulation led to a 10% increase in innovative technology and waste minimisation and 10% increase in recycling of waste materials. This led to a 10% reduction in the emission from feedback loops G1–G5. The results show the per capita carbon emission achieves stability at 2.6 metric tonne.
- Scenario 2: An annual increase of 10% in the CSR led to a 10% increase in recycling of waste materials, 10% reduction in emission from logistics and 10% reduction from onsite emissions. This led to a 10% reduction in the emission from feedback loops C1–C5. The results show the per capita carbon emission achieves stability at 2.7 metric tonne.
- Scenario 3: An annual increase of 10% for both government rules and regulation and CSR is considered. This led to a 10% reduction in emission throughout the feedback loops G1–G5 and C1–C5. The results show per capita carbon emission achieves stability at 2.45 metric tonne.

The result of scenarios 1–3 is provided in Figure 6.

- Scenario 4: A practical scenario in which random and transitory fluctuations are considered depending on the construction industry growth and market demand. The government regulations fluctuate between from 10%to 30%, while the CSR fluctuates between 5% and 25%. The results show the per capita carbon emission varies around two metric tonne.

The result of scenario 4 is provided in Figure 7.

Figure 6 Simulation results of per capita net carbon emission against scenarios 1–3 (see online version for colours)

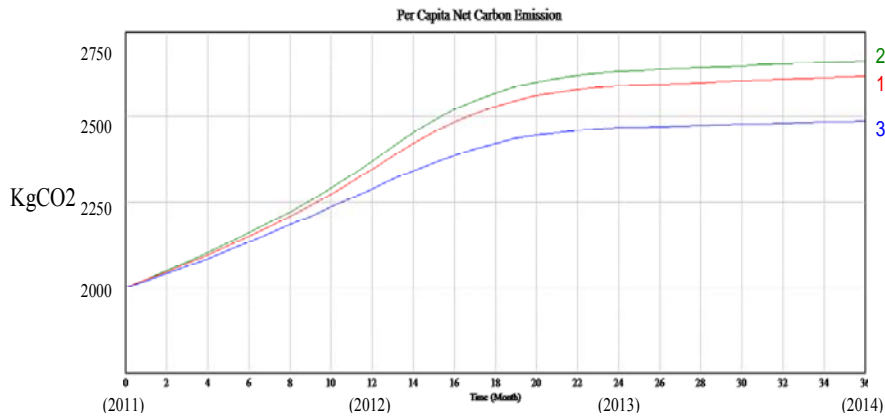
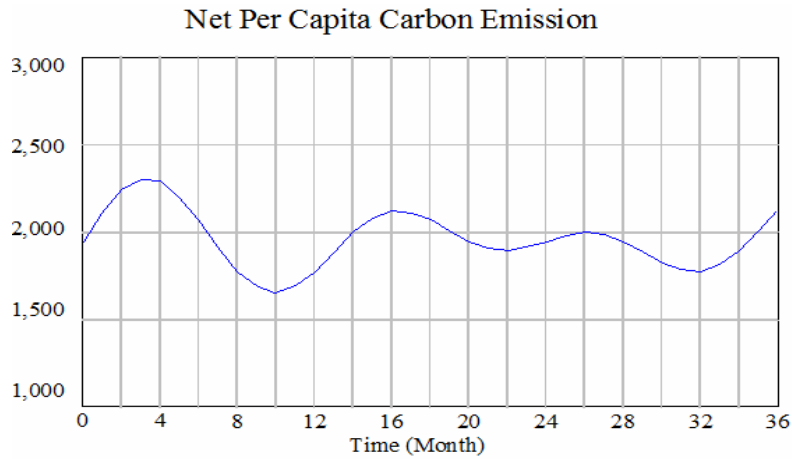


Figure 7 Simulation result of per capita net carbon emission against scenario 4 (see online version for colours)



7 Managerial implications

The research provides useful implications for real world applications on reducing the carbon emissions across the construction industry supply chain. System dynamics simulation helps managers to experimentally test every scenario and immediately evaluate the effectiveness of each scenario for potential carbon savings. This includes the potential benefits from carbon emission by incorporating CSR, training and awareness, green design, recycling of raw materials and innovative technologies. Quantifiable benefits of each factor enhance their commitment to become more energy efficient and more responsive to the demands of stakeholders for sustainable development.

Since most of the emissions are resulting from raw materials used in the construction, companies involved in green purchasing, especially for purchasing building material, should consider from where raw materials are obtained and how raw materials are extracted and processed. Hence the companies can mitigate the emission from the design stage itself. Green designs include low material consumption design, selection of environmentally friendly materials, and substitution of hazardous material and facilitate the reuse, recycle, and recovery of component materials and parts.

Additionally the firm needs to carefully select and assess the suppliers, decide the purchasing location having the least distance for transportation to avoid more emissions.

The model also provides the government insight how policies related to environmental protection could impact on carbon emission and also quantify the impact of such policies. This would help the government make a choice between different policies and regulation regarding implementation of GSC in the construction industry.

8 Conclusions

8.1 Finding highlights

In this paper, the system dynamics model of the construction industry supply chain has been developed based on the casual relationship for the identified factors. This provides a quantitative measure of the net carbon emission. Simulation of the model for different scenarios is used to evaluate the effectiveness of the model. The system dynamics model presented helps governments, environmental agencies, companies and managers to understand the underlying factors in the construction industry supply chain and thereby come up with different policies, strategies, rules and regulation to help reduce carbon emission. The proposed model specifically contributes to the literature of GSC and adds value to the empirical side of the operations management by highlighting the importance of green SC practices. In the current scenario, where eco-friendliness is playing an increasingly important role in the construction industry, this research is expected to provide valuable inputs for the construction industry supply chain for UAE and across the world.

8.2 Limitations of study

Only few factors are selected for the study and considering the fact there are more factors involved in the construction process, the study needs to be extended with the increased

number of factors and their interaction. Certain assumptions and approximation is used in the factors in order to quantify the subjective factors like CSR, government rules, etc. Life cycle assessment of the construction industry is not considered as this research is only limited to the construction phase of the building and not the operational phase. Since the construction phase accounts for only 13%–18% of the life cycle emission, study has to be extended to include life cycle assessment of carbon emission in the construction industry.

8.3 Future study/extensions

Extended system dynamics model of the construction industry supply chain can be developed from this model by including new variables and factors having direct or indirect influence on the supply chain. Cost implications of greening the construction industry has to be studied, since there will be always a trade-off between the cost involved and reducing carbon emissions. Future studies can incorporate cost implication as one of the factors. Similar studies can be extended to GCC especially Qatar, Kuwait and Saudi Arabia where the construction industry is similar to UAE.

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References

- Adolfo, C.M. and Carol, B. (2004) 'The procurement of strategic parts. Analysis of a portfolio of contracts with suppliers using a system dynamics simulation model', *International Journal of Production Economics*, Vol. 88, No. 1, pp.29–49.
- Agarwal, A. and Shankar, R. (2002) 'Modeling integration and responsiveness on a supply chain performance: a system dynamics approach', *International Journal of System Dynamics and Policy Planning*, Vol. XIV, Nos. 1 and 2, pp.61–83.
- Alphen Capital (2012) *GCC Construction Industry-Residential and Commercial Building Construction* [online] <http://www.alpencapital.com/media-reports-main.htm> (accessed 27 March).
- Angerhofer, B.J. and Angelidis, M.C. (2000) 'System dynamics modeling in supply chain management: research view', *Proceedings of the 2000 Winter Simulation Conference*, pp.342–351.
- Ashayeri, J. and Keij, R. (1998) 'Global business process re-engineering: a system dynamics based approach', *International Journal of Operations and Production Management*, Vol. 18, Nos. 9/10, pp.817–831.
- Bacallan, J.J. (2000) 'Greening the supply chain', *Business and Environment*, Vol. 6, No. 5, pp.11–12.
- Banerjee, S.B., Lyer, E.S. and Kashyap, R.K. (2003) 'Corporate environmentalism: antecedents and influence of industry type', *Journal of Marketing*, Vol. 67, No. 2, pp.106–122.
- Bansal, P. (2005) 'Evolving sustainably: a longitudinal study of corporate sustainable development', *Strategic Management Journal*, Vol. 26, No. 3, pp.197–218.

- Beamon, B.M. (1999) 'Designing the green supply chain', *Logistics Information Management*, Vol. 12, No. 4, pp.332–342.
- Beaver, R. (1993) 'Structural comparison of the models in EMF 12', *Energy Policy*, 3 March, Vol. 21, No. 3, pp.238–248.
- Bernhard, J. and Angerhofer, M.C.A. (2000) 'System dynamics modeling in supply chain management: research review', *Proceedings of the 2000 Winter Simulation Conference*, pp.342–351.
- BIS (2010) *Estimating the Amount of CO2 Emissions that the Construction Industry can Influence*, Department for Business and Innovation, Autumn, London, UK.
- Butner, K., Geuder, D. and Hittner, J. (2008) *Mastering Carbon Management: Balancing Trade-Offs to Optimize Supply Chain Efficiencies*, pp.1–13, IBM Global Business Services, New York, USA.
- De Souza, Z.R. and Chaoyang, L. (2000) 'Supply chain dynamics and optimization', *Integrated Manufacturing Systems*, Vol. 11, No. 5, pp.348–364.
- De Vries, B. and Janssen, M. (1996) *Global Energy Futures: An Integrated Perspective with the TIME Model*, National Institute for Public Health and the Environment (RIVM) Netherlands, GLOBO Series No. 17.
- DEWA (2011) *Green Buildings Regulations and Specifications* [online] http://www.dewa.gov.ae/images/greenbuilding_eng.pdf (accessed 1 March 2013).
- DiMaggio, P. and Powell, W.W. (1983) 'The iron cage revisited: institutional isomorphism and collective rationality in organizational fields', *American Sociological Review*, Vol. 48, No. 2, pp.147–160.
- Disney, S.M. and Towill, D.R. (2003) 'The effect of vendor managed inventory (VMI) dynamics on the bullwhip effect in supply chains', *International Journal of Production Economics*, Vol. 85, No. 2, pp.199–215.
- Dowlatabadi, H. (1995) 'Integrated assessment models of climate change: an incomplete overview', *Energy Policy*, Vol. 23, Nos. 4/5, pp.289–296.
- Dubai Chamber of Commerce and Industry (2008) [online] <http://web2.dubaichamber.ae/pdf/reports/GREEN%20SUPPLY%20CHAIN%20IN%20DUBAI.pdf> (accessed December 2010).
- EPA Report (2000) *The Lean and Green Supply Chain: A Practical Guide for Materials Managers and Supply Chain Managers to Reduce Costs and Improve Environmental Performance*, EPA 742-R-00-001, January.
- Forrester, J.W. (1961) *Industrial Dynamics*, MIT Press, Cambridge (Massachusetts), USA.
- GCC Powers of Construction (2010) *Construction Sector Overview*, December.
- Gonzalez-Benito, J. and Gonzalez-Benito, O. (2006) 'The role of stakeholder pressure and managerial values in the implementation of environmental logistics practices', *International Journal of Production Research*, Vol. 44, No. 7, pp.1353–1373.
- Hall, J. (2006) 'Environmental supply chain innovation', in: J. Sarkis (Ed.): *Greening the Supply Chain*, Springer, London.
- Higuchi, T. and Troutt, M.D. (2004) 'Dynamic simulation of the supply chain for a short life cycle product – lessons from the Tamagotchi case', *Computers & Operations Research*, Vol. 31, No. 7, pp.1097–1114.
- Hoffman, W. (2007) 'Who's carbon-free? Wal-Mart takes on supply chains of products as expansive carbon measuring plan eyes distribution', *Traffic World*, October 22, pp.1–2.
- Hsieh, C.I., Katul, G. and Chi, T. (2000) 'An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows', *Advanced Water Resource*, Vol. 23, No. 7, pp.765–772.
- Lai, C.L., Lee, W.B. and Ip, W.H. (2003) 'A study of system dynamics in just-in-time logistics', *Journal of Materials Processing Technology*, Vol. 138, No. 1, pp.265–269.
- Lamming, R. and Hampson, J. (1996) 'The environment as a supply chain issue', *British Journal of Management*, Vol. 7, No. 1, pp.45–62.

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- Lee, D.S., Kingdon, R.D., Jenkin, M.E. and Garland, J.A. (2000) 'Modeling the atmospheric oxidized and reduced nitrogen budgets for the UK with a Lagrangian multi-layer long range transport model', *Environmental Modeling and Assessment*, Vol. 5, No. 2, pp.83–104.
- Lee, H.L., Padmanabhan, B. and Whang, S. (1997a) 'Information distortion in a supply chain: the bullwhip effect', *Management Science*, Vol. 43, No. 4, pp.546–558.
- Lee, H.L., Padmanabhan, B. and Whang, S. (1997b) 'The bullwhip effect in supply chain', *Sloan Management Review*, Vol. 38, No. 3, pp.93–102.
- Levin, H. (1997) 'Systematic evaluation and assessment of building environmental performance (SEABEP)', Paper for presentation to *Buildings and Environment*, Paris, 9–12 June 1997.
- Oscar, R.O. and Adolfo, C.M. (2003) 'The effectiveness of using e-collaboration tools in the supply chain: An assessment study with system dynamics', *Journal of Purchasing & Supply Management*, Vol. 9, No. 4, pp.151–163.
- Parry, P., Martha, J. and Grenon, G. (2007) 'The energy efficient supply chain', *Strategy+Business*, Booz Allen Hamilton, No. 47, pp.1–10.
- Rao, P. and Holt, D. (2005) 'Do green supply chains lead to competitiveness and economic performance?' *International Journal of Operations & Production Management*, Vol. 25, No. 9, pp.898–916.
- Research and Market (2010) *The Future of Construction in United Arab Emirates (UAE) to 2014* [online] http://www.researchandmarkets.com/reports/1207132/the_future_of_construction_in_united_arab (accessed 1 March 2013).
- Sahay, B.S., Vrat, P. and Jain, P.K. (1996) 'Long term fertilizer demand, production imports in India: a system dynamics approach', *System Dynamics: An International Journal of Policy Modeling*, Vol. VIII, Nos. 1 & 2, pp.19–45.
- Schuepp, P.H., Leclerc, M.Y., MacPherson, J.I. and Desjardins, R.L. (1990) 'Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation', *Boundary-Layer Meteorology*, Vol. 50, Nos. 1–4, pp.355–373.
- Shah, R and Bullock, T. (2010) *GCC Powers of Construction 2010 Building the Future and Growing Stronger*, Deloitte Report [online] http://www.deloitte.com/view/en_AE/ae/industries/real-estate/a2e6e8c488f67310VgnVCM2000001b56f00aRCRD.htm (accessed March 2013).
- Sheu, J-B., Chou, Y-H. and Hu, C-C. (2005) 'An integrated logistics operational model for green-supply chain management', *Transportation Research Part E*, Vol. 41, No. 4, pp.287–313.
- Shotaro, M. and Daniel, T. (2000) 'System dynamics modeling and simulation of a particular food supply chain', *Simulation Practice and Theory*, Vol. 8, No. 5, pp.321–339.
- Simpson, D. and Power, D. (2007) 'Greening the automotive supply chain: a relationship perspective', *International Journal of Operations and Production Management*, Vol. 27, No. 1, pp.28–48.
- Spengler, T. and Schröter, M. (2003) 'Strategic management of spare parts in closed loop supply chains: a system dynamics approach', *Interfaces*, Vol. 33, No. 6, pp.7–17.
- Srivastava, S.K. (2007) 'Green supply-chain management: a state-of-the-art literature review', *International Journal of Management Reviews*, Vol. 9, No. 1, pp.53–80.
- Sundarakani, B., De Souza, R., Goh, M., Wagner, S. and Manikandan, S. (2010) 'Modeling the carbon footprint across the supply chain', *International Journal of Production Economics*, Vol. 128, No. 1, pp.43–50.
- Sundarakani, B., Sikdar, A., Balasubramanian, S. and Wagner, S.M. (2011) 'Greening the construction industry supply chain –using system dynamics', Published in the *Proceedings of 18th EUROMA Conference*, University of Cambridge, UK, ISBN 978-1-902546-94-0.
- Swaminathan, J., Smith, S.F. and Sadah, N. (1998) 'Modeling supply chain dynamics: a multiagent approach', *Decision Sciences*, Vol. 29, No. 3, pp.607–632.
- Taylor, J.A. (1989) 'A stochastic Lagrangian atmospheric transport model to determine global CO₂ sources and sinks – a preliminary discussion', *Chemical and Physical Meteorology*, Vol. 41-B, No. 3, pp.272–285.

- UAE Construction Industry Outlook (2012) [online] <http://www.rncos.com/Report/IM183.htm> (accessed 1 March 2013).
- UAE Interact (2009) [online] http://uaeinteract.com/docs/UAE_GDP_soars_23_to_Dh934_billion_in_2008_/36962.htm (accessed 05/11/2012).
- Udel, J. (2006) 'The carbon-adjusted supply chain', *Infoworld*, November 22.
- UNEP (2009) *Buildings and Climate Change*, United Nations Environmental Programme, Paris, France.
- World Bank Country Report of UAE (2008) [online] (accessed December 2011) <http://data.worldbank.org/country/united-arab-emirates>.
- WWF – The 2008 Living Planet Report (2008) [online] http://wwf.panda.org/about_our_earth/all_publications/living_planet_report/living_planet_report_timeline/lpr_2008/ (accessed December 2011).
- Yohe, G. and Wallace, R. (1996) 'Near term mitigation policy for global change under uncertainty: minimizing the expected cost of meeting unknown concentration thresholds', *Environmental Modeling and Assessment*, Vol. 1, No. 1, pp.47–57.
- Zhu, Q. and Sarkis, J. (2007) 'The moderating effects of institutional pressures on emergent green supply chain practices and performance', *International Journal of Production Research*, Vol. 45, Nos. 18–19, pp.4333–4355.
- Zhu, Q., Sarkis, J. and Lai, K. (2006) 'An inter-sectional comparison of green supply chain management in china: drivers and practices', *Journal of Cleaner Production*, Vol. 14, No. 5, pp.472–486.
- Zhu, Q., Sarkis, J. and Lai, K. (2008) 'Green supply chain management implications for closing the loop', *Transportation Research Part E*, Vol. 44, No. 1, pp.1–18.

Websites

- http://assets.wwf.ca/downloads/lpr_2008.pdf.
- http://uaeinteract.com/docs/UAE_GDP_soars_23_to_Dh934_billion_in_2008_/36962.htm.
- <http://www.meed.com/supplements/2010/quality-in-construction/turning-the-construction-industry-green/3006552.article> (accessed January 2011).
- <http://www.pe-international.com/america/services-solutions/green-building/>.
- <http://www.deloitte.com/.../GCC%20PPT%20CONSTRUCTION%20%20v2.pdf>.