ADAPTIVE LOGISTICS: PREPARING LOGISTICAL SYSTEMS FOR CLIMATE CHANGE.

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Abstract
Purpose: This paper outlines what is likely to become a new field of logistics research, focusing on the adaptation of logistical systems and supply chains to climate change. This research will essentially reverse the traditional causality of green logistics research, which examines the effects of logistical activities on the environment, to consider how logistics will have to be modified in response to the effects of climate change. The paper discusses five key areas of research that will require investigation, in each case reviewing relevant literature.

Research Approach: As this is a new field of research, the approach is essentially exploratory and speculative. It is based on a review of relevant literature, brainstorming sessions and discussions with a range of logistics specialists.

Findings and Originality: The paper highlights the difficulty of conducting research in this field when the nature and scale of climatic / ecological change is highly uncertain and its geographical impact highly variable. It argues that adaptive logistics should focus on five key themes and uses secondary data drawn from various sources to demonstrate their importance.

Research Impact:
The paper will highlight the need for research on this emerging topic, identify the key issues requiring investigation and suggest that a new branch of logistics be developed to address them. It will present classifications and frameworks that researchers can use in preliminary studies of the direct and indirect climate change impacts on logistics. It will also introduce logistics specialists to some of the relevant scientific literature.

Practical Impact:
Companies undertaking medium to long term strategic planning in logistics are beginning to factor the possible effects of climate change into their modelling. Meanwhile public policy-makers are assessing the likely impacts of climate change on the economy and built environment at national, regional and local levels. The paper should be interest to both sets of practitioner.

Keywords: Climate change, environmental impacts, logistical adaptation.

1. Introduction

Given atmospheric and ecological time lags, even if we were to achieve a dramatic decarbonisation of human activity today it would take several decades for this to have a noticeable impact on global climate. In other words, to use a logistical metaphor, there is a significant amount of climate change 'in the pipeline' which we cannot avert. Regardless of the long term effectiveness of carbon reduction measures being adopted today, it will be necessary, for at least several decades, to adapt our logistical systems and supply chains to the stresses of a climate-changed world. We have coined the expression 'adaptive logistics' as a collective term for the modifications that will be required to logistics systems to adjust to the effects of climate change. This new area of research could become an integral part of a wider, multi-disciplinary field of 'adaptive sciences'. One UK university has already set up a Centre for Adaptive Sciences[1].

In the climate change literature, an important distinction is made between 'mitigation' and 'adaptation'. To date, most of the research and debate on climate change has focused on mitigation, with the aim of reducing the rate of global warming and keeping it within environmentally sustainable limits. It is now accepted, however, that our response to climate change must be 'twin-pronged', with the implementation

[1] At the time of writing (June 2010), the website for this Centre is blank and 'awaiting content'.

of mitigation measures accompanied by efforts to adapt economies, societies, built environments and individual lifestyles to a warmer climate.

In essence, ‘adaptive logistics’ reverses the causality that has underpinned green logistics research, namely that logistics causes environmental damage, and considers how logistics will have to respond to environmental change. This response can either be *direct* where logistics systems must be modified to minimise adverse climate impacts or *indirect*, where climatic change alters the demand for logistical services and systems must be reconfigured accordingly. The scope of the subject can also be expanded to include the impact on logistics and supply chains of mitigation efforts by businesses, governments and individuals to cut their greenhouse gas (GHG) emissions (Figure 1).

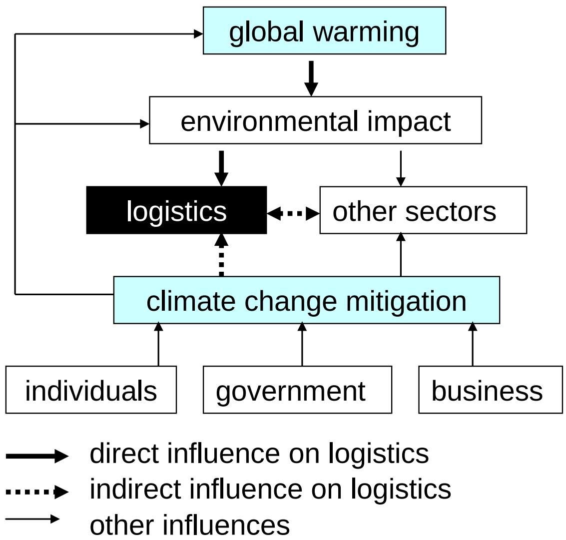

Figure 1: Direct and Indirect Pressures on Logistics to Adapt to Climate Change

This paper will outline the possible scope of this new field of logistics research. It will outline key areas for future research and the methodological challenges ahead. As it is a new field of research, the approach is inevitably exploratory, speculative and conceptual at this stage. It is based on a review of relevant literature, brainstorming sessions and discussions with a range of logistics specialists. The paper begins by considering the likely nature and scale of the environmental change. It then outlines five key areas of research that will require investigation, in each case reviewing relevant literature.

2. Nature and Scale of the Environmental Change

One obvious problem for this new branch of logistics is that the nature and scale of the environmental change is highly uncertain. The science of climate change is probabilistic, forecasting within wide confidence limits. This is illustrated by Figure 1, from the seminal report on the economics of climate change by Stern (2007). It shows the 5% and 95% confidence limits for particular concentrations of GHGs (expressed as parts per million of CO_2 equivalent [CO_{2e}]) raising average global temperature by differing amounts. It is the mean values, represented by the vertical lines, which are generally quoted, particularly the link between 450ppm and a 2^o C temperature rise, though, given the accuracy of current climate models, the degree of warming may vary within quite wide margins. As also shown in Figure 1, the concentrations of CO2e in the atmosphere by 2050 or beyond could also vary widely, partly dependent on the effectiveness of carbon mitigation efforts over the next few decades.

Scientists have greatest confidence in predictions of global mean temperate rises (DEFRA, 2009). This confidence is much lower for other climatic effects such as rainfall and the incidence and intensity of storms. It also diminishes as the geographical scale is reduced from global through continental and national to regional, making it very difficult to anticipate climate impacts at the smaller spatial scales at which many logistical systems are planned and managed.

Our understanding of the mechanisms by which rising temperature affect physical and biological systems is also limited. This introduces a third level of uncertainty into the prediction of environmental impacts. It is reflected, for instance, in differing estimates of the relationship between average global temperatures and sea level rise. The resulting predictions of sea level rise by 2100 (against a 1990 base level) vary enormously both within and between studies. IPCC (2007), Rahmstorf (2007) and Pfeffer (2008), for example, forecast sea level rises, respectively, within the ranges 18-59cm, 50-140cm and 80-200cm. A further dimension of uncertainty is added when one tries to predict the geographical distribution of geophysical responses to climate change. Some of the physical effects have a worldwide extent, such as sea level rise, while others, such as drought, extreme temperatures and the severity of storms, will be more localised. This makes forecasting the impact of climate change at national or regional levels even more formidable.

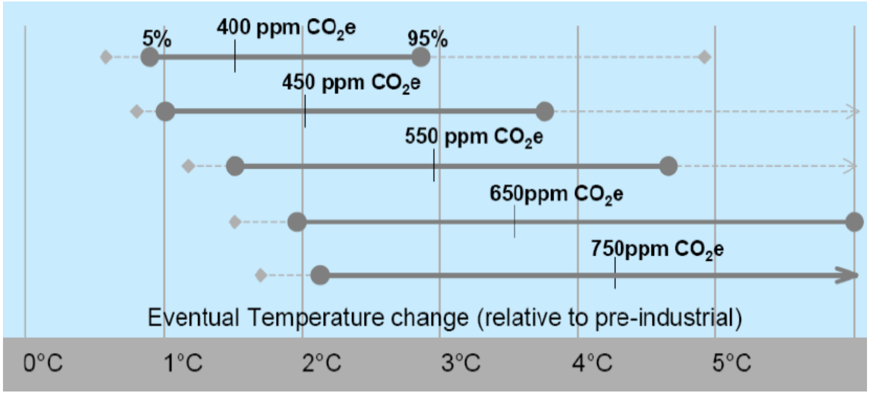

Figure 2: Estimated changes in average global temperatures for different GHG concentrations (Source: Stern, 2006).

When assessing the scale of the environmental challenge, it is not enough simply to predict the extent of the likely change. The rate of change is also very important. Many of the climatic and ecological projections, as well as government climate change mitigation programmes, assume steady incremental changes over a long period. There is mounting concern in the scientific community, however, that climate change and its related environmental effects will prove to be non-linear. The climatic record suggests that when certain thresholds (or 'tipping points') are crossed, abrupt changes in climatic conditions can occur within a few decades or even years (Pearce, 2007). We may not, therefore, have the luxury of adapting gradually to a warming planet. If climate change proves to be catastrophic rather than incremental, we will have to rely more heavily on humanitarian logistics, with its emphasis on emergency relief, than on adaptive logistics, which anticipates a more regular process of adjustment.

One could take the view that there is currently too much uncertainty about the magnitude and severity of climatic and ecological changes in the medium to long term to conduct meaningful research on the extent to which logistics systems and supply chains should be adapted. We consider this to be too negative a view. The uncertainty can be accommodated by constructing differing scenarios and incorporating sensitivity analysis into the logistics / supply chain modelling. A major goal of adaptive logistics will be to assess the vulnerability of logistics systems / supply chains to differing degrees of global warming and environmental impact.

3. Five Key Themes in Adaptive Logistics

These themes can be divided in three categories:

1. Responses to direct environmental impacts
2. Responses to indirect environmental impacts
3. Effects of climate change mitigation measures on logistics

1 (a) *Assessments of the impact of climate change on transport:* The Transportation Research Board (2008) has already made such an assessment of US transport infrastructure, focusing on five climatic effects: increases in the number of hot days / heat-waves, increase in Arctic temperatures, rising sea-level, increase in the number of 'intense precipitation events' and increase in 'hurricane intensity'. It acknowledges that the climatic tolerance limits within which transport infrastructure has been built will need to be widened to cope with the effects of global warming. Much of the existing infrastructure will be subject to temporary disruption, short-term damage and longer term degradation. For example, on the US Eastern seaboard, roughly 2200 miles of major roads and 900 miles of railroad in Maryland, Virginia,

North Carolina and the District of Columbia will be 'at regular risk of inundation' if the mid-range estimate of a 0.6 metre rise in sea-level occurs by 2100. The effect of sea level rise is amplified by the related increase in the frequency of storm surges (Jacob et al, 2007). Several studies have focused on the possible impact of sea-level rise and storm surges on port infrastructure (e.g. Nichols et al, 2008; Ligteringen, 2009 and the California State Lands Commission, 2009). In a wide ranging review of the effects of climate on transport system Koetse and Rietveld (2008) draw several conclusions of particular relevance to logistics. They note, for example, that climate change will alter the competitive position of different freight transport modes and that, as a result of sea-level rise, '*freight transport patterns by sea may be affected to a substantial extent*' (p.208).

Not all the impacts of climate change on the transport system will be negative, however. For example, seaways and inland waterways in northern latitudes will be open for more of the year and a continuation of the recent rate of summer ice-melt in the Arctic could open a 'Northern Sea Route' (NSR) between the Pacific and Atlantic Oceans. The NSR route between Yokohama and Rotterdam is approximately 4300km (39%) shorter than the route via the Suez canal. Somanathan et al (2007) established that the most critical factor affecting the economic viability of the NSR route for container vessels was the capital cost differential between a conventional Panamax ship and a vessel able to withstand with the remaining Arctic ice. Lui and Kronbak (2010) have recently assessed the relative economic attractiveness of the NSR route for a 4300 TEU containership, under varying conditions, and concluded that it could be profitable. Econ (2007), on the other hand, are more pessimistic about the prospects for an NSR concluding that 'it is still unclear whether continued growth in east-west trade would lead to an effective opening of the trans-arctic corridors by 2030, even with rapidly melting ice cap' (p. 14).

As transport infrastructure strongly influences the design and operation of logistics system, its sensitivity to climate change would be a major research focus within the new field of 'adaptive logistics'.

1 (b) *Assessments of the exposure of supply chains to climate change risks.* Some of these risks will be transport infrastructure-related and covered by 1(a). Others will be related to the nature and location of logistical facilities, particularly distribution centres and freight terminals. In a review of 'resilience in the food chain', Peck (2006) identifies flooding as a major risk factor. One food processor contributing to this study explained that, 'Major floods are our biggest danger… Most of the East Anglia sites are on the same flood plain. Head Office is on a flood plain, with flooding every 8 years and we have multiple distribution locations and 10 factory sites which are focussed factories which could not switch to other lines' (p. 102). Heavy snow cover on the roofs of some distribution centres in Germany during the severe winter of 2009-10 increased the risk of collapse to the level where staff had to be evacuated and operations disrupted. Around the same time, the roofs of 21 long term whisky warehouses in the highlands of Scotland, storing around 100 million gallons of malt whisky, collapsed under the weight of snow (McAllister and Christie, 2010), effectively illustrating the effects of climatic extremes on logistics operations. Climate change will exacerbate these problems. As the probability of severe weather events and scale of the related damage increases, companies will have to weigh up the relative costs of logistical disruption, 'climate-proofing' existing buildings or relocation to less vulnerable sites.

The analytical frameworks developed over the past decade to measure supply chain risk and resilience (e.g. Christopher and Peck, 2004; Peck, 2006) can be applied to research on topics 1(a) and 1(b) though they may need to be extended and tailored to the specific needs of climate change. Koetse and Rietveld (2008) outline three ways in which the effects of climate change on transport systems can be modelled:

(i) *Geographical comparison across different climatic zones:* In essence, climate change involves the migration of warmer climatic regions towards the poles: Mediterranean conditions, for example, will move northwards into more temperate latitudes. By comparing the current impact of climate on transport and logistics in different climatic zones, it is possible to predict, for a given region, future climatic stresses. One can also observe how companies and public agencies in a particular region have already adapted transport and logistics systems to prevailing climatic and environmental conditions.

(ii) *Temporal comparison of climatic impacts*: transport and logistics systems within a given region are routinely adjusted to variations in weather, both seasonally and over several years. One can extrapolate from these short-term variations in weather conditions and logistical responses to the longer term requirements for adaptation to climate change.

(iii) *Analysis of the past impact of extreme weather events*: the first two methods permit modelling of marginal changes in climate, but are unlikely to provide sufficient insight into the effects of extreme weather conditions on transport / logistics systems, conditions which currently may only occur every few decades but are likely to become much more frequent. The study by Grenzeback and Lukmann (2007) of the impact of hurricanes Katrina and Rita on the transport system of the SE USA and the subsequent human response provides a good illustration of this research approach.

2. *Analysis of the impact of climate-induced changes in agricultural patterns and human settlements on logistical systems and supply chains*: According to the IPCC (2007), changes in temperature regimes, water availability and disease will cause significant shifts in agricultural zones. Supply chains will have to be reconfigured to the new geography of food production and distribution. The IMPACT model, developed by the International Food Policy Research Institute (2009) to project 'global food supply, food demand and food security to 2020 and beyond' indicates that climate change will induce major changes to patterns of food production and trade flow. There will a large investment in new reservoirs, flood prevention and new settlements to accommodate populations displaced by extreme temperatures, drought and inundation (Agrawala and Fankhauser, 2008). The so-called low-elevation coastal zone (less than 10m above sea level) contains 10% of the global population and 13% of urban population, with China, India, Japan, Indonesia, the USA and Bangladesh particularly exposed (McGranahan et al., 2007). 'Climate-proofing' some vulnerable areas and relocating population from other areas likely to become uninhabitable will, *inter alia,* generate enormous flows of construction materials and transform supply chains for a wide variety of other products.

3.(a) Analysis of the impact of economy-wide decarbonisation programmes on logistical systems and supply chains. The demand for freight transport services will be affected by carbon reduction measures in other sectors. National governments and multi-national organisations have set economy-wide targets for the reduction in GHG emissions by years ranging from 2020 to 2050. The UK government, for example, is aiming to cut GHG emissions by 34% by 2020 and 80% by 2050 against a 1990 base-level. To our knowledge, no government has yet published sectoral GHG-emission targets. Targets should vary by sector in relation to the potential for GHG abatement and its relative cost effectiveness. Inter-sectoral variations in these key parameters are illustrated, in idealised fashion, in Figure 3 by the height and slope of the GHG-abatement lines. The reduction in GHG emissions in these other sectors will have an impact on the nature and demand for logistical services, depicted by the varying thickness of the arrows converging on the logistics sectors (again on an idealised basis). The complex interaction between decarbonisation initiatives in logistics and all these other sectors will make it extremely difficulty to model both the potential magnitude and cost-effectiveness of GHG-abatement in the logistics sector. This uncertainty is illustrated by the broken lines on Figure 3.

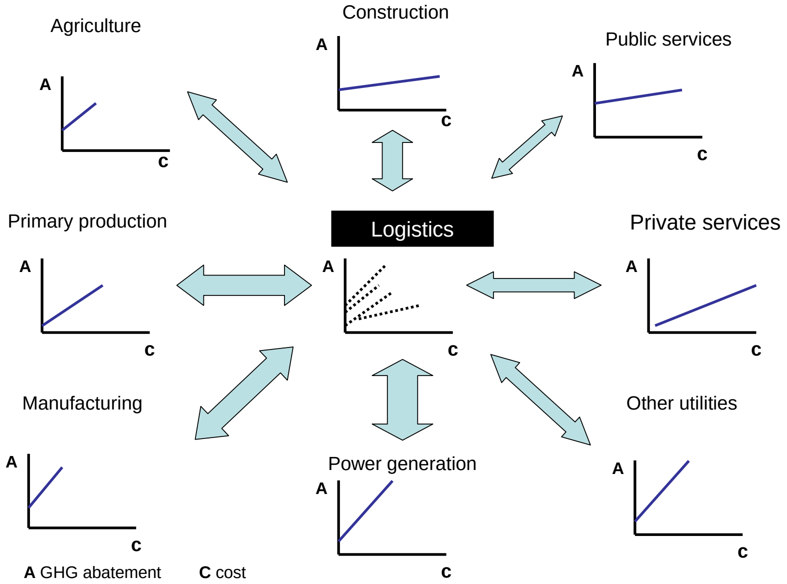

Figure 3: Sectoral Variations in the Potential for and Cost of GHG Abatement: Impact on Logistics

Critical to the creation of low carbon economies will be the decarbonisation of electricity generation (Committee on Climate Change, 2008). The transformation of the national energy mix from fossil fuels to renewables and nuclear power and the installation of carbon capture and storage systems on some of the remaining coal-fired power plants is likely to prove relatively transport-intensive during the construction phase. For example, the wind turbine industry is rapidly expanding, hugely increasing the amount of materials requiring transport and storage. Between 2004 and 2009 total global wind turbine capacity (measured in megawatts) increased 334% (World Wind Energy Assoc, 2010). The average wind turbine contains 8000 different components (Aubrey, 2007), sourced from numerous, geographically-dispersed suppliers. Lack of capacity in the component supply sector has been forcing the main turbine assemblers to source parts more widely (De Vries, 2008), though blade and tower suppliers are endeavouring to source more materials locally to minimise transport costs (Emerging Energy Research, 2009). As shown in Figure 4, wind power requires the installation of much more steel and concrete per megawatt of power generated than coal-fired, natural gas or nuclear power stations (Petersen, 2006). On the other hand, once they are installed wind turbines can remove the need to move large quantities of fossil fuel. If, for example, sufficient wind turbine capacity were installed in the EU27 by 2020 to generate 180 gigaWatts of power (enough to meet the needs of 107 million households), around 28 million tonnes of oil could be removed from the fuel supply chain annually. The substitution of fossil fuel by biofuel, batteries and, possibly, hydrogen, will also require complete restructuring of the energy supply chain. Bonilla and Whittaker (2008) have examined the freight transport implications of a major expansion of bioenergy production and distribution in the UK. New global supply chains will have to be established to transport large quantities of lithium from the major sources of this mineral in countries such as Bolivia and China to battery manufacturing plants around the world.

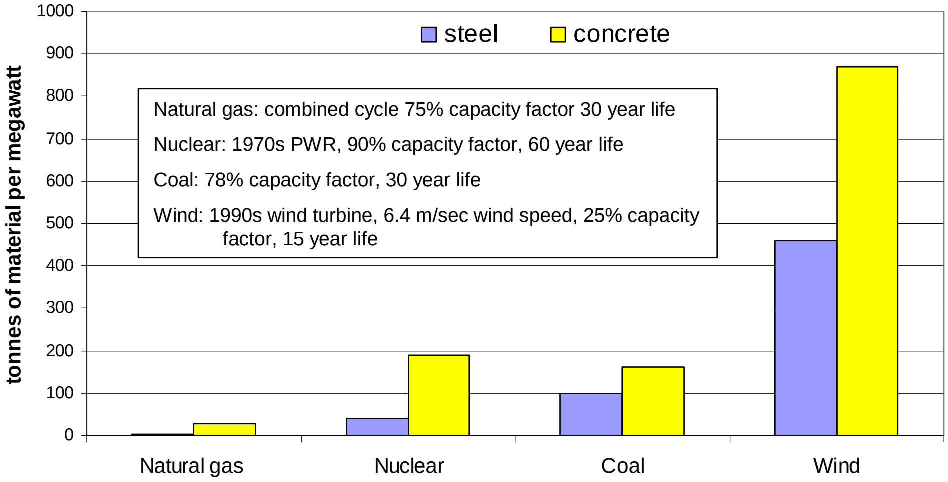

Figure 4: Quantities of Steel and Concrete Required per megawatt for Different Types of Power Generation

The expansion of rail-based public transport systems to divert personal travel from aircraft and private cars will also require a high level of logistical support. So too, for example, will steep increases in the insulation of homes, commercial premises and public buildings and the creation of new value chains for the batteries required to 'electrify' much of the car, van and rigid truck fleet. Ironically the freight transport-intensity of national economies may rise temporarily as governments strive to decarbonise the built environment. There is a danger that we could get into a logistical 'vicious circle' with our efforts to cut GHG emissions, particularly on capital projects, actually generating a net increase in emissions , at least in the short to medium term.

3 (b) Exploring the logistical implications of the geo-engineering options that may be required to rescue mankind from runaway climate change: Should current efforts to cut GHG emissions drastically over the next few decades fail or prove inadequate, it may be necessary to resort to the much more radical, geo-engineering options. These fall into two categories: carbon dioxide removal (CDR) and solar radiation management (SRM). CDR techniques which absorb (or 'sequester') CO_2 from the atmosphere, artificially reinforcing the earth's natural systems for keeping CO_2 concentrations in check. They would address the main cause of climate change and carry lower risks than SRM, though would take longer to restrain the increase in global temperatures. CDR could be achieved by constructing machines capable of capturing CO_2 from ambient air (know as 'carbon scrubbers') (Adam, 2008), by fertilising the oceans with nutrients to promote 'algal blooms' which would absorb more CO_2 and enhancing the weathering of silicate rocks, a chemical process which converts CO_2 gas into a solid mineral. SRM techniques would weaken the greenhouse effect by reflecting a small proportion of the sun's rays back into space. The most promising

SRM option is to disperse aerosols, mainly of sulphur dioxide, in the stratosphere in more northerly and southerly latitudes.

These geo-engineering measures would have to be applied on a planetary scale to exert enough influence on global climate. As Launder and Thompson (2008) explain,'While such geo-scale interventions may be risky, the time may well come when they are accepted as less risky than doing nothing.' Little research has so far been done on the logistical support required to implement these geo-engineering measures. Clearly they would entail the movement of vast amounts of material by land, sea and air. Order of magnitude estimates have been made of the quantities of material that would have to be distributed for some of the options. For example, the enhanced weathering option would entail mining and grinding huge quantities of rock and dispersing it widely over fields. A study by the Royal Society (2009) has estimated that 'a volume of about 7 km^3 per year (approximately twice the current rate of coal mining) of such ground silicate minerals, reacting each year with CO2, would remove as much CO_2 as we are currently emitting' (p.14). Rasch et al (2008) have estimated that between 1.5 and 5 million tonnes of sulphur would need to dispersed in the stratosphere to neutralise the global warming effect. The Royal Society study concludes that this would be 'feasible' as the 'mass involved is less that a tenth of the annual payload of global air transportation, and commercial transport aircraft already reach the lower stratosphere' (p.32). As the aircraft dispersing the aerosol would emit CO_2, compounding the root cause of the climate change problem, it has been proposed that instead a 'hose to the sky' suspended from helium balloons be used to pump the aerosol into the stratosphere. This plan, known as 'StratoShield', is discussed by Levitt and Dubner (2009). Lambitt et al (2008) envisage the use of a 'submarine pipe' to pump 'cocktails of macro- and micronutrients' into the oceans to increase their carbon sequestration potential. They express concern however that 'the energetic costs of producing the cocktail and piping it from the land to regions of nutrient limitation are likely to be large with a carbon footprint that may be greater than the carbon sequestered' (p.7). Strenuous efforts would have to be made to minimise the carbon footprints of these geo-engineering schemes to maximise the net environmental benefit and much of these 'footprints' would be logistics-related. Logistics would be a particularly important issue for the use of carbon scrubbing devices as they would have to manufactured in enormous numbers and, presumably, distributed to locations well endowed with low / zero carbon electricity from renewable or nuclear sources.

Discussion

This paper advocates the development of a new branch of logistics focusing on the adaptation of logistics systems and supply chains to the direct and indirect effects of climate change. It has identified five related topics that could be investigated under the heading of 'adaptive logistics'. It is not our intention, however, to be too prescriptive. Other topics could usefully be studied within this emerging field. For example, patterns of consumption will inevitably change as a result of global warming, inducing another indirect form of logistical adaptation. As people switch to products and services more suited to a warmer climate and to greener goods with lower 'embedded' carbon, there will be a corresponding redistribution of material flows between supply chains. Researchers, however, will have difficulty disentangling these climate change-related shifts in final demand from all the other factors affecting consumer behaviour such as advances in technology, demographic trends, changing fashions and life-styles, trends in oil and other raw material prices and government economic policy.

This highlights a more general problem that one encounters when trying to define the boundaries of adaptive logistics. Logistics systems and supply chains are constantly evolving. As demonstrated by numerous PEST / PESTEL studies over the years, they are subject to a variety of political, economic, social, technological, environmental and legislative pressures, interacting in complex ways. The direct and indirect effects of global warming on logistics and supply chains will be mediated through these six dimensions of change, often making them difficult to isolate and assess. If, over the next 30-40 years, global warming comes to dominate political and corporate agendas, as many commentators now predict, other issues typically addressed in the PESTEL framework may be subordinated to the twin goals of decarbonisation and climate change adaptation. Climate may then become the main driver of logistical change, permeating most areas of government and company decision-making in this field.

References:

- Adam, D. (2008), 'Could US scientist's 'CO_2 catcher' help to slow warming' *Guardian*, 31 May.
- Agrawala, S. and Fankhauser, S. (eds) (2008), *Economic Aspects of Adaptation to Climate Change*, OECD, Paris.
- Aubrey, C. (2007), 'Supply chain; the race to meet demand' *Wind Directions*, Jan / Feb.

- Bonilla, D. and Whittaker, C. (2009), *Freight Transport and Deployment of Bioenergy in the UK,* Working paper 1043, Transport Studies Unit, Oxford University, Oxford.
- Christopher, M. and Peck, H. (2004), 'Building the resilient supply chain' *Inter. Jour. of Logistics* Management, vol 15 no. 2, pp.1-13.
- Committee on Climate Change (2008), *Building a Low Carbon Economy: the UK's Contribution to Tackling Climate Change*. London.
- DEFRA (2009), *Adapting to Climate Change: UK Climate Projections*. London
- De Vries, E. (2008), '*The Challenge of Growth: Supply Chain and Wind Turbine Upscaling challenges'* http://www.renewableenergyworld.com/rea/news/article/2008/06/the-challenge-of-growth-supply-chain-and-wind-turbine-upscaling-challenges-52689
- Econ (2007), *Arctic Shipping 2030.* Report 2007-070. Commissioned by Norshipping, Oslo.
- Emerging Energy Research (2009), *Wind Turbine Supply Chain Strategies 2009-2010*, Cambridge, Mass.
- European Environment Agency (2008), *Impact of Europe's Changing Climate: 2008 Indicator-based Assessment,* Copenhagen.
- European Wind Energy Association (2007) *Wind Energy: the Facts,* Brussels.
- Grenzeback, L.R. and Lukmann,A.T. (2007), *Case Study of the Transportation Sector's Response to and Recovery from Hurricanes Katrina and Rita*, Cambridge Systematics, Cambridge Mass.
- International Food Policy Research Institute (2009), *Climate Change: Impact on Agriculture and Costs of Adaptation*, Washington DC.
- Kenny, B. (2008), 'Wind turbine supply chain spinning up' *Industry Week*, December 15.
- Koetse, M.J. (2009), 'The impact of climate change and weather on transport: an overview of empirical findings' *Transportation Research*, part D, vol. 14, pp. 205-221.
- Lampitt, R.S. et al (2008), 'Ocean fertilisation: a potential means of geoengineering' *Phil. Trans. of the Royal Society A*., doi: 10.1098.
- Launder, B. and Thompson, J.M.T. (2008), 'Preface to Theme Issue on 'Geoscale engineering to avert dangerous climate change', *Philosophical Transactions of the Royal Society*.
- Levitt, S.D. and Dubner, S.J. (2009), *Superfreakonomics.* Allen Lane, London.
- Ligteringen, H. (2009), *Consequences of Climate Change and Inland Waterways in the Netherlands,* TU Delft, Delft.
- McAllister, D. and Christie, E. (2010), 'Whisky warehouse roofs collapse under weight of snow and ice' *Press and Journal,* 8 January.
- Liu, M. and Kronbak, J. (2010), 'The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe' *Jour. of Transport Geography*, vol.18, no.3
- McGranahan,G., Balk,D. and Anderson, B. (2007), 'The rising tide: assessing the risks of climate change and human settlements in low-elevation coastal zones' *Environment and Urbanization,* vol. 19 no.1.
- Nicholls, R.J. et al (2008), *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates*, OECD Environment working paper 1. OECD, Paris.
- Pearce, F. (2007), *The Last Generatio*n Eden Project Books, London.
- Peck, H. (2006), 'Reconciling supply chain vulnerability, risk and supply chain management' *Inter. Jour. of Logistics: Research and Applications,* vol 9, no. 2, pp. 127-142.
- Petersen, P.F. (2006), *Current and Future Activities for Nuclear Energy in the United States,* presentation to CITRIS Research Exchange, University of Berkeley.
- Pfeffer, W.T., Harper, J.T. and O'Neal, S. (2008), 'Kinematic constraints on glacier contribution to 21st century sea-level rise' *Science*, vol. 321, no. 5894, pp. 1340-1343.
- Rasch, P.J. et al (2008), 'An overview of geoengineering of climate using stratospheric sulphate aerosols' *Phil. Trans. of the Royal Society A*., doi: 10.1098.
- Rahmstorf, S. (2007), 'A semi-empirical approach to projecting future sea-level rise' *Science*, vol. 315, no. 5810, pp. 368-70
- Royal Society (2009), *Geoengineering the Climate: Science, Governance and Uncertainty* London.
- Somanathan, S., Flynn, P.C. and Szymanski, J.K. (2007), 'Feasibility of a sea route through the Canadian arctic' *Maritime Economics and Logistics*, vol. 9, pp. 324-334.
- Stern, N. (2007), *Stern Review: the Economics of Climate Change,* HM Treasury, London.
- Transportation Research Board (2008), *Potential Impacts of Climate Change on US Transportation*, TRB Special Report 290, TRB, Washington DC.
- World Wind Energy Assoc. (2010), *World Wind Energy Report 2009*, Bonn.